

Congestion Management for Pool Based Renewable Hybrid Power System Using a Novel Bidding Approach

Aditi Gupta

Submitted: 25/08/2022

Revised: 01/10/2022

Accepted: 10/10/2022

Abstract: After deregulation of power system, system operator faces many challenges to manage transmission operations. This challenge further increase with rapidly growing share of renewables in generation mix. Further, these renewable power plants are located at remote areas and need long transmission lines of electric power for power transmission. Due to all these reasons, transmission lines are forced to operate at or very near to their operating limits and leads to congestion, that cause voltage limit violation and line overload. In this paper, a novel rescheduling based technical congestion management approach has been proposed that includes combined bidding plan between hydro and wind units of hybrid power market. Performance of the proposed plan has been studied by implementing it on modified IEEE-24 bus RTS system and its comparison has been done with existing individual bidding plan.

Keywords: Renewables, Congestion, Bidding, Rescheduling, Wind plant.

Nomenclature Sets

N = set of no. of nodes

t = set of no. of time blocks

T = set of thermal units

H = set of total hydro units

W = set of wind units

$H1$ = set of hydro units bidding individually

HW = set of hydro-wind combination offering combined bids

Parameters

shp = scheduled hydro power

swp = scheduled wind power

sh = slope of characteristics curve of hydro

ϕh = water discharge of hydro

v = wind velocity

P_d & Q_d = Real and reactive power demand

u_i = voltage at node i

δ_i = angle at node i

P_{db} & P_{dp} = bilateral and pool power demand

P_{tmin} & P_{tmax} = Min and max limits of real generation of thermal units

P_{hmin} & P_{hmax} = Min and max limits of real generation of hydro units

P_{wmin} & P_{wmax} = Min and max limits of real generation of wind units

Q_{tmin} & Q_{tmax} = Min and max limits of reactive power of thermal units

Q_{hmin} & Q_{hmax} = Min and max limits of reactive power of hydro units

Q_{wmin} & Q_{wmax} = Min and max limits of reactive power of wind units

u_{min} & u_{max} = Min and max node voltage limits

δ_{min} & δ_{max} = Min and max node angle limits

R_{tu} & R_{td} = up and down raw bids of thermal unit

$\delta_{\min}$ & $\delta_{\max}$ = Min and max node angle limits
 R_{tu} & R_{td} = up and down raw bids of thermal units
 R_{hu} & R_{hd} = up and down raw bids of hydro units, bidding individually
 P_{t0} , P_{h0} & P_{w0} = initial generation of thermal, hydro and wind units
 $\phi_{h\min}$ & $\phi_{h\max}$ = min and max water discharge limits

Variables

a_{hp} = actual hydro power generation
 a_{wp} = actual wind power generation
 C_u & C_d = combined up and down bids of hydro and wind units
 P_g & Q_g = total real and reactive power generation
 P_t , P_h & P_w = real power generation of thermal, hydro and wind units
 Q_t , Q_h & Q_w = reactive power generation of thermal, hydro and wind units
 dt_u & dt_d = increment and decrement in thermal generation
 dh_u & dh_d = increment and decrement in generation of hydro units bidding individually
 dc_u & dc_d = increment and decrement in combined generation of hydro & wind units
 dh_{lu} & dh_{ld} = increment and decrement in generation of hydro unit involved in combined bidding
 d_{wu} & d_{wd} = increment and decrement in generation of wind unit involved in combined bidding
 h_i = binary variable showing on - off status of hydro units

Introduction

After restructuring of power market, different market players are experiencing competitiveness among themselves. With increasing share of renewables like wind power in generation mix and their remote location has exaggerated the problem of congestion on existing transmission networks in past many years. Variable nature of wind power is one of the major reasons for this. Congestion occurs when transmission lines are forced to operate very close to their operating limits like voltage levels and loading levels, due to above mentioned reasons [1-2]. Broadly, congestion management strategies are classified into two categories: technical and non-technical. Many research papers are present in literature which incorporate these strategies of congestion management. A comprehensive literature review has been done on :

congestion management [3-4]. Congestion management by improving voltage stability margin has been introduced in literature and is further used by different authors for congestion management [5-6]. Generation rescheduling based congestion management approach has been proposed by Khemani et al. for all thermal system in pool based electricity market [7]. Generator sensitivity factor based approach has been discussed as congestion management solution for the system having wind farm [8] and for the system having pumped storage hydro plant [9-10] in pool based electricity market. Comparison between different congestion management schemes has been done by many authors in [11-12]. Congestion management scheme for hydro-thermal combination in a pool based market has been discussed in [13-14]. The authors have proposed rescheduling of generation after congestion, on the basis of individual raw biddings of hydro and thermal units. Combined hydro-wind bids have been proposed by different authors for minimization of operating cost of power system [15-16].

