

## IMPACT OF SHUNT FACTS DEVICES ON SECURITY CONSTRAINED UNIT COMMITMENT

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**Abstract-** Shunt FACTS Devices (SFD) are playing an important role in maintaining security and reduce Total Generation Cost (TGC) in the economical operation of power systems. The ability of SFD to control the power flow and voltage support on the AC model of security-constrained unit commitment (SCUC) for the day ahead scheduling are studied. The proposed SCUC with SFD increases the network controllability at normal and contingency operation. A general SFD model is introduced for the reactive power management in SCUC which is based on the reactive power injection model (RPIM). Case studies demonstrate the combined use of these devices to SCUC have a significant impact on maintaining network security, preventing Load Shedding (LS), lower TGC and increase transfer capability of the existing transmission network.

**Keywords:** Shunt FACTS Devices (SFD), Unit Commitment (UC), Security-Constrained Unit Commitment (SCUC), Network-Constrained Unit Commitment (NCUC), Network-Constrained Optimal Power Flow (NCOPF), Security-Constrained Optimal Power Flow (SCOPF), Benders Decomposition (BD), Load Shedding (LS), Total Generation Cost (TGC).

### I. INTRODUCTION

The primary objective of the SCUC problem is to obtain the minimum TGC simultaneously maintaining the security of the system. The ISO executes the SCUC program to plan a secure and economic scheduling of units over a given time horizon for serving the hourly load while satisfying operational limits of generation and transmission facilities in power systems [1-6].

The maximum transfer capability, without adversely affecting the stability and security margin, can be achieved through a fast power flow control. FACTS enhance controllability and increase power transfer capability of the network. The first application of FACTS devices is a fast power flow control and voltage stability [7-10]. In this paper, a general model of SFD is incorporated in the proposed SCUC formulations.

Figure 1 shows the flowchart of the proposed SCUC model. This figure includes UC and NCOPF/SCOPF. In accordance UC result, NCOPF calculates the optimal

dispatch of units to minimize the bid-based operating cost at steady state. In accordance NCUC result, SCOPF calculates the optimal dispatch of units to minimize the bid-based operating cost at contingency condition. BD is utilized to decompose the SCUC problem into smaller and easier to solve subproblems [11-18].

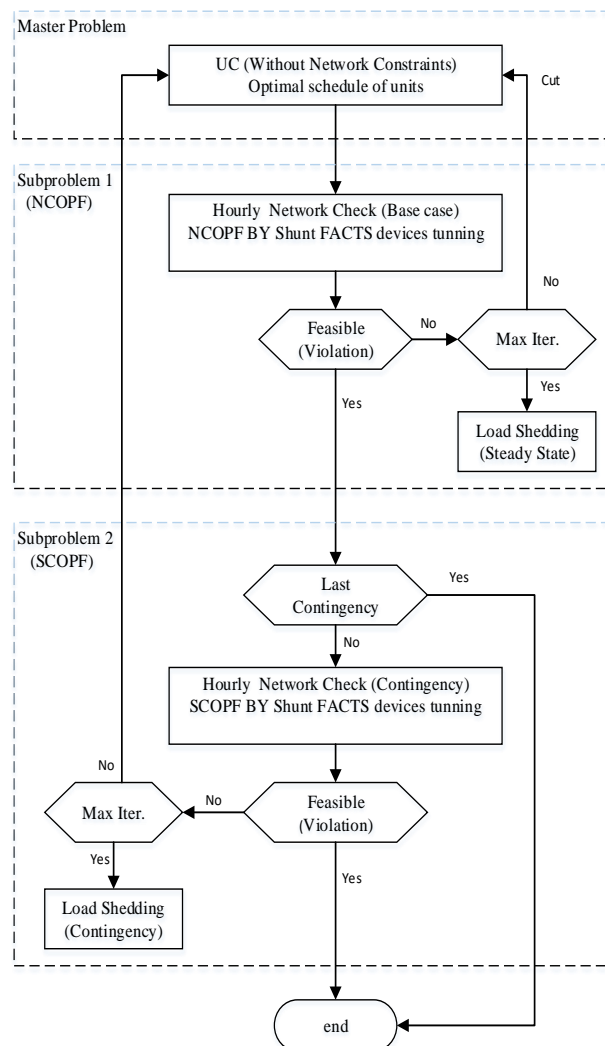


Figure 1. Flowchart of SCUC with shunt FACTS devices for reactive power management

The master problem uses the available market information to find the optimal hourly schedule of units. The hourly solution of UC is used in the subproblems to test the AC network constraints at steady state and contingency [15-26]. The SFD are incorporated in the subproblems. In accordance unit schedule by the UC solution, the Subproblem 1 will check the base case network feasibility. In this subproblem, slack variables for real and reactive power mismatches are minimized based on line flow and SFD tuning.

The proposed Benders cut incorporates slack variables for the real and reactive power mismatch that is mitigated by recalculating the unit schedules. If NCOPF cannot converged, LS may be used to manage a feasible solution. A converged base case power flow will be achieved based on the UC results. The contingencies network check subproblem, i.e., subproblem 2, uses the UC solution for the base case to check the system security in case of contingencies. Using AC power flow equations, both real and reactive power mismatches are minimized in this subproblem. If SCOPF cannot converged, LS shall be used to manage a feasible solution [18].

## II. PROBLEM FORMULATION

### A. UC Formulation

The objective of the UC problem is to determine the set of generating units while minimizes the total production cost over the scheduling period [18]:

$$\min TGC = \sum_{i=1}^{Nu} \sum_{h=1}^{Nh} \left\{ \begin{aligned} &F_i(P_{ih}) + SU_{ih}(1 - Z_{i(h-1)}) \\ &+ SD_{ih}(1 - Z_{ih})Z_{i(h-1)} \end{aligned} \right\} Z_{ih} \quad (1)$$

Due to the operational requirements, the objective function minimization is subjected to the following constraints:

