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Shunt-Series FACTS Devices on Network Constrained Unit Commitment

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ABSTRACT

Shunt-Series FACTS Devices (SSFD) would play an important role in maintaining security and reduce Total Generation Cost (TGC) in the economical operation of power systems. The application of this devices to the AC model of Network-Constrained Unit Commitment (NCUC) for the day ahead scheduling is presented in this paper. The proposed AC model of NCUC with SSFD would include active and reactive power flow constraints which increase the network controllability at normal operation. A general SSFD model is introduced for the reactive power management in NCUC which is based on the reactive power injection model (RPIM). The case studies reveal that power transfer capability and voltage profile of the power system is improved by compensating SSFD. Meanwhile simulation results demonstrate the combined use of these devices to NCUC have a significant impact on maintaining network security, lower TGC and increase using the maximum capacity of the existing transmission network.

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NOMENCLATURE

b	Index for bus.
i	Index for unit.
h	Index for time.
k	Index for virtual unit.
Nb	Number of buses.
Nu	Number of units.
Nh	Number of hours under study.
Nk	Number of virtual units.
$F_i(.)$	Bid-based production cost function of unit i.
$F_{sk}(.)$	Load curtailment 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 SSFD *f*.
$\underline{P}_{sf}$ Lower limit of active power generation of SSFD *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 SSFD *f*.
$\underline{Q}_{sf}$ Lower limit of reactive power generation of SSFD *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*.

1. INTRODUCTION

The ISO has the authority and responsibility to commit and dispatch units and curtail loads for maintaining the system security at normal operation and contingency (i.e., balance load demands and satisfy fuel, environmental aspects, and network security requirements) [1]-[3]. The ISO executes the SCUC program to plan a secure and economic scheduling of generating units start-ups and shut-downs over a given time horizon for serving the hourly load demand while satisfying temporal and operational limits of generation and transmission facilities in power systems [2]-[3].

Maximum transfer capability, without adversely affecting the stability and security margin, can be achieved through a fast power flow control. FACTS provide controllability of power flow and voltage [4]. FACTS obtained a well-known reputation for higher controllability in power systems by means of power electronic devices. The first application of FACTS devices is a fast power flow control and voltage stability, which can help to improve the system security [4]-[8].

In this paper, an effective ac contingency dispatch over a day ahead period based on the Network-constrained unit commitment (NCUC) model is proposed. A general model of SSFD is incorporated in the proposed NCUC formulations. GENCOs will submit their bids to the ISO. The ISO will then use this model to minimize the bid-based system operating cost while maintaining the system security at both normal state and pre-defined contingency cases.

This paper is organized as follows. Section II provides an outline of the proposed model. Section III describes the formulations of NCUC. Section IV presents and discusses test cases considering the prevailing constraints. The conclusion drawn from the study is provided in Section V.

2. MODEL OUTLINE

Figure 1 depicts the flowchart of the proposed NCUC model. This model encompasses NCOPF over the 24-h horizon. NCOPF utilizes the UC solution, the optimal dispatch of units, to minimize the bid-based operating cost at steady state. Benders decomposition is utilized to decompose the NCUC problem into smaller and easier to solve subproblems [9]-[12]. The master problem uses the available market information to find the optimal hourly schedule of units (UC). The hourly solution of UC is used in the subproblem to test the network constraints at steady state [13]-[24]. The SSFD are incorporated in the subproblem to minimize violations. In accordance unit schedule by the UC solution, the NCUC checks the base case network feasibility. In this subproblem, slack variables are minimized based on SSFD tuning. The proposed Benders cut is used to mitigate slack variables by recalculating the UC. If NCOPF cannot guarantee the system security at steady-state, LC is utilized to prepare a feasible solution. A converged base case power flow will be achieved based on the UC results. In our approach, augmented Lagrangian relaxation (ALR) is applied to solve UC.