Studies present in the literature mainly focus on generation rescheduling based congestion management strategies by considering individual raw bids of different generating units including renewables. Among various renewables, wind is the most variable type of energy source due to variable wind speeds. Generally, there is a mismatch between their scheduled power and actual power generation, due to which they face financial penalties. So, price bids of wind plants have a very critical role in economical congestion management solution.

In this paper, combined bidding plan between hydro and wind units has been proposed, in which they take care of power imbalances of each other so that their total power imbalances are reduced. Rest of the paper includes problem formulation, system investigated, simulations and results, conclusions, references and appendix.

2. Problem Formulation

2.1 Combined bidding approach for hydro-wind combination

Combined bidding approach for hydro-wind combination, based on power mismatch between day-ahead schedule and actual generation has been presented in this section. Firstly, total power deviations (TPD) are minimized and objective function becomes

$$\text{Min TPD} = \sum_i^N \sum_k^t PD_{ik} \quad (1)$$

subject to following constraints:

The equation for power deviation (PD) is:

$$PD_{ik} = \sum_i \sum_k \{(shp - a_{hp}) + (swp - a_{wp})\} \quad (2)$$

Hydro and wind power generation are:

$$a_{hp} = [\sum_i \sum_k s_h] \cdot \phi_h \quad (3)$$

$$awp = 0 \text{ if } v \leq v_s \cup v \geq v_0 \quad (4a)$$

$$= WP_r \left(\frac{v-v_s}{v_s-v_r} \right) \text{ if } v_s \leq v < v_r \quad (4b)$$

$$= WP_r \text{ if } v_r \leq v < v_0 \quad (4c)$$

where, v_s , v_r and v_0 are cut-in speed, rated speed and cut-out velocities respectively. WP_r is rated power output of wind plant. Combined up and down bids for hydro-wind combination are:

$$C_{uik} = PD_{ik} \cdot R_u \cdot \varphi_u \text{ if } PD < 0 \quad (5)$$

$$C_{dik} = PD_{ik} \cdot R_d \cdot \varphi_d \text{ if } PD > 0 \quad (6)$$

where, φ_u & φ_d are revenue factor and penalty factor respectively.

These combined bids will be used in overall optimization problem of congestion management cost, for modifying generation of hydro-wind units during congestion.

Power injection equations for real and reactive powers are:

$$P_{ik} = P_{gik} - P_{dik} = \sum_j \sum_k u_{ik} u_{jk} Y_{ijk} \cos(\delta_{ik} - \delta_{jk} - \theta_{ijk}) \quad (7)$$

$$Q_{ik} = Q_{gik} - Q_{dik} = \sum_j \sum_k u_{ik} u_{jk} Y_{ijk} \sin(\delta_{ik} - \delta_{jk} - \theta_{ijk}) \quad (8)$$

Total real and reactive powers are sum of respective generations of thermal, hydro and wind units and are written as:

$$P_{gik} = P_{tik} + P_{hik} + P_{wik} \quad (9)$$

$$Q_{gik} = Q_{tik} + Q_{hik} + Q_{wik} \quad (10)$$

Inequality constraints for real and reactive power generation:

$$P_{tik}^{\min} \leq P_{tik} \leq P_{tik}^{\max} \quad \forall i \in TH \text{ \& } k \in T \quad (11)$$

$$P_{hik}^{\min} \leq P_{hik} \leq P_{hik}^{\max} \quad \forall i \in H \text{ \& } k \in T \quad (12)$$

$$P_{wik}^{\min} \leq P_{wik} \leq P_{wik}^{\max} \quad \forall i \in W \text{ \& } k \in T \quad (13)$$

$$Q_{tik}^{\min} \leq Q_{tik} \leq Q_{tik}^{\max} \quad \forall i \in TH \text{ \& } k \in T \quad (14)$$

$$Q_{hik}^{\min} \leq Q_{hik} \leq Q_{hik}^{\max} \quad \forall i \in H \text{ \& } k \in T \quad (15)$$

$$Q_{wik}^{\min} \leq Q_{wik} \leq Q_{wik}^{\max} \quad \forall i \in W \text{ \& } k \in T \quad (16)$$