#### a) Power balance constraints

$$\sum_{i=1}^{Nu} P_{ih} Z_{ih} = P_{Dh} + P_{Lh} \quad (2)$$

$$\sum_{i=1}^{Nu} Q_{ih} Z_{ih} = Q_{Dh} + Q_{Lh}$$

#### b) Spinning and operating reserve constraints

$$\sum_{i=1}^{Nu} [R_{S,ih} Z_{ih}] \geq R_{Sh} \quad (3)$$

$$\sum_{i=1}^{Nu} [R_{O,ih} Z_{ih}] \geq R_{Oh}$$

#### c) Minimum up/down time constraints

$$[X_{i(h-1)}^{on} - T_i^{on}] \cdot [Z_{i(h-1)} - Z_{ih}] \geq 0 \quad (4)$$

$$[X_{i(h-1)}^{off} - T_i^{off}] \cdot [Z_{ih} - Z_{i(h-1)}] \geq 0$$

#### d) Power generation limit constraints

$$P_i Z_{ih} \leq P_{ih} \leq \bar{P}_i Z_{ih} \quad (5)$$

$$Q_i Z_{ih} \leq Q_{ih} \leq \bar{Q}_i Z_{ih}$$

#### e) Ramping Up/Down limits

$$P_{ih} - P_{i(h-1)} \leq \leq [1 - Z_{ih}(1 - Z_{i(h-1)})] RU_i + Z_{ih}(1 - Z_{i(h-1)}) P_i \quad (6)$$

$$P_{i(h-1)} - P_{ih} \leq \leq [1 - Z_{i(h-1)}(1 - Z_{ih})] RD_i + Z_{i(h-1)}(1 - Z_{ih}) P_i$$

### B. NCUC/SCOPF with Load Shedding [18]

$$\min TGC = \sum_{i=1}^{Nu} \sum_{h=1}^{Nh} \{ F_i(P_{ih}) Z_{ih} \} + \sum_{k=1}^{Nvu} \sum_{h=1}^{Nh} F_{sk}(VP_{kh}) \quad (7)$$

#### a) Power balance constraints

$$\sum_{i=1}^{Nu} P_{ih} Z_{ih} + \sum_{k=1}^{Nvu} VP_{kh} = P_{Dh} + P_{Lh} \quad (8)$$

$$\sum_{i=1}^{Nu} Q_{ih} Z_{ih} + \sum_{k=1}^{Nvu} VQ_{kh} = Q_{Dh} + Q_{Lh}$$

#### b) Spinning and operating reserve constraints

$$\sum_{i=1}^{Nu} [R_{S,ih} Z_{ih}] \geq \frac{R_{Sh}}{P_{D,h}} \left( P_{D,h} - \sum_{k=1}^{Nvu} VP_{kh} \right) \quad (9)$$

$$\sum_{i=1}^{Nu} [R_{O,ih} Z_{ih}] \geq \frac{R_{Oh}}{P_{D,h}} \left( P_{D,h} - \sum_{k=1}^{Nvu} VP_{kh} \right)$$

#### c) Generation limit constraints

$$P_i Z_{ih} \leq P_{ih} \leq \bar{P}_i Z_{ih} \quad (10)$$

$$Q_i Z_{ih} \leq Q_{ih} \leq \bar{Q}_i Z_{ih}$$

#### d) Ramping Up/Down limits

$$P_{ih} - P_{i(h-1)} \leq \leq [1 - Z_{ih}(1 - Z_{i(h-1)})] RU_i + Z_{ih}(1 - Z_{i(h-1)}) P_i \quad (11)$$

$$P_{i(h-1)} - P_{ih} \leq \leq [1 - Z_{i(h-1)}(1 - Z_{ih})] RD_i + Z_{i(h-1)}(1 - Z_{ih}) P_i$$

#### e) The power flow equations

$$G_b(X, U, C) = 0 \quad , \quad b = 1, 2, \dots, N_b \quad (12)$$

#### f) The transmission line flows constraint

$$P_l \leq P_{lh} \leq \bar{P}_l \quad , \quad l = 1, 2, \dots, N_l \quad (13)$$

#### g) The voltage of the buses

$$V_b \leq V_b \leq \bar{V}_b \quad , \quad b = 1, 2, \dots, N_b \quad (14)$$

#### h) The shunt FACTS devices constraint

$$P_{sf} \leq P_{sf} \leq \bar{P}_{sf} \quad , \quad f = 1, 2, \dots, N_f \quad (15)$$

$$Q_{sf} \leq Q_{sf} \leq \bar{Q}_{sf} \quad , \quad f = 1, 2, \dots, N_f$$

## III. CASE STUDIES

The proposed model is applied to a thirty -bus test system to illustrate the performance of SCUC. The thirty-bus system depicted in Figure 2 has five units, forty-one transmission lines. The characteristics of units, transmission lines, and the hourly load distribution over the 24-h horizon are given in Tables 1-3, respectively [28].

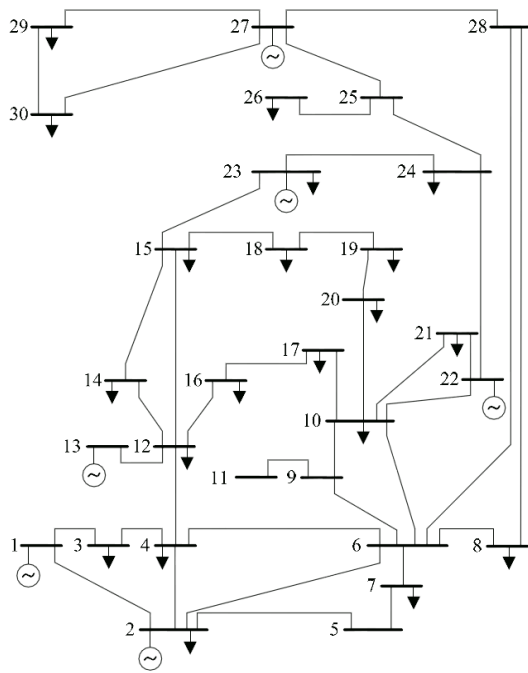


Figure 2. The 30-bus system [27]

- Case 1) UC;
  - Case 2) NCUC;
  - Case 2-1) NCUC without SFD.
  - Case 2-2) NCUC with SFD at bus 8.
  - Case 2-3) NCUC with SFD at buses 7, 8, 21 and 30.
  - Case 3) NCUC; SFD device at bus 8 are used to;
  - Case 3-1) committed to minimizing TGC.
  - Case 3-2) regulate related magnitude voltage bus 8 at 1.0 (pu).
  - Case 4) SCUC by outage of line 6-8 (contingency dispatch);
  - Case 4-1) SCUC without SFD.
  - Case 4-2) SCUC with SFD at buses 7, 8, 21 and 30.
  - Assume the LS contract is 500\$/MWh.
  - Case 5) failure in unit 3 (contingency dispatch);
  - Case 5-1) SCUC without SFD.
  - Case 5-2) SCUC with SFD at buses 7, 8, 21 and 30.
  - Assume the LS contract is 500\$/MWh.
- In some cases, according Table IV, SFD are considered. This devices are modeled using the proposed RPIM [18].