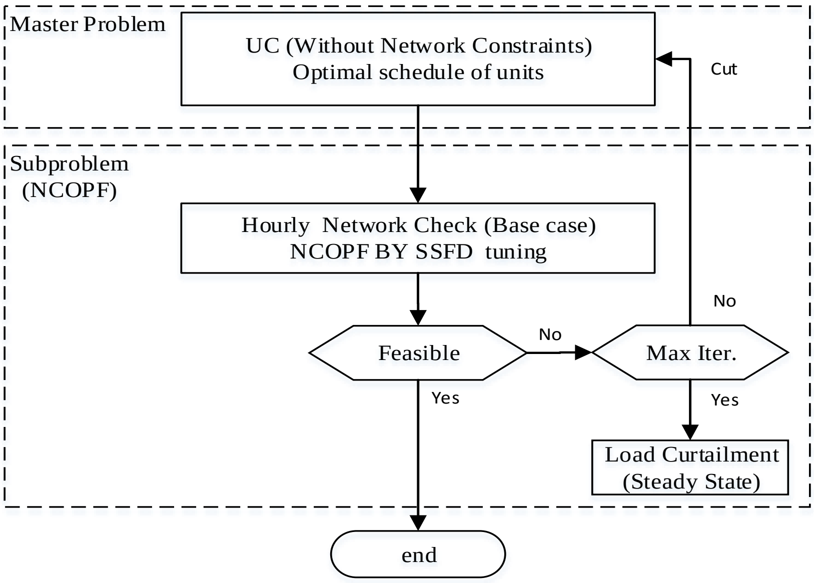


Figure 1. Flowchart of NCUC with SSFD for reactive power management

3. PROBLEM FORMULATION

3.1. 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. Therefore, the objective function is expressed as the sum of fuel, start-up and shut down costs of the generating units. The UC problem can be mathematically formulated as [18]:

Min. TGC=

$$\sum_{i=1}^{Nu}\sum_{h=1}^{Nh}\left\{\begin{matrix}\left[F_i(P_{ih})+SU_{ih}\cdot\left(1-Z_{i(h-1)}\right)\right]\cdot Z_{ih}\\ +SD_{ih}\cdot(1-Z_{ih})\cdot Z_{i(h-1)}\end{matrix}\right\} \quad (1)$$

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

(a) Power balance constraints

$$\begin{aligned}&\sum_{i=1}^{Nu}P_{ih}\cdot Z_{ih}=P_{Dh}+P_{Lh}\\&\sum_{i=1}^{Nu}Q_{ih}\cdot Z_{ih}=Q_{Dh}+Q_{Lh}\end{aligned} \quad (2)$$

(b) Spinning and operating reserve constraints

$$\sum_{i=1}^{Nu}\left[R_{S,ih}\cdot Z_{ih}\right] \geq R_{Sh} \qquad (3)$$
$$\sum_{i=1}^{Nu}\left[R_{O,ih}\cdot Z_{ih}\right] \geq R_{Oh}$$

(c) Minimum up/down time constraints

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

(d) Power generation limit constraints

$$\underline{P_i}\cdot Z_{ih} \leq P_{ih} \leq \overline{P}_i\cdot Z_{ih} \qquad (5)$$
$$\underline{Q_i}\cdot Z_{ih} \leq Q_{ih} \leq \overline{Q}_i\cdot Z_{ih}$$

(e) Ramping Up/Down limits

$$P_{ih}-P_{i(h-1)} \leq \left[1-Z_{ih}\cdot\left(1-Z_{i(h-1)}\right)\right]\cdot RU_i + Z_{ih}\cdot\left(1-Z_{i(h-1)}\right)\cdot\underline{P_i}$$
$$P_{i(h-1)}-P_{ih} \leq \left[1-Z_{i(h-1)}\cdot\left(1-Z_{ih}\right)\right]\cdot RD_i + Z_{i(h-1)}\cdot\left(1-Z_{ih}\right)\cdot\underline{P_i} \qquad (6)$$

In order to solve UC, the ALR method is employed for relaxing power system constraints (2), (3). The relaxed problem is decomposed into N subproblems for each unit. Dynamic programming (DP) including minimum up/down time limit (5), and ramp rate limits (6) is used to search for the optimal commitment of a single unit over the entire study period. Lagrangian multipliers are updated based on violations of system constraints. The convergence criterion is satisfied if the duality gap between primal and dual solutions is within a given limit. [18].

2.2. NCUC with LC

Based on UC results, the objective function (9) is to minimize OPF and LC costs at steady state and when considering contingencies. The second term in the objective function is for modeling virtual units that will be used if OPF is infeasible. Constraints (10) and (11) represent the power balance and system spinning/operating reserve requirement. Note that the ratio of system spinning/operating reserve requirement to the total load should be fixed based on the above assumption for LC [18].