Bus voltage and bus angle limit equations are:

$$u_{ik}^{\min} \leq u_{ik} \leq u_{ik}^{\max} \quad (17)$$

$$\delta_{ik}^{\min} \leq \delta_{ik} \leq \delta_{ik}^{\max} \quad (18)$$

2.2 Congestion management model based on combined bidding strategy

Problem formulation of congestion management is done by considering combined bids for hydro and wind plant as given by (5) and (6). All thermal units and rest of the hydro

units are offering their individual raw bids. The objective of congestion management problem is to minimize congestion management cost (CMC) for hybrid system, having combined bidding for hydro – wind combination. The objective function is formulated as:

$$\text{Minimize CMC} = \sum_i^T \sum_k^t (R_t^u d_t^u + R_t^d d_t^d) + \sum_i^{H1} \sum_k^t (R_h^u d_h^u + R_h^d d_h^d) + \sum_i^{HW} \sum_k^t (C_u d_c^u + C_d d_c^d) \quad (19)$$

subject to equality constraints given by:

$$\sum_i^T \sum_k^t d_t^u - \sum_i^T \sum_k^t d_t^d + \sum_i^{H1} \sum_k^t d_h^u - \sum_i^{H1} \sum_k^t d_h^d + \sum_i^{HW} \sum_k^t d_c^u - \sum_i^{HW} \sum_k^t d_c^d = 0 \quad (20)$$

Further, by summing the up generations and down generations of hydro and wind units participating in combined bidding plan, combined up and down generations are obtained as:

$$\sum_k^t d_{c_k}^u = \sum_k^t d_{h1_k}^u + \sum_k^t d_{w_k}^u \quad (21)$$

$$\sum_k^t d_{c_k}^d = \sum_k^t d_{h1_k}^d + \sum_k^t d_{w_k}^d \quad (22)$$

Inequality constraints equations for hydro units are given by:

$$\phi_{h_{ik}}^{\min} \leq \phi_{h_{ik}} \leq \phi_{h_{ik}}^{\max} \quad \forall i \in H \quad \& \quad k \in T \quad (23)$$

$$u_{h_{ilk}}^{\min} \leq u_{h_{ilk}} \leq u_{h_{ilk}}^{\max} \quad \forall i \in H, \quad l \in L \quad \& \quad k \in T \quad (24)$$

Rescheduling of different units in terms of power generation is done either in increment or in decrement manner. The equations for the same are:

$$P_{t_{ik}} = P_{t_{ik}}^0 + v_{ti} d_{t_{ik}}^u - (1 - v_{ti}) d_{t_{ik}}^d \quad (25)$$

$$P_{h_{ik}} = P_{h_{ik}}^0 + v_{hi} d_{h_{ik}}^u - (1 - v_{hi}) d_{h_{ik}}^d \quad (26)$$

$$P_{w_{ik}} = P_{w_{ik}}^0 + v_{wi} d_{w_{ik}}^u - (1 - v_{wi}) d_{w_{ik}}^d \quad (27)$$

where, v_{ti} , v_{hi} and v_{wi} are the binary variables for ensuring generation rescheduling in either increment or in decrement manner for thermal, hydro and wind units respectively.

Test System Investigated

Modified IEEE-24 bus system has been used for solving congestion management problem [16]. In this test system, thermal units are present at bus number 1, 2, 7, 15, 16, 21, 22 and 23, and hydro units are added at bus number 8, 13 and 18 as used in [5, 13]. To model wind plant, weakest bus in terms of reactive power margin has been found out, which is bus no. 19 [17]. To force congestion on transmission lines, most critical transmission lines are found out by different sensitivity analysis, which are line

15 -16 and line 16 – 19 [5, 13].

Wind velocity data for 24 hours is shown in Figure 1 [5]. As congestion is a short term phenomenon, average value of wind velocity is taken for 4 time blocks. vs , vr , $v0$ and WPr are 3 m/s, 11.5 m/s, 20 m/s and 25 MW respectively [5-6]. Also, revenue factor and penalty factor are taken as 1.0 and 1.2 respectively [18]. Data of day-ahead schedule, up/down raw bids and maximum/ minimum generation limits of different units are given in Table 1.