Case 1) In this case, UC will determine the base case schedule of units without considering the network constraints. The commitment schedule is shown in Table 4. Hour 0 illustrates the initial condition. The TGC is \$ 142203.6145. The optimal generation dispatch given in Table 5. In this case, the economical units 1, 2 and 4 supplies the base load, which are committed at the entire scheduling horizon. The unit 3 are committed at certain hours (11-21) to supply peak load and to minimize the TGC. More costly units, four and five, are not committed at all hours.

Case 2) In cases 2-1 to 2-3, NCUC is studied. If the UC results in Case 1 utilizes for NCOPF calculations, magnitude voltage violations will occur at buses 12-20. By

considering the network constraints, the other unit commitment shall be find. The NCUC commitment schedule and optimal generation dispatch is shown in Tables 4 and 5, respectively. The highlighted items show differences between Case 1 and these section cases. In order to maintaining the magnitude voltage buses to their limits ( $0.95 \leq V \leq 1.05$ ) and line capacity limits in accordance Table 2, the generation dispatch of the economical units 1, 2, 3 and 4 is changed. The costly units 5 and 6 are committed to supply the system peak loads. So, the TGC increases to \$ 169505.19. In cases 2-2 and 2-3, the SFD inject the controllable reactive power to the network and also manage reactive power flows and accordingly adjust bus voltage levels. The SFD decrease the reactive power flow on the network lines and therefore increase the transfer capability of the lines. In case 2-2 and 2-3 the voltage at all buses and the reactive power flow at network lines is changed by the SFD. In case 2-2, the reactive power generation by SFD at bus 8 is shown in Table 7. In case 2-3, the reactive power generation by SFD is shown in Figure 3. The NCUC commitment schedule and optimal generation dispatch are shown in Table 6 and 7. Without the SFD the voltage drop occur at all buses mostly at peak hours. However, the reactive power injection to the network increases the bus voltages and prevents voltage and line capacity violations. Without the SFD, voltages are adjusted by the neighboring generating units. The reactive power generation of units is increased for adjusting the voltage level at buses, which would also increase the reactive power flow at network lines. So, the SFD could reduce the active and reactive power dispatch of units, decrease reactive power line flows, bus voltage support and minimize the TGC. In the whole cases are mentioned, case 2-3 has the minimum TGC and less committed more expensive units. Therefore distributed SFD in load buses is better choice for power system planning.

Case 3) In these cases (3-1 and 3-2), NCUC will determine schedule of units when SFD is committed to minimizing total generation cost (case 3-1) and regulate related bus voltage at 1 pu. The commitment schedule is shown in Table 8 and active power generation dispatch in Table 9. It is clear that when the SFD committed to regulating corresponding bus voltage is less effective on minimizing cost function. Therefore, it is desirable this controllable devices should be adjust based on NCUC planning. If contingency is occurred, the SCUC determines the setting of SFD. The capacity of this equipment should be determined based on long-term planning. The reactive power generation by SFD is given in Table 9. The highlighted items in Tables 8 show differences between all these section cases compared to case 1.

Case 4) The transmission line outage, line 6-8, according to NCUC results, will cause the line capacity 6-28, 8-28, 21-24 and 22-24 out of permissible range. The addition of Benders cuts to the SCOPF for a preventive dispatch control will provide a feasible dispatch solution. Then Benders cuts are generated to recalculate unit commitment.

The unit commitment is given in Table 10. However, at hours 1-24, because of bus voltage and mentioned line capacity limits, if all of the units is committed still cannot satisfy the network constraints. Thus, virtual generator are added at bus 8 to curtail certain amount of load at violated hours (1-24). Despite LS cost, the daily bid-based dispatch cost is more increased. The new generation dispatch in SCOPF is illustrated in Table 11. In case 4\_2, the considering of SFD in the network has caused that magnitude voltage of the buses are not out of range. But because of line capacity limits or network congestion in this case, the SFD does not help to prevent load curtailment at hours 8-24. The highlighted items in Tables 10 show differences between all this section cases compared to case 1. In case 4-2, Because of entire reactive power injection controlling and reactive power flow managing in network, the SFD are the best option in optimizing cost, less load curtailment and maintaining network security. It is clear with distributed SFD in network and supporting of all bus voltages has the better result in NCUC/SCUC problems. The reactive power generation by SFD is shown in Figure 4.

Case 5) In cases 5-1 to 5-2, the generating unit 2 out of service. Thus, the Benders cut is generated to recalculate unit commitment for this contingency. The commitment schedule is shown in Table 12 and active power generation dispatch in Table 13. The highlighted items in Tables 12 show differences between all this section cases compared to case 1. By comparison optimal generation dispatch in Tables 7 and 13, it is clear that the expensive units 3, 5 and 6 replaces unit 2 to supply more loads. In case 5-2, by

economic adjusting of SFD in the network has caused that magnitude voltage of the buses are not out of range. The reactive power generation by SFD is shown in Figure 5.

IV. CONCLUSIONS

The NCUC/SCUC results of case studies display the effectiveness of the proposed method to minimize the TGC and maintain network security in steady state and contingency. Impact of SFD tuning was investigated into the NCUC/SCUC with AC network constraints at steady state and contingency. To enhance the proposed AC solution of SCUC, SFD were considered. A RPIM was used to model the effect of SFD in the AC power flow, using reactive power injections to system load buses. We concluded that the incorporation of SFD would enhance the hourly SCUC solution when considering bus voltage and line capacity constraints.

If the SFD with the sufficient capacity at full load centers to be installed and utilized, more effective in the short-term power system planning will yield. Distributed fast controllable shunt reactive power resources will regulate bus voltage, less reactive power flow and reduce losses in the power system. Furthermore, the use of maximum capacity of the transmission system will be provided. Meanwhile, economic dispatch of load between power plants can provide. With turn off more expensive units in low and medium demand hours, the total production cost decreases. More expensive units may be used in terms of network emergency event if needed to maintain network security. Therefore proper operation of this equipment in the SCUC is necessary.