Min. TGC=

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

(a) Power balance constraints

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

(b) Spinning and operating reserve constraints

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

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

(c) Generation limit constraints

$$\underline{P_i} \cdot Z_{ih} \leq P_{ih} \leq \overline{P}_i \cdot Z_{ih} \tag{10}$$

$$\underline{Q_i} \cdot Z_{ih} \leq Q_{ih} \leq \overline{Q}_i \cdot Z_{ih}$$

(d) Ramping Up/Down limits

$$P_{ih} - P_{i(h-1)} \leq \left[1 - Z_{ih} \cdot \left(1 - Z_{i(h-1)}\right)\right] \cdot RU_i + Z_{ih} \cdot \left(1 - Z_{i(h-1)}\right) \cdot \underline{P_i}$$

$$P_{i(h-1)} - P_{ih} \leq \left[1 - Z_{i(h-1)} \cdot (1 - Z_{ih})\right] \cdot RD_i + Z_{i(h-1)} \cdot (1 - Z_{ih}) \cdot \underline{P_i} \tag{11}$$

(e) The power flow equations

$$G_b(X, U, C) = 0 \qquad b = 1,2, \dots, Nb \tag{12}$$

(f) The transmission line flows constraint

$$\underline{P_l} \leq P_{lh} \leq \overline{P}_l \qquad l = 1,2, \dots, Nl \tag{13}$$

(g) The voltage of the buses

$$\underline{V_b} \leq V_b \leq \overline{V}_b \qquad b = 1,2, \dots, Nb \tag{14}$$

(h) The SSFD constraint

$$\underline{P_{sf}} \leq P_{sf} \leq \overline{P}_{sf} \qquad f = 1,2, \dots, Nf \tag{15}$$

$$\underline{Q_{sf}} \leq Q_{sf} \leq \overline{Q}_{sf} \qquad f = 1,2, \dots, Nf$$

$$SCF_l = \frac{\text{series reactance compensation in line } l \text{ by SCFD}}{\text{series reactance of line } l}$$

The state vector X comprises of the bus voltage phase angles and magnitudes. The control vector U comprises of all the controllable system variables like real power generations and reactive power generated by SSFD. The parameter vector C includes all the uncontrollable system parameters such as line parameters, loads, etc [18].

3. CASE STUDIES

The proposed model is applied to a thirty -bus test system to illustrate the performance of NCUC.

3.1. Thirty -Bus test System

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 I–III, respectively []. The magnitude of voltage at each bus must be between 0.95 and 1.05. In order to analyze the efficiency of the proposed method, the following five case studies with corresponding constraints is considered:

Case 1) UC (without network constraints);

Case 2) NCUC;

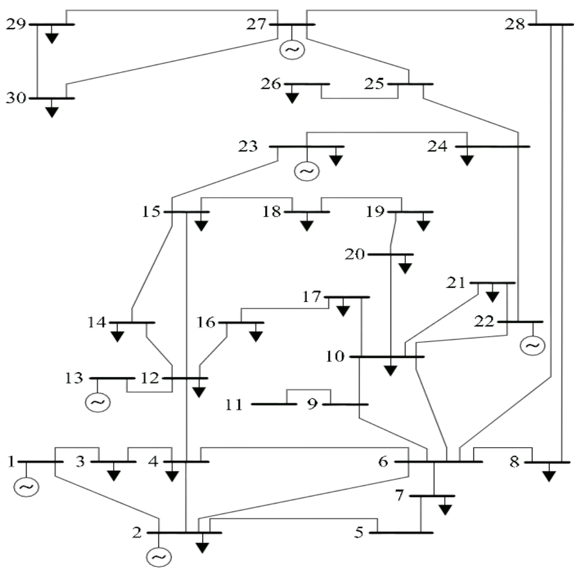
- Case 2_1) NCUC without SSFD.
- Case 2_2) NCUC with SCFD in lines 29 and 30.
- Case 2_3) NCUC with SFD at buses 8, 17, 19, 20, 21 and 30.
- Case 2_4) NCUC with SCFD in lines 29 and 30 and SFD at buses 8, 17, 19, 20, 21 and 30.

In some cases, according Table IV, SSFD are considered. These devices are modeled using the proposed RPIM [18].

Case 1) in this case, UC will determine the base case schedule of units, when disregarding the network constraints. The commitment schedule is shown in Table IV in which 1 and 0 represent hourly on/off states of units, and hour 0 represents the initial condition. The optimal generation dispatch of units is shown in Table V. In addition, the daily bid-based generation dispatch cost given in Table IV is $ 142203.6145. The optimal generation dispatch given in Table V. In this case, the economical units 1, 2 and 4 supply the base load, which are committed at the entire scheduling horizon. The unit 3 is committed at certain hours (11-21) to supply peak load and to minimize TGC. More expensive units 5 and 6 are not committed at all hours.