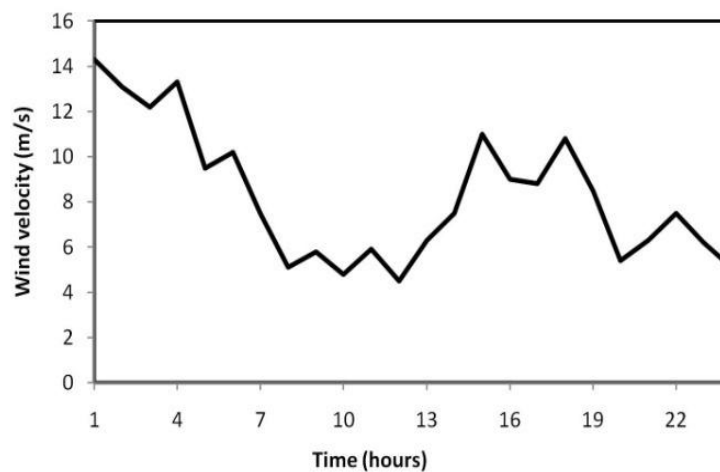


Fig. 1. Wind velocity data

Table 1 Day-ahead schedule, individual bids and generation of all units [13]

Gen no.	Bus no.	Type of unit	P0 (MW) for different time blocks				Up bids * (\$/MWh)	Down bids * (\$/MWh)	Pmin * (MW)	Pmax * (MW)
			1	2	3	4				
1	1	Thermal	152	152	152	152	18	20	15	192
2	2	Thermal	152	152	152	152	14	15	15	192
3	7	Thermal	150	150	150	150	15	17	24	300
4	8	Hydro	239.9	353.4	68.8	464.1	10	14	51	590
5	13	Hydro	239.9	353.4	68.8	464.1	10	14	51	590
6	15	Thermal	295	295	295	295	12	15	24	315
7	16	Thermal	150	150	150	150	7	9	21	265
8	18	Hydroc	387.0	570.0	110.0	748.5	10	12	68	550
9	19	Windc	32.8	55.94	21.45	14.61	10	12	5	300
10	21	Thermal	300	300	300	300	20	18	68	400
11	22	Thermal	310	310	310	310	12	12.5	24	400
12	23	Thermal	350	350	350	350	12.5	15.5	102	600

* Same in all 4 time blocks

C plants participating in combined bidding

Simulations And Results

Congestion management optimization problem has been solved using GAMS 23.4 software [19] in interfacing with

MATLAB [20]. Combined up and down bids for bus 18 hydro unit and bus 19 wind unit have been obtained using novel combined bidding plan and are tabulated in Table 2.

Table 2 Combined up and down bids of hydro-wind combination

	Time block 1	Time block 2	Time block 3	Time block 4
C_u (\$/MWh)	6.63	6.63	5.34	4.52
C_d (\$/MWh)	9.67	9.678	7.24	6.87

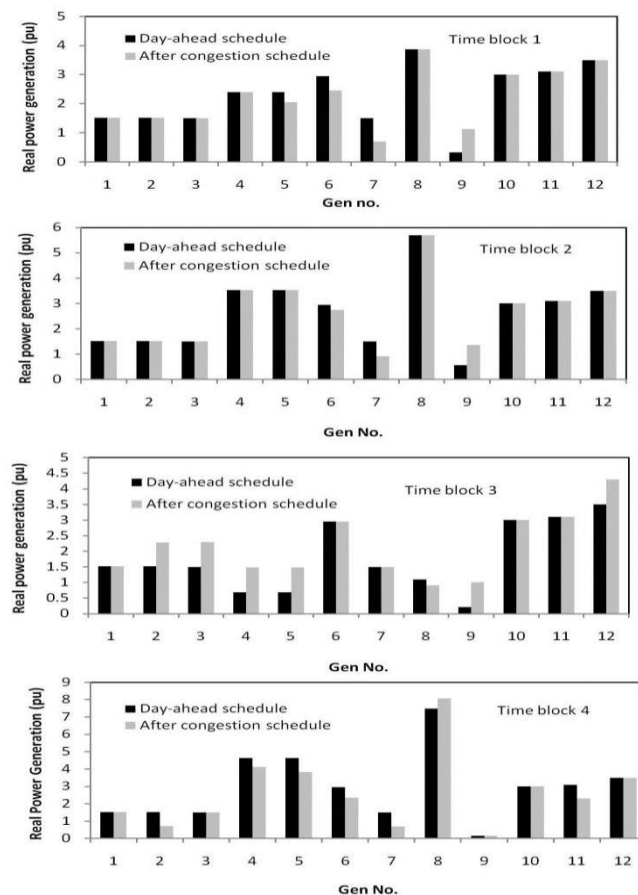


Fig. 2. Before and after congestion schedule for 2-line congestion case for all time blocks