APPENDICES

Appendix 1. Characteristics of Units, Transmission Lines and Load

Table 1. Characteristics of units [28]

Unit No.	1	2	3	4	5	6	
Bus No.	1	2	13	22	23	27	
Unit Cost coefficients	<i>a</i> (MBtu)	150	180	125	200	90	75
	<i>b</i> (MBtu/MWh)	30	20.75	36.3	12.9	42.6	45.8
	<i>c</i> (MBtu/MW <sup>2</sup> h)	0.02	0.0175	0.0125	0.00625	0.0135	0.0124
<i>P</i> <sub>min</sub> (MW)	10	10	10	10	10	10	
<i>P</i> <sub>max</sub> (MW)	90	80	70	80	90	90	
<i>Q</i> <sub>min</sub> (Mvar)	-20	-15	-10	-15	-20	-20	
<i>Q</i> <sub>max</sub> (Mvar)	70	60	50	60	70	70	
Start Up cost (\$)	20	30	10	40	10	10	
Shut down cost (\$)	40	60	20	80	20	20	
Fuel Cost (\$/MBtu)	1.00	1.00	1.00	1.00	1.00	1.00	
Initial Hour State (h)	2	4	1	4	1	1	
Minimum Up Time (h)	2	4	1	4	1	1	
Minimum Down Time (h)	-1	-2	-1	-2	-1	-1	
Ramp Up Rate (MW/h)	50	40	30	40	20	30	
Ramp Down Rate (MW/h)	60	45	25	50	25	40	

Table 2. Characteristics of transmission lines [28]

Line No.	From Bus	To Bus	<i>R</i> (pu)	<i>X</i> (pu)	<i>B</i> (pu)	Flow Limit (MW)	Line No.	From Bus	To Bus	<i>R</i> (pu)	<i>X</i> (pu)	<i>B</i> (pu)	Flow Limit (MW)
1	1	2	0.02	0.06	0.03	130	22	15	18	0.11	0.22	0	16
2	1	3	0.05	0.19	0.02	130	23	18	19	0.06	0.13	0	16
3	2	4	0.06	0.17	0.02	65	24	19	20	0.03	0.07	0	32
4	3	4	0.01	0.04	0	130	25	10	20	0.09	0.21	0	32
5	2	5	0.05	0.2	0.02	130	26	10	17	0.03	0.08	0	32

6	2	6	0.06	0.18	0.02	65	27	10	21	0.03	0.07	0	32
7	4	6	0.01	0.04	0	90	28	10	22	0.07	0.15	0	32
8	5	7	0.05	0.12	0.01	70	29	21	22	0.01	0.02	0	32
9	6	7	0.03	0.08	0.01	130	30	15	23	0.1	0.2	0	16
10	6	8	0.01	0.04	0	40	31	22	24	0.12	0.18	0	16
11	6	9	0	0.21	0	65	32	23	24	0.13	0.27	0	16
12	6	10	0	0.56	0	32	33	24	25	0.19	0.33	0	16
13	9	11	0	0.21	0	65	34	25	26	0.25	0.38	0	16
14	9	10	0	0.11	0	65	35	25	27	0.11	0.21	0	16
15	4	12	0	0.26	0	65	36	28	27	0	0.4	0	65
16	12	13	0	0.14	0	65	37	27	29	0.22	0.42	0	16
17	12	14	0.12	0.26	0	32	38	27	30	0.32	0.6	0	16
18	12	15	0.07	0.13	0	32	39	29	30	0.24	0.45	0	16
19	12	16	0.09	0.2	0	32	40	8	28	0.06	0.2	0.02	32
20	14	15	0.22	0.2	0	16	41	6	28	0.02	0.06	0.01	32
21	16	17	0.08	0.19	0	16							

Table 3. Characteristics of load [28]

Hour	$P_d$ (MW)	$Q_d$ (Mvar)	Hour	$P_d$ (MW)	$Q_d$ (Mvar)	Hour	$P_d$ (MW)	$Q_d$ (Mvar)
1	191.9610	108.7893	9	230.6920	130.7392	17	278.3770	157.7635
2	181.1370	102.6551	10	244.8930	138.7873	18	279.4000	158.3433
3	177.0450	100.3360	11	253.2640	143.5313	19	274.8240	155.7499
4	174.1740	98.7090	12	264.9350	150.1456	20	267.4870	151.5919
5	175.1420	99.2575	13	272.8550	154.6341	21	258.5660	146.5361
6	181.9730	103.1289	14	274.5930	155.6190	22	244.7940	138.7312
7	197.8020	112.0996	15	276.1000	156.4731	23	228.2390	129.3490
8	214.8410	121.7560	16	277.3320	157.1713	24	221.8590	125.7333

Appendix 2. Simulation Results

Table 4. UC (Case 1), NCUC (Case 2-1)

Hour		0	1-6	7-10	11	12-21	22-24	
Case 1	Unit No.	1	1	1	1	1	1	
		2	1	1	1	1	1	
		3	1	0	0	1	1	0
		4	1	1	1	1	1	1
		5	1	0	0	0	0	0
		6	1	0	0	0	0	0
Case 2-1	Unit No.	1	1	1	1	1	1	1
		2	1	1	1	1	1	1
		3	1	0	1	1	1	1
		4	1	1	1	1	1	1
		5	1	0	0	0	1	0
		6	1	1	1	1	1	1

Table 5. Active Power (MW) Generation Dispatch UC (Case 1), NCUC (Case 2-1)

Hour	The daily cost of bid based generation dispatch (\$)											
	142203.6145						169505.19					
	Case 1						Case 2-1					
	Unit No.						Unit No.					
	1	2	3	4	5	6	1	2	3	4	5	6
1	31.961	80	0	80	0	0	57.56	80	0	48.95	0	10
2	21.137	80	0	80	0	0	42.88	80	0	52.21	0	10
3	17.045	80	0	80	0	0	37.69	80	0	53.06	0	10
4	14.174	80	0	80	0	0	34.09	80	0	53.62	0	10
5	15.142	80	0	80	0	0	35.30	80	0	53.44	0	10
6	21.973	80	0	80	0	0	43.97	80	0	52	0	10
7	37.802	80	0	80	0	0	46.27	80	10	55.82	0	10
8	54.841	80	0	80	0	0	65.96	80	10	54.07	0	10
9	70.692	80	0	80	0	0	86.27	80	10	50.74	0	10
10	84.893	80	0	80	0	0	90	80	24.99	46.58	0	10
11	83.264	80	10	80	0	0	90	80	36.98	43.10	0	10
12	90	80	14.935	80	0	0	90	80	37.42	44.80	10	10
13	90	80	22.855	80	0	0	90	80	48.46	41.87	10	10
14	90	80	24.593	80	0	0	90	80	51.02	41.08	10	10
15	90	80	26.1	80	0	0	90	80	53.30	40.34	10	10
16	90	80	27.332	80	0	0	90	80	55.21	39.69	10	10
17	90	80	28.377	80	0	0	90	80	56.86	39.11	10	10