Case 2) in case 2_1, the impact of ac network constrained at steady state on unit commitment (NCUC) is studied. If we use the UC results in Case 1 for NCOPF calculations, magnitude voltage violations will occur at buses 12-20. In order to considering the network constraints, we find that the other UC in Case 2_1. So, the commitment schedule is shown in Table VI and the optimal generation dispatch of NCOPF is changed as shown in Table VII. The highlighted items in mentioned Table show differences between Case 1 and Case 2_1. 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 II, the generation dispatch of the economical units 1, 2, 3 and 4 is changed. The relatively expensive units 5 and 6 are dispatched to supply the system load. Accordingly, the daily cost of bid-based generation dispatch increases to $ 169505.19.

In Cases 2_2-2_4, the SCFD, SCF and SSFD inject the controllable reactive power to the network and also manage reactive power flows and accordingly adjust bus voltage levels. The SSFD is the best option to decrease the reactive power flow on the network lines and therefore increase the transfer capability of the lines. In case 2_2-2_4 the voltage at all buses and the reactive power flow at network lines is changed. The reactive power generation by SFD is shown in Figure 3.The commitment schedule is shown in Table VI and the optimal generation dispatch of NCOPF is changed as shown in Table VII. Without the SCFD, SCF and SSFD, 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 SCFD, SCF and SSFD, bus voltages are adjusted by the neighboring 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 SCFD, SCF and SSFD 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_4 has the minimum TGC and less committed more expensive units. Therefor distributed SSFD in load buses is the best choice for power system planning.



Figur 2. The 30-bus system [25]

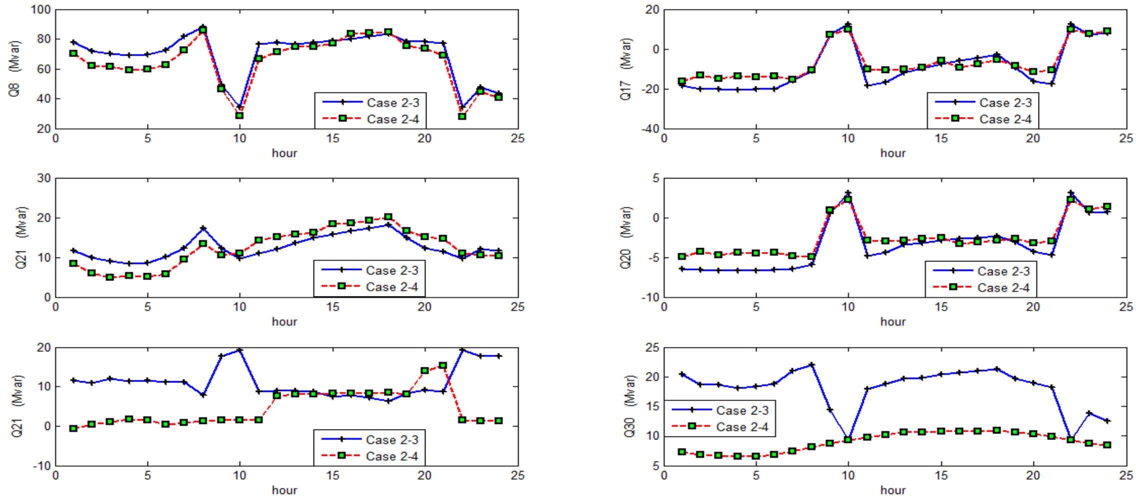


Figure 3. Reactive Power generation by SFD (cases 2_3 and 2-4)

Table 1. Unit Data [26]

Unit No.		1	2	3	4	5	6
Bus No.		1	2	13	22	23	27
	a (MBtu)	150	180	125	200	90	75
Unit Cost coefficients	b (MBtu/MWh)	30	20.75	36.3	12.9	42.6	45.8
	c (MBtu/MW^{2}h)	0.02	0.0175	0.0125	0.00625	0.0135	0.0124
P_{min} (MW)		10	10	10	10	10	10
P_{max}(MW)		90	80	70	80	90	90
Q_{min}(Mvar)		-20	-15	-10	-15	-20	-20
Q_{max}(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. Transmission Line Data [26]

Line No.	From Bus	To Bus	R (pu)	X (pu)	B (pu)	Flow Limit (MW)	Line No.	From Bus	To Bus	R (pu)	X (pu)	B (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	80	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. Hourly Load Distribution Data [26]

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

Table 4. Uc (Case 1)