Congestion on two lines viz. 15-16 and 16-19 has been forced by reducing its line flow limit from 500 MVA to 120 MVA and 90 MVA respectively. This is done by calculating their base power flows. Due to congestion on these lines, generation of different units has been rescheduled in different time blocks as shown in Table A1 (Appendix). Total congestion management cost considering combined bidding plan for all the time blocks is 12430.0 \$/h. It has been noted that generator unit no. 1 and 10 are not participating in congestion management due to their high individual raw bids. Also, generator unit no. 2, 3, 11 and 12 are participating in congestion management in certain time intervals, but their level of participation is less as they have high values of individual raw bids as compared to rest of the units. Figure 2 gives day-ahead schedule and after congestion schedule of different units in different time blocks for 2-line congestion case.

To show the effect of combined operation of hydro and wind plants, segregation of total congestion cost for different time blocks is shown in Table 3. As wind speed is highest in first time block, power imbalances due to wind unit are less and

hydro units need not change their scheduled generation much. Hence, congestion management cost is least in this time block (2007.5 \$/h). On the other hand, wind velocity in fourth time block is less than that in first and third time blocks. Thus, its power imbalances are taken care of by hydro units by doing more rescheduling in their own generation. Hence, congestion management cost in fourth interval is highest (4179.1 \$/h).

For comparative analysis between combined bidding plan and individual raw bidding plan, a case has also been executed when there is no combined bidding between units of bus numbers 18 and 19 and they are offering their individual up and down bids. Total congestion management cost for this case has come out to be 19782.51 \$/h, as given in Table 4. These results show the superiority of combined bidding plan over individual raw bidding plan. There is significant reduction in congestion management cost because total power imbalances are reduced when hydro and wind units operate in coordination with each other and offer combined bids

Table 3 Congestion cost in all time blocks for 2-line congestion case

	Time block 1	Time block 2	Time block 3	Time block 4
Congestion cost (\$/h)	2007.5	2240.0	4003.1	4179.4

Table 4 Comparison of congestion cost for different cases

Case	CB (\$/h)	IB (\$/h)	% decrease when CB is used
Congestion (2-line)	12430.0	19782.51	37.17

* CB: Combined bidding

* IB: Individual biddings

Conclusions

A new combined bidding plan for hydro – wind combination in a hybrid power market for congestion management is proposed in this paper. This plan is based on power imbalance between day-ahead schedule and actual generation of hydro wind combination. Congestion management cost is significantly reduced as hydro-wind coordination is shown in their operation which reduces their power imbalances. It is finally concluded that with the proposed novel combined bidding strategy, congestion in wind integrated hybrid power system is managed in a more economical way.

References

- [1] Pillay, A., Karthikeyan, S.P., Kothari, D.P.: ‘Congestion management in power system’, *Int. Jour. of Elect. Power Comp. and Syst.*, 2015, 70, pp. 83-90
- [2] Nappu, M.B., Arief, A., Bansal, R.C.: ‘Transmission management for congested power system: A review of concepts, technical challenges and development of a new methodology’, *Int. Jour. of Renew. and Sustain. Energy*
- [3] Aishvarya, N., Srivastava, S.K., Singh, S.P.: ‘Congestion management approaches in restructured power systems: key issues and challenges’, *The Electricity Journal*, 2020, 33(3)
- [4] Deb, S., Gope, S., and Goswami, A.K.: ‘Real power rescheduling for congestion management with integration of wind farm using firefly algorithm’, *Proc. IEEE International Conference on Energy, Power and Environment: Towards Sustainable Growth (ICEPE)*, 2015, pp. 1-6
- [5] Sagwal, R., Kumar, A.: ‘Voltage stability margin based congestion management for hybrid system considering secure bilateral trading: MINLP approach’. *Proc. IEEE 6th Int. Conf. on Power Syst. (ICPS)*, 2016, pp. 1-6
- [6] Sagwal, R., Kumar, A.: ‘Congestion management solution for hybrid system considering voltage stability margin’. *Global Colloq. in Recent Advanc. and Effectual Res. in Engg., Sci. and Tech. (RAEREST)*, 2016, pp. 726-734