18	90	80	29.4	80	0	0	90	80	57.37	38.35	10.93	10.33
19	90	80	24.824	80	0	0	90	80	51.37	40.97	10	10
20	90	80	17.487	80	0	0	90	80	40.92	43.90	10	10
21	88.566	80	10	80	0	0	90	80	45.20	40.34	10	10
22	84.794	80	0	80	0	0	90	80	24.85	46.62	0	10
23	68.239	80	0	80	0	0	83.03	80	10	51.31	0	10
24	61.859	80	0	80	0	0	74.75	80	10	52.72	0	10

Table 6. NCUC (Case 2-2, Case 2-3)

Hour		0	1-2	3-5	6-8	9	10	11-16	17-18	19-21	22	23	24	
Case 2-2	Unit No.	1	1	1	1	1	1	1	1	1	1	1	1	
		2	1	1	1	1	1	1	1	1	1	1	1	1
		3	1	0	0	0	1	1	1	1	1	1	1	0
		4	1	1	1	1	1	1	1	1	1	1	1	1
		5	1	0	1	0	0	0	0	0	0	0	0	0
		6	1	1	0	1	1	1	1	1	1	1	1	1
Case 2-3	Unit No.	1	1	1	1	1	1	1	1	1	1	1	1	
		2	1	1	1	1	1	1	1	1	1	1	1	
		3	1	0	0	0	0	1	1	1	1	1	0	0
		4	1	1	1	1	1	1	1	1	1	1	1	1
		5	1	0	0	0	0	1	1	0	1	0	1	1
		6	1	0	0	0	0	0	0	0	0	0	1	0

Table 7. Active Power (MW) Generation Dispatch, NCUC (Case 2-2, Case 2-3)

Hour	The daily cost of bid based generation dispatch (\$)												
	164063.2							159658.89					
	Case 2-2							Case 2-3					
	Unit No.						Q <sub>SF</sub> (MVAR)	Unit No.					
1	2	3	4	5	6	Q <sub>SF</sub> (MVAR)	1	2	3	4	5	6	
1	48.85	80	0	57.15	0	10	77.97	61.13	80	0	55.69	0	0
2	36.80	80	0	57.85	0	10	74.87	48.55	80	0	56.74	0	0
3	23.13	80	0	57.34	10	0	64.33	43.83	80	0	57.12	0	0
4	29.99	80	0	57.42	10	0	64.06	40.53	80	0	57.40	0	0
5	31.05	80	0	57.40	10	0	64.15	41.64	80	0	57.31	0	0
6	37.72	80	0	57.82	0	10	75.27	49.52	80	0	56.66	0	0
7	55.59	80	0	56.55	0	10	79.27	68.09	80	0	54.94	0	0
8	76.44	80	0	53.85	0	10	83.05	89.52	80	0	51.71	0	0
9	81.02	80	10	55.59	0	10	81.78	89.15	80	0	57.28	10	0
10	90	80	16.92	54.64	0	10	86.64	84.31	80	10	56.15	10	10
11	90	80	26.42	53.59	0	10	87.31	79.42	80	44.25	56.02	0	0
12	90	80	40.29	51.55	0	10	87.73	86.95	80	49.51	55.58	0	0
13	90	80	50.22	49.73	0	10	88.02	90	80	54.99	55.32	0	0
14	90	80	52.47	49.27	0	10	88.09	90	80	56.81	55.27	0	0
15	90	80	54.44	48.85	0	10	88.15	90	80	58.46	55.22	0	0
16	90	80	56.07	48.50	0	10	88.20	90	80	60.07	54.91	0	0
17	90	80	56.98	48.09	0	10.55	88.22	90	80	49.72	55.16	10	0
18	90	80	56.98	47.51	0	12.14	88.18	90	80	50.83	55.10	10	0
19	90	80	52.77	49.21	0	10	88.10	90	80	57.06	55.26	0	0
20	90	80	43.44	51.01	0	10	87.82	88.67	80	50.61	55.48	0	0
21	90	80	32.62	52.75	0	10	87.50	82.69	80	46.77	55.81	0	0
22	90	80	16.81	54.65	0	10	86.62	84.20	80	10	56.16	10	10
23	78.27	80	10	55.69	0	10	80.72	86.41	80	0	57.39	10	0
24	85.59	80	0	52.27	0	10	84.47	79.30	80	0	57.67	10	0

Table 8. NCUC (Case 3-1, Case 3-2)

Hour		0	1-2	3-5	6	7-8	9-10	11	12-20	21	22-23	24	
Case 3-1	Unit No.	1	1	1	1	1	1	1	1	1	1	1	
		2	1	1	1	1	1	1	1	1	1	1	1
		3	1	0	0	0	0	1	1	1	1	1	0
		4	1	1	1	1	1	1	1	1	1	1	1
		5	1	0	1	0	0	0	0	0	0	0	0
		6	1	1	0	1	1	1	1	1	1	1	1
Case 3-2	Unit No.	1	1	1	1	1	1	1	1	1	1	1	
		2	1	1	1	1	1	1	1	1	1	1	
		3	0	0	0	0	1	1	1	1	1	1	1
		4	1	1	1	1	1	1	1	1	1	1	1
		5	0	0	0	0	0	0	0	1	0	0	0
		6	1	1	1	1	1	1	1	1	1	1	1

Table 9. Active Power (MW) Generation Dispatch, NCUC (Case 3-1, Case 3-2)