Hour	THE DAILY COST OF BID BASED GENERATION DISPATCH ($) 142203.6145 UNIT NO.					
	1	2	3	4	5	6
0	1	1	1	1	1	1
1-10	1	1	0	1	0	0
11-21	1	1	1	1	0	0
22-24	1	1	0	1	0	0

Table 5. Active Power (Mw) Generation Dispatch Uc without Network Constraints (Case 1)

Hour	UNIT NO.					
	1	2	3	4	5	6
1	31.961	80	0	80	0	0
2	21.137	80	0	80	0	0
3	17.045	80	0	80	0	0
4	14.174	80	0	80	0	0
5	15.142	80	0	80	0	0
6	21.973	80	0	80	0	0
7	37.802	80	0	80	0	0
8	54.841	80	0	80	0	0
9	70.692	80	0	80	0	0
10	84.893	80	0	80	0	0
11	83.264	80	10	80	0	0
12	90	80	14.935	80	0	0
13	90	80	22.855	80	0	0
14	90	80	24.593	80	0	0
15	90	80	26.1	80	0	0
16	90	80	27.332	80	0	0
17	90	80	28.377	80	0	0
18	90	80	29.4	80	0	0
19	90	80	24.824	80	0	0
20	90	80	17.487	80	0	0
21	88.566	80	10	80	0	0
22	84.794	80	0	80	0	0
23	68.239	80	0	80	0	0
24	61.859	80	0	80	0	0

Table 6. Ncuc without Ssfd (Case 2_1), Ncuc with Scfd (Case 2_2), Ncuc With Sfd (Case 2_3), Ncuc with Ssfd (Case 2_4)

Hour	THE DAILY COST OF BID BASED GENERATION DISPATCH ($)																											
	169505.19						166079.97								159406						158212.75							
	CASE 2_1						CASE 2_2								CASE 2_3						CASE 2_4							
	UNIT NO.						UNIT NO.						SCF_{29}	SCF_{30}	UNIT NO.						UNIT NO.						SCF_{29}	SCF_{30}
	1	2	3	4	5	6	1	2	3	4	5	6			1	2	3	4	5	6	1	2	3	4	5	6		
0	1	1	1	1	1	1	1	1	1	1	1	1	-	-	1	1	1	1	1	1	1	1	1	1	1	1	-	-
1	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.3	0.9
2	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.2	0.9
3	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.1	0.9
4	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.1	0.9
5	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.1	0.9
6	1	1	0	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.2	0.9
7	1	1	1	1	0	1	1	1	0	1	0	1	0.9	-0.7	1	1	0	1	0	0	1	1	0	1	0	0	-0.4	0.9
8	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	0	1	0	0	1	1	0	1	0	0	-0.7	0.9
9	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	0	1	1	0	1	1	0	1	1	0	0.9	0.9
10	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7
11	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	1	1	0	0	1	1	1	1	0	0	0.3	-0.7
12	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.5	-0.7
13	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.6	-0.7
14	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.6	-0.7
15	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.6	-0.7
16	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.7	-0.7
17	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.7	-0.7
18	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.7	-0.7
19	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.6	-0.7
20	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7	1	1	1	1	0	0	1	1	1	1	0	0	0.6	-0.7
21	1	1	1	1	1	1	1	1	1	1	1	1	0.9	0.9	1	1	1	1	0	0	1	1	1	1	0	0	0.4	-0.7
22	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	1	1	1	1	1	1	1	1	1	1	0.9	-0.7
23	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	0	1	1	0	1	1	0	1	1	0	0.9	0.9
24	1	1	1	1	0	1	1	1	1	1	0	1	0.9	0.9	1	1	0	1	1	0	1	1	0	1	1	0	0.9	0.9

Table 7. Active Power (Mw) Generation Dispatch Ncuc without Ssfd (Case 2_1), Ncuc with Scfd (Case 2_2), Ncuc with Sfd (Case 2_3), Ncuc with Ssfd (Case 2_4)