- [7] Khemani, A.K., Patel, N.K.: 'Generation rescheduling of most sensitive zone for congestion management'. Proc. NUICoNE., 2011, pp. 01-05
- [8] Gope, S., Goswami, A.K., Tiwari, P.K., 'Transmission congestion management with integration of wind farm: a possible solution methodology for deregulated power market', Int. Journal of System Assurance Engineering and Management (Springer), 2020, 11, pp. 287-296
- [9] Matevosyan, J., Olsson, M., and Soder, L.: 'Hydropower planning coordinated with wind power in areas with congestion problems for trading on the spot and the regulating market', Int. Jour. of Elect. Power Syst. Res., 2009, 79, pp. 39-48
- [10] Rabiee, A., Vanouni, M., and Parniani, M.: 'Optimal reactive power dispatch for improving voltage stability margin using a local voltage stability index', Energy Convers. Manag., 2012, 59, pp. 66-73
- [11] Mandala, M., Gupta, C.P.: 'Comparative studies of congestion management in deregulated electricity market'. Proc. NPSC, 2010, pp. 628-635
- [12] Kumar, A., and Sekhar, C.: 'Congestion management with FACTS devices in deregulated electricity markets ensuring loadability limit', Electr. Power Energy Syst., 2013, 46(1), pp. 258-273
- [13] Singh, K., Padhy, N.P., Sharma, J.D.: 'Congestion management considering hydro-thermal combined operation in a pool based electricity market', Int. Jour. of Elect. Power and Ener. Syst, 2011, 33, pp. 1513-1519
- [14] Verma, Y.P., Kumar, A.: 'Congestion management solution under secure bilateral transactions in hybrid electricity market for hydro-thermal combination', Int. Jour. of Elect. Power and Ener. Syst., 2015, 64, pp. 398-407
- [15] Nieta, A.S., Contreras, J., and Munoz, J.I.: 'Optimal coordinated wind-hydro bidding strategies in day-ahead markets', IEEE Trans. on Power Syst., 2013, 28, (2), pp. 798 809
- [16] IEEE Reliability Test System', IEEE Trans. on Power App. & Syst., 1979, 98, (6), pp. 2047-2054
- [17] Aziz, T., Saha, T.K., Mithulananthan, N.: 'Identification of the weakest bus in a distribution system with load uncertainties using reactive power margin'. Proc. IEEE Universities Power Engg. Conf., 2010, pp. 1-6
- [18] 'Renewable Resource Data Centre (RRDC), National Renewable Energy Laboratory www.rred.nrel.gov/wind/new_data/India/about.html (NREL),'
- [19] Brooke, A., Kendrick, D., Meeraus, A., Raman, R., Rosenthal, R.E.: 'GAMS: A User's Guide', Washington DC: GAMS Development Cooperation, 1998
- [20] MATLAB and Simulink for technical computations', <http://www.mathworks.com>

Appendix

Table A1 Day-ahead schedule and after-congestion generation schedule for 2-line congestion

Gen no.	Bus No.	Time block 1				Time block 2				Time block 3				Time block 4			
		P0	P	du	dd	P0	P	du	dd	P0	P	du	dd	P0	P	du	dd
1	1	1.52	1.52	-	-	1.52	1.52	-	-	1.52	1.52	-	-	1.52	1.52	-	-
2	2	1.52	1.52	-	-	1.52	1.52	-	-	1.52	2.276	0.75	-	1.52	0.72	-	0.8
3	7	1.5	1.5	-	-	1.5	1.5	-	-	1.5	2.3	0.8	-	1.5	1.5	-	-
4	8	2.39	2.39	-	-	3.534	3.534	-	-	0.688	1.488	0.8	-	4.641	4.13	-	0.51
5	13	2.39	2.05	-	0.34	3.534	3.534	-	-	0.688	1.488	0.8	-	4.641	3.841	-	0.8
6	15	2.95	2.45	-	0.49	2.95	2.743	-	0.20	2.95	2.95	-	-	2.95	2.348	-	0.60
7	16	1.5	0.7	-	0.8	1.5	0.918	-	0.58	1.5	1.5	-	-	1.5	0.7	-	0.8

8	18	3.87	3.87	-	-	5.7	5.7	-	-	1.1	0.914	-	0.18 6	7.485	8.057	0.57 2	-
9	19	0.32 8	1.12 8	0. 8	-	0.559 4	1.359 4	0. 8	-	0.214 5	1.014 5	0.8	-	0.146 1	0.146 1	-	-
10	21	3	3	-	-	3	3	-	-	3	3	-	-	3	3	-	-
11	22	3.1	3.1	-	-	3.1	3.1	-	-	3.1	3.1	-	-	3.1	2.3	-	0.8
12	23	3.5	3.5	-	-	3.5	3.5	-	-	3.5	4.3	0.8	-	3.5	3.5	-	-

*All values in pu