Hour	The daily cost of bid based generation dispatch (\$)													
	164063.2						167852.04							
	Case 3-1						Case 3-2							
	Unit No.						$Q_{SF}$ (Mvar)	Unit No.						$Q_{SF}$ (Mvar)
1	2	3	4	5	6	1		2	3	4	5	6		
1	48.85	80	0	57.15	0	10	77.97	57.01	80	0	49.35	0	10	4.62
2	36.80	80	0	57.85	0	10	74.87	42.67	80	0	52.19	0	10	5.6
3	33.13	80	0	57.34	10	0	64.33	37.40	80	0	53.19	0	10	5.71
4	29.99	80	0	57.42	10	0	64.06	33.76	80	0	53.83	0	10	5.05
5	31.05	80	0	57.40	10	0	64.15	34.98	80	0	53.62	0	10	5.27
6	37.72	80	0	57.82	0	10	75.27	43.76	80	0	51.99	0	10	5.54
7	55.59	80	0	56.55	0	10	79.27	45.98	80	10	55.87	0	10	18.71
8	76.44	80	0	53.85	0	10	83.05	64.99	80	10	54.87	0	10	13.18
9	81.02	80	10	55.59	0	10	81.78	83.88	80	10	52.81	0	10	16.28
10	90	80	16.92	54.64	0	10	86.64	90	80	21.91	49.37	0	10	18.38
11	90	80	26.42	53.59	0	10	87.31	90	80	33.24	46.53	0	10	18.83
12	90	80	40.29	51.55	0	10	87.73	90	80	34.11	48.02	10	10	23.04
13	90	80	50.22	49.73	0	10	88.02	90	80	44.07	46.02	10	10	23.36
14	90	80	52.47	49.27	0	10	88.09	90	80	46.34	45.49	10	10	23.43
15	90	80	54.44	48.85	0	10	88.15	90	80	48.35	45.01	10	10	23.49
16	90	80	56.07	48.50	0	10	88.20	90	80	50.02	44.59	10	10	23.54
17	90	80	56.98	48.09	0	10.55	88.22	90	80	51.45	44.22	10	10	23.58
18	90	80	56.98	47.51	0	12.14	88.18	90	80	52.86	43.84	10	10	23.62
19	90	80	52.77	49.21	0	10	88.10	90	80	46.65	45.42	10	10	23.44
20	90	80	43.44	51.01	0	10	87.82	90	80	37.25	47.44	10	10	23.14
21	90	80	32.62	52.75	0	10	87.50	90	80	40.83	44.36	0	10	19.06
22	90	80	16.81	54.65	0	10	86.62	90	80	21.78	49.40	0	10	18.37
23	78.27	80	10	55.69	0	10	80.72	80.86	80	10	53.22	0	10	15.49
24	85.59	80	0	52.27	0	10	84.47	73.17	80	10	54.140	0	10	13.59

Table 10. SCUC (Case 4-1, Case 4-2)

Hour		0	1	2	3	4	5	6	7-10	11	12	13	14-19	20	21	22-24	
Case 4-1	Unit No.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
		2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		3	1	0	1	0	1	0	0	1	1	1	1	1	1	1	1
		4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		5	1	0	0	0	0	0	0	0	1	1	0	1	0	0	0
		6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Case 4-2	Unit No.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		3	1	0	0	0	0	0	0	0	0	1	1	1	1	0	0
		4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 11. Active Power (MW) Generation Dispatch, SCUC (Case 4-1, Case 4-2)

Hour	The daily cost of bid based generation dispatch (\$)													
	287742.43							239067.86						
	The daily cost of bid based generation dispatch without Shedding Cost (\$)													
	166345.63							160032.86						
The daily Shedding Cost (\$)														
121396.8							79035							
Case 4-1							Case 4-2							
Unit No.						$LC_8$ (MW)	Unit No.						$LC_8$ (MW)	
1	2	3	4	5	6		1	2	3	4	5	6		
1	46.71	80	0	48.62	0	18.01	3.3490	41.01	80	0	58.03	0	17.09	-
2	24.43	80	10	55.01	0	14.07	1.4364	32.98	80	0	58.92	0	13.03	-
3	32.31	80	0	52.77	0	15.35	0.8424	29.88	80	0	59.22	0	11.59	-
4	23.18	80	10	42.28	0	21.51	0.2762	27.71	80	0	59.41	0	10.60	-
5	30.56	80	0	53.22	0	14.98	0.5556	28.44	80	0	59.35	0	10.93	-
6	36.98	80	0	51.57	0	16.06	1.7317	33.62	80	0	58.86	0	13.33	-
7	38.10	80	10	52.98	0	17	4.0783	44.94	80	0	57.39	0	19.77	-
8	51.17	80	10	52.01	0	19.97	6.8148	57.88	80	0	56.24	0	23.05	2.66
9	64.34	80	10	49.98	0	22.73	9.5128	70.14	80	0	55.22	0	25.92	5.18
10	69.23	80	18.65	46.71	0	24.74	11.6520	80.85	80	0	54.18	0	28.90	7.43
11	31.64	80	61.75	32.28	10	28.31	12.8537	87.07	80	0	53.51	0	30.84	8.76
12	35.39	80	61.26	29.89	10	38.61	14.7065	88.29	80	10	53.48	0	29.15	10.61
13	70.72	80	49.05	35.74	0	27.87	16.0117	89.96	80	14.84	52.90	0	30.05	11.87
14	68.02	80	39.33	41.21	10	26.04	16.5492	89.99	80	16.26	52.76	0	30.22	12.15

15	66.33	80	42.84	40.55	10	26.24	16.64	90	80	17.52	52.65	0	30.36	12.39
16	62.17	80	49.35	39.34	10	26.08	16.7142	90	80	18.55	52.55	0	30.47	12.58
17	67.19	80	43.92	40.38	10	26.24	17.2187	90	80	19.42	52.47	0	30.57	12.75
18	66.04	80	46.34	39.91	10	26.38	17.2820	90	80	20.28	52.39	0	30.67	12.91
19	67.76	80	39.87	41.11	10	26.07	16.5631	89.99	80	16.45	52.75	0	30.24	12.18
20	72.03	80	40.83	38.58	0	27.21	15.2724	90	80	10	53.19	0	29.95	11.01
21	72.53	80	29.84	42.38	0	26.19	13.9429	90	80	0	52.79	0	33.28	9.60
22	69.39	80	18.38	46.74	0	24.73	11.6473	90	80	0	54.19	0	28.88	7.42
23	62.15	80	10	50.38	0	22.43	9.0497	68.23	80	0	55.38	0	25.47	4.79
24	56.93	80	10	51.27	0	21.02	8.093	63.29	80	0	55.79	0	24.31	3.78

