Graphical Abstract

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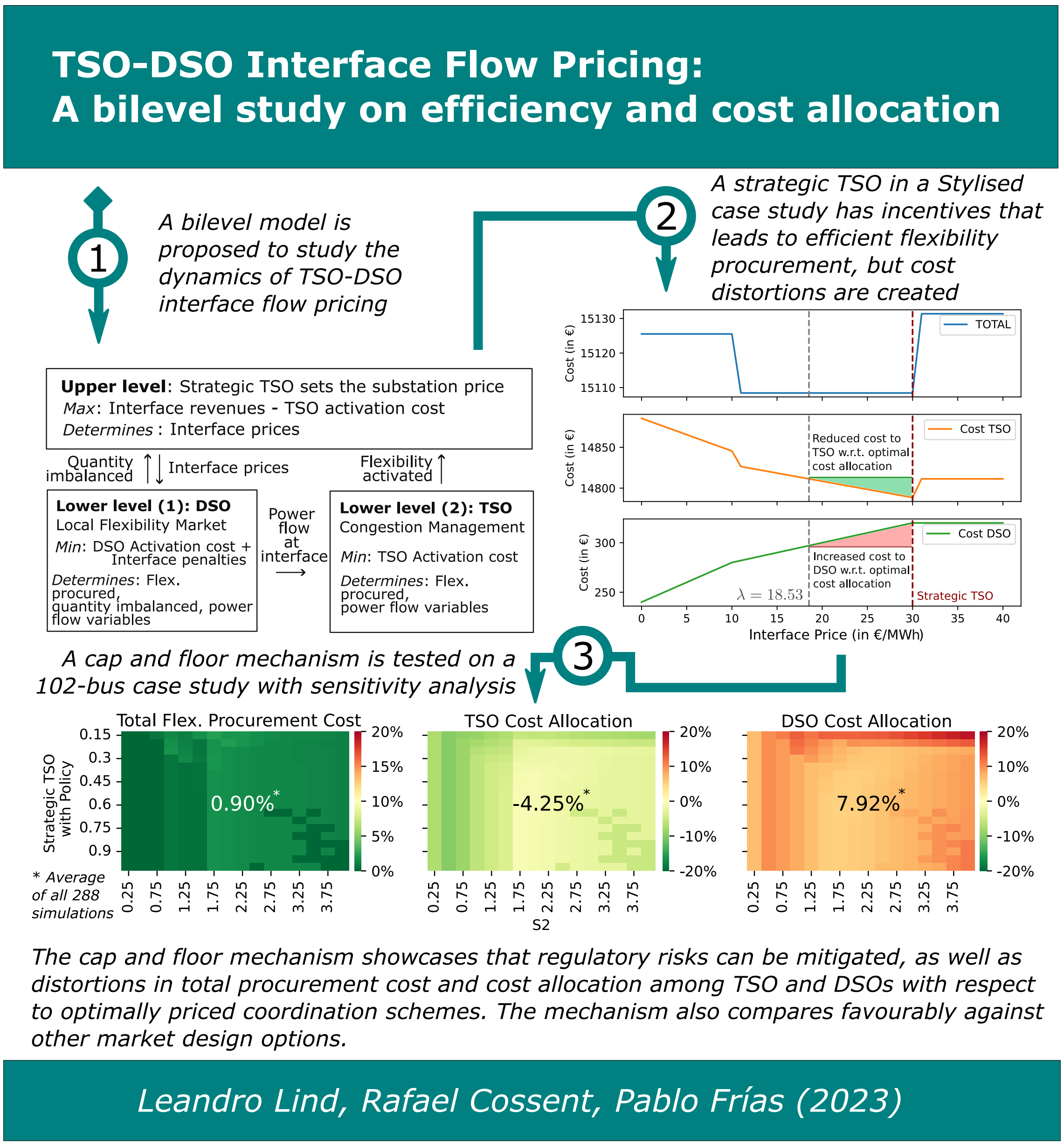

TSO-DSO Interface Flow Pricing: A bilevel study on efficiency and cost allocation

Leandro Lind, Rafael Cossent, Pablo Frías

[a] *Institute for Research in Technology (IIT)-ICAI School of Engineering, Universidad Pontificia Comillas, Santa Cruz de Marcenado 26, Madrid, 28015, Spain*

Abstract

In the context of increasing distributed flexibility, enhanced TSO-DSO coordination is needed when procuring and activating flexibility. The literature shows that pricing the changes in the power flow over the TSO-DSO interfacing substation leads to optimal flexibility procurement cost in sequential TSO-DSO flexibility markets. This paper proposes a bilevel model, considering a TSO leader which sets interface flow prices freely, and DSO-followers in a Stackelberg game. This game-theoretical approach allows for the identification of regulatory risks and the testing of regulatory mechanisms. Based on two case studies, results show that, if left unregulated, the strategic TSO creates significant cost allocation distortions, creating unwanted financial transfers from DSOs to the TSO. However, when acting strategically, the TSO also activates (or leads to the activation of) economical flexibility providers, having as a reference the first-best option, namely the Common Coordination Scheme (CS). Leveraging on these results, a cap and floor mechanism is proposed, limiting unwanted cost allocation distortions and retaining incentives for efficient flexibility activations. Results showcase that a Fragmented CS with regulated interface flow prices could be an efficient second-best compared to the Common CS, outperforming other regulatory options found in the literature.