Hour	CASE 2_1 UNIT NO.						CASE 2_2 UNIT NO.						CASE 2_3 UNIT NO.						CASE 2_4 UNIT NO.					
	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
1	57.56	80	0	48.95	0	10	51.23	80	0	55.19	0	10	60.99	80	0	56.11	0	0	59.21	80	0	57.73	0	0
2	42.88	80	0	52.21	0	10	37.10	80	0	57.96	0	10	48.31	80	0	57.31	0	0	46.82	80	0	58.56	0	0
3	37.69	80	0	53.06	0	10	32.06	80	0	58.69	0	10	43.55	80	0	57.76	0	0	42.07	80	0	59.08	0	0
4	34.09	80	0	53.62	0	10	28.95	80	0	59.17	0	10	40.22	80	0	58.07	0	0	38.85	80	0	59.21	0	0
5	35.30	80	0	53.44	0	10	29.73	80	0	59.01	0	10	41.35	80	0	57.97	0	0	39.93	80	0	59.17	0	0
6	43.97	80	0	52	0	10	38.16	80	0	57.78	0	10	49.29	80	0	57.22	0	0	47.76	80	0	58.52	0	0
7	46.27	80	10	55.82	0	10	59.36	80	0	53.25	0	10	67.90	80	0	55.39	0	0	66	80	0	57.12	0	0
8	65.96	80	10	54.07	0	10	60.79	80	10	59.16	0	10	88.34	80	0	53.18	0	0	86.06	80	0	55.28	0	0
9	86.27	80	10	50.74	0	10	80.71	80	10	56.05	0	10	89.14	80	0	57.22	10	0	85.80	80	0	60.42	10	0
10	90	80	24.99	46.58	0	10	90	80	19.31	52.33	0	10	84.23	80	10	56.07	10	10	80.04	80	10	59.81	10	10
11	90	80	36.98	43.10	0	10	90	80	30.75	49.34	0	10	81.20	80	42.69	56.12	0	0	81.26	80	41.23	57.12	0	0
12	90	80	37.42	44.80	10	10	90	80	30.12	52.03	10	10	87.80	80	48.80	55.63	0	0	85.42	80	49.10	57.33	0	0
13	90	80	48.46	41.87	10	10	90	80	40.90	49.29	10	10	90	80	55.03	55.30	0	0	89.04	80	53.81	57.35	0	0
14	90	80	51.02	41.08	10	10	90	80	43.34	48.64	10	10	90	80	56.86	55.23	0	0	90	80	54.73	57.29	0	0
15	90	80	53.30	40.34	10	10	90	80	45.47	48.07	10	10	90	80	58.46	55.17	0	0	90	80	56.30	57.22	0	0
16	90	80	55.21	39.69	10	10	90	80	47.25	47.55	10	10	90	80	59.79	55.11	0	0	90	80	57.48	57.49	0	0
17	90	80	56.86	39.11	10	10	90	80	48.79	47.08	10	10	90	80	60.93	55.07	0	0	90	80	58.58	57.46	0	0
18	90	80	57.37	38.35	10.93	10.33	90	80	50.32	46.59	10	10	90	80	62.07	55.2	0	0	90	80	59.67	57.42	0	0
19	90	80	51.37	40.97	10	10	90	80	43.66	48.56	10	10	90	80	57.10	55.22	0	0	90	80	54.97	57.27	0	0
20	90	80	40.92	43.90	10	10	90	80	33.54	51.18	10	10	89.35	80	50.05	55.52	0	0	84.98	80	51.96	57.57	0	0
21	90	80	45.20	40.34	10	10	90	80	38.51	46.98	10	10	84.17	80	45.49	55.89	0	0	82.93	80	44.98	57.25	0	0
22	90	80	24.85	46.62	0	10	90	80	19.18	52.36	0	10	84.12	80	10	56.07	10	10	79.93	80	10	59.81	10	10
23	83.03	80	10	51.31	0	10	77.49	80	10	56.64	0	10	86.39	80	0	57.33	10	0	83.06	80	0	60.53	10	0
24	74.75	80	10	52.72	0	10	69.34	80	10	58.01	0	10	79.27	80	0	57.61	10	0	75.96	80	0	60.81	10	0

4. CONCLUSIONS

The NCUC results of numerical tests show the effectiveness of the proposed method in minimizing bid based generation cost and maintain network security in steady state and contingency. The proposed method could solve both NCUC modules based on ac constraints and advice a good set of corrective and preventive control protocol for the secure and economical operation of power systems.

Impact of SCFD, SCF and SSFD adjustment was investigated into the NCUC with AC network constraints at steady state and contingency. To enhance the proposed AC solution of NCUC, SCFD, SCF and SSFD were considered. A RPIM was used to model the effect of SCFD, SCF and SSFD in the AC power flow, using reactive power injections to system load buses. We concluded that the incorporation of SCFD, SCF and SSFD would enhance the hourly NCUC solution when considering bus voltage and line capacity constraints.

If the SCFD, SCF and SSFD 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 NCUC is necessary.

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