Table 12. SCUC (Case 4-1, Case 4-2)

Hour		0	1-7	8	9-10	11-21	22-24
Case 5-1	Unit No.	1	1	1	1	1	1
		2	1	0	0	0	0
		3	1	1	1	1	1
		4	1	1	1	1	1
		5	1	0	1	1	1
		6	1	1	1	1	1
Case 5-2	Unit No.	1	1	1	1	1	1
		2	1	0	0	0	0
		3	1	1	1	1	1
		4	1	1	1	1	1
		5	1	0	1	1	0
		6	1	0	0	1	1

Table 13. Active Power (MW) Generation Dispatch, SCUC (Case 5-1, Case 5-2)

Hour	The daily cost of bid based generation dispatch (\$)													
	262955.52							202171.96						
	The daily cost of bid based generation dispatch without Shedding Cost (\$)													
	198946.17							198096.96						
Hour	The daily Shedding Cost (\$)													
	64009.35							4075						
	Case 5-1							Case 5-2						
	Unit No.						LC <sub>21</sub> (MW)	Unit No.						LC <sub>21</sub> (MW)
1	2	3	4	5	6	1		2	3	4	5	6		
1	90	0	42.75	53.24	0	10	-	90	0	46.66	58.73	0	0	-
2	90	0	30.08	55	0	10	-	90	0	35.10	59.29	0	0	-
3	90	0	25.46	55.42	0	10	-	90	0	30.76	59.48	0	0	-
4	90	0	22.24	55.72	0	10	-	90	0	27.74	59.61	0	0	-
5	90	0	23.32	55.62	0	10	-	90	0	28.76	59.57	0	0	-
6	90	0	31.03	54.89	0	10	-	90	0	35.98	59.25	0	0	-
7	90	0	49.93	51.99	0	10	-	90	0	52.95	58.41	0	0	-
8	90	0	59.80	47.56	10	12.39	-	90	0	62.56	56.26	10	0	-
9	90	0	57.72	40.67	10.01	37.35	-	90	0	64.94	51.51	18.69	10	-
10	90	0	56.21	31.72	19.04	53.33	-	90	0	64.94	47.24	11.51	35.70	-
11	90	0	55.33	28.73	26.08	55.93	-	90	0	64.94	43.69	15.63	43.78	-
12	90	0	55.39	32.78	25.54	58.08	2.5770	90	0	64.84	38.50	21.18	55.65	-
13	90	0	55.30	37.20	23.67	55.93	8.5773	90	0	64.68	33.42	28.78	61.41	-
14	90	0	55.55	37.10	24.06	59.70	12.8719	90	0	64.32	31.96	30.85	62.77	-
15	90	0	56.08	36.25	24.82	60.06	13.7159	90	0	64.32	32.60	30.65	63.05	0.21
16	90	0	56.19	36.56	24.78	60.28	14.4552	90	0	64.32	33.13	30.48	63.28	1
17	90	0	56.15	37.19	24.52	60.44	15.1123	90	0	64.32	33.58	30.33	63.47	1.65
18	90	0	56.12	37.77	24.29	60.61	15.6765	90	0	64.32	34.02	30.19	63.66	2.21
19	90	0	55.94	36.03	24.81	59.82	16.2278	90	0	64.32	32.06	30.82	62.82	2.75
20	90	0	55.77	32.87	25.86	58.58	13.7783	90	0	64.84	36.98	23.54	57.40	0.33
21	90	0	55.78	28.41	27.52	57.12	9.8723	90	0	64.93	41.74	10	56.89	-
22	90	0	56.22	31.82	18.87	53.28	5.1542	90	0	64.78	46.77	0	47.82	-
23	90	0	58.07	41.75	10	33.39	-	90	0	64.74	52.44	0	25.07	-
24	90	0	58.94	44.53	10	23.25	-	90	0	64.70	54.34	0	16.72	-



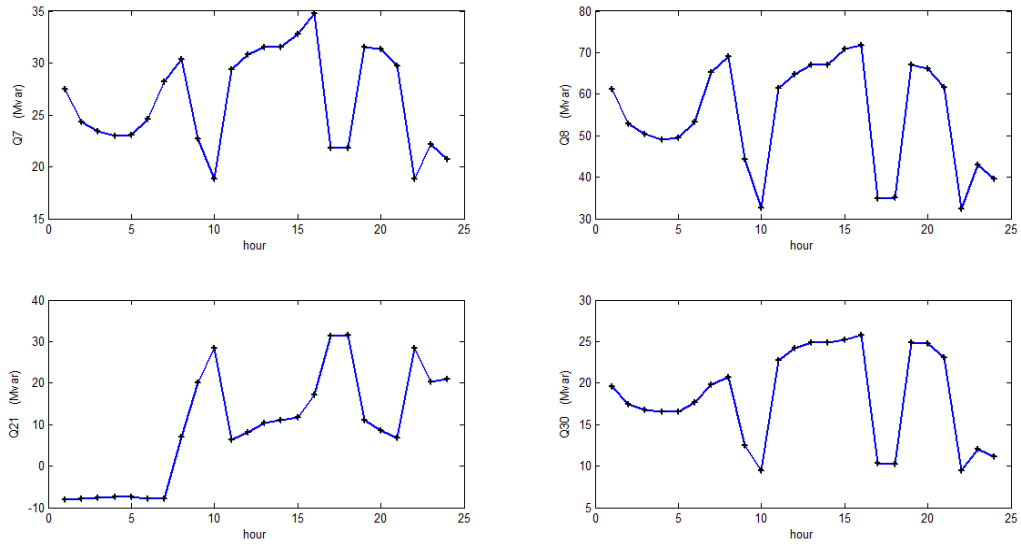


Figure 3. Reactive power generation by SFD (Case 2-3)

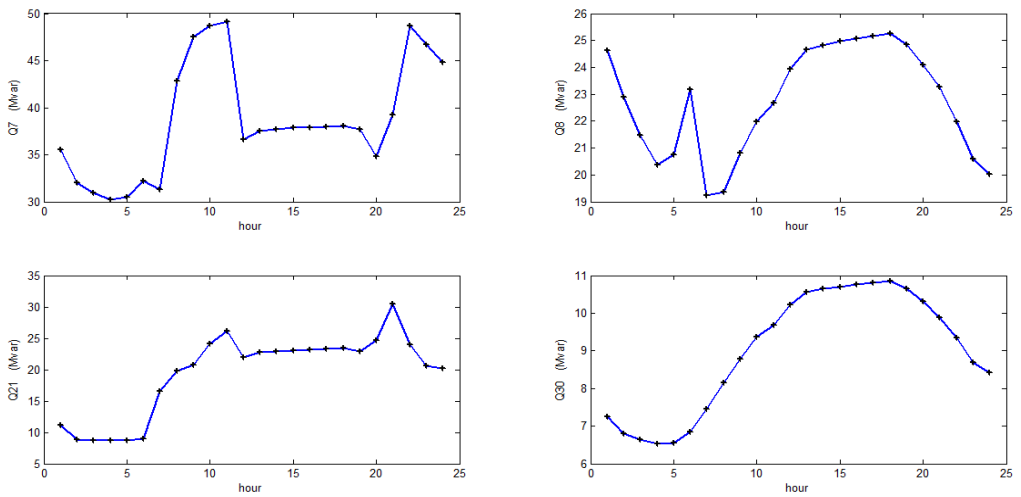


Figure 4. Reactive power generation by SFD (Case 4-2)

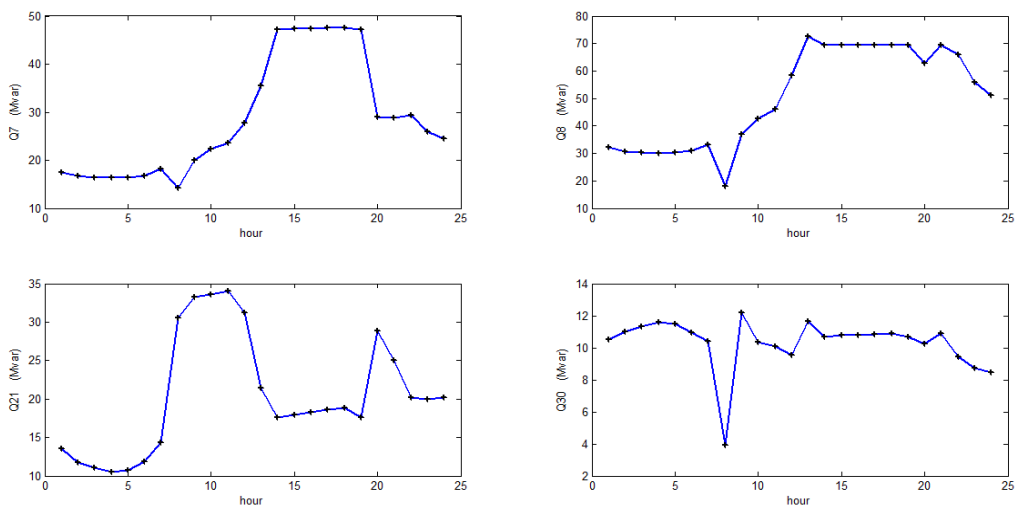


Figure 5. Reactive power generation by SFD (Case 5-2)

**NOMENCLATURES**

$b$ : Index for bus.  
 $i$ : Index for unit.  
 $h$ : Index for time.  
 $k$ : Index for virtual unit.  
 $N_b$ : Number of buses.  
 $N_u$ : Number of units.  
 $N_h$ : Number of hours under study.  
 $N_k$ : Number of virtual units.  
 $F_i(\cdot)$ : Bid-based production cost function of unit  $i$ .  
 $F_{sk}(\cdot)$ : Load shedding cost function of virtual unit  $k$ .  
 $Z_{ih}$ : Commitment state of unit at time  $h$ .  
 $P_{Dh}$ : System real power demand at time  $h$ .  
 $Q_{Dh}$ : System reactive power demand at time  $h$ .  
 $P_{Lh}$ : System active power losses at time  $h$ .  
 $Q_{Lh}$ : System reactive power losses at time  $h$ .  
 $P_{ih}$ : Active power generation of unit  $i$  at time  $h$ .  
 $Q_{ih}$ : Reactive power generation of unit  $i$  at time  $h$ .  
 $VP_{kh}$ : Active power generation of virtual unit  $k$  at time  $h$ .  
 $VQ_{kh}$ : Reactive power generation of virtual unit  $k$  at time  $h$ .  
 $\underline{P}_i$ : Lower limit of active power generation of unit  $i$ .  
 $\bar{P}_i$ : Upper limit of active power generation of unit  $i$ .  
 $\bar{P}_{sf}$ : Upper limit of active power generation of SFD  $f$ .  
 $\underline{P}_{sf}$ : Lower limit of active power generation of SFD  $f$ .  
 $\underline{Q}_i$ : Lower limit of reactive power generation of unit  $i$ .  
 $\bar{Q}_i$ : Upper limit of reactive power generation of unit  $i$ .  
 $\bar{Q}_{sf}$ : Upper limit of reactive power generation of SFD  $f$ .  
 $\underline{Q}_{sf}$ : Lower limit of reactive power generation of SFD  $f$ .  
 $R_{Sh}$ : System spinning reserve requirement at time  $h$ .  
 $R_{Oh}$ : System operating reserve requirement at time  $h$ .  
 $R_{S,ih}$ : Spinning reserve of unit  $i$  at time  $h$ .  
 $R_{O,ih}$ : Operating reserve of unit  $i$  at time  $h$ .  
 $SU_{ih}$ : Bid-based startup cost of unit  $i$  at time  $h$ .  
 $SD_{ih}$ : Bid-based shutdown cost of unit  $i$  at time  $h$ .  
 $\bar{P}_l$ : Upper limit of transmission line flows  $l$ .  
 $\underline{P}_l$ : Lower limit of transmission line flows  $l$ .  
 $T_i^{off}$ : Minimum down time of unit  $i$ .  
 $T_i^{on}$ : Minimum up time of unit  $i$ .  
 $RU_i$ : Ramp-up rate limit of unit  $i$ .  
 $RD_i$ : Ramp-down rate limit of unit  $i$ .  
 $X_i^{off}$ : OFF time of unit  $i$  at time  $h$ .  
 $X_i^{on}$ : ON time of unit  $i$  at time  $h$ .  
 $\bar{V}_b$ : Upper limit of magnitude bus voltage  $b$ .  
 $\underline{V}_b$ : Lower limit of magnitude bus voltage  $b$ .

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