Keywords: TSO-DSO Coordination, Distributed Flexibility, Bilevel Optimisation, Interface Flow Pricing

1. Case Study Data

Scalar	Value
SB	100
$\theta^{+,-}$	± 1.5
PF	0.95
V^+	1.1
V^-	0.9
$IntPrice_s^+$	1000[1]

Table 1: Scalars for both Stylised and 102-Bus Case Studies

1.1. Stylised Case Study

i	j	$R_{i,j}$ **(p.u.)**	$X_{i,j}$ **(p.u.)**	$F_{i,j}^{p,+}$ **(MW)**
T1	T2	0.00281	0.0281	400
T2	T3	0.00304	0.0304	400
T3	T4	0.00064	0.0064	400
T1	T4	0.00108	0.0108	400
T4	T5	0.00297	0.0297	400
T5	T1	0.00297	0.0297	400
T2	S1	0.005	0.0344	400
D1002	S1	0.003	0.006	10
D1002	D1003	0.003	0.006	6

Table 2: Branch data for Stylized Case Study

[1] For the Fragmented-Strategic CS

i	s	$SLACK$	D_i^p **(MW)**	D_i^q **(MVAr)**	$DispatchDA_i$ **(MW)**
T1	TSO		0		
T2	TSO		100		
T3	TSO		300		1,010
T4	TSO		600		
T5	TSO		0		
D1002	D1	DSO	0		
D1003	D1		10	3.287	
S1		TSO			

Table 3: Bus data for Stylised Case Study

k	i	s	P_k^- **(MW)**	P_k^+ **(MW)**	Bid_k^{dw} **(€/MWh)**	Bid_k^{up} **(€/MWh)**
G3	T3	TSO	500	500	50	50
G4	T4	TSO	300	300	20	20
FSP1	D1002	DSO	2	0	10	10
FSP2	D1002	DSO	2	0	30	30
FSP3	D1003	DSO	5	5	60	60

Table 4: FSP data for Stylised Case Study

1.2. 102-bus Case Study

i	j	$R_{i,j}$ **(p.u.)**	$X_{i,j}$ **(p.u.)**	$F_{i,j}^{p,+}$ **(MW)**
1	2	0.02	0.06	130
1	3	0.05	0.19	130
2	4	0.06	0.17	65
3	4	0.01	0.04	130
2	5	0.05	0.2	130
2	6	0.06	0.18	65
4	6	0.01	0.04	90
5	7	0.05	0.12	70

continued . . .

i	j	$R_{i,j}$ (p.u.)	$X_{i,j}$ (p.u.)	$F^{p,+}_{i,j}$ (MW)
6	7	0.03	0.08	130
6	8	0.01	0.04	**23**
6	9	0	0.21	65
6	10	0	0.56	32
9	11	0	0.21	65
9	10	0	0.11	65
4	12	0	0.26	65
12	13	0	0.14	65
12	14	0.12	0.26	32
12	15	0.07	0.13	32
12	16	0.09	0.2	32
14	15	0.22	0.2	16
16	17	0.08	0.19	16
15	18	0.11	0.22	16
18	19	0.06	0.13	16
19	20	0.03	0.07	32
10	20	0.09	0.21	32
10	17	0.03	0.08	32
10	21	0.03	0.07	32
10	22	0.07	0.15	32
21	22	0.01	0.02	32
15	23	0.1	0.2	16
22	24	0.12	0.18	16
23	24	0.13	0.27	16
24	25	0.19	0.33	16
25	26	0.25	0.38	16
25	27	0.11	0.21	16
28	27	0	0.4	65
27	29	0.22	0.42	16
27	30	0.32	0.6	16
29	30	0.24	0.45	16
8	28	0.06	0.2	32
6	28	0.02	0.06	32
1001	1002	0.0431	0.1204	4
1002	1003	0.0601	0.1677	4

continued ...

i	j	$R_{i,j}$ **(p.u.)**	$X_{i,j}$ **(p.u.)**	$F^{p,+}_{i,j}$ **(MW)**
1003	1004	0.0316	0.0882	**2**
1004	1005	0.0896	0.2502	4
1005	1006	0.0295	0.0824	1.5
1006	1007	0.172	0.212	1.5
1007	1008	0.407	0.3053	1.5
1002	1009	0.1706	0.2209	1.5
1001	1020	0.291	0.3768	4
1020	1021	0.2222	0.2877	4
1021	1022	0.4803	0.6218	1.5
1021	1023	0.3985	0.516	1.5
1023	1024	0.291	0.3768	1.5
1023	1025	0.3727	0.4593	1.5
1025	1026	0.1104	0.136	1.5
1001	111	0.0	0.001	6
111	110	0.0312	0.6753	6
2	110	0.005	0.0344	6
2001	2002	0.0431	0.1204	4
2002	2003	0.0601	0.1677	4
2003	2004	0.0316	0.0882	4
2004	2005	0.0896	0.2502	4
2005	2006	0.0295	0.0824	1.5
2006	2007	0.172	0.212	1.5
2007	2008	0.407	0.3053	1.5
2002	2009	0.1706	0.2209	1.5
2001	2020	0.291	0.3768	4
2020	2021	0.2222	0.2877	4
2021	2022	0.4803	0.6218	1.5
2021	2023	0.3985	0.516	1.5
2023	2024	0.291	0.3768	1.5
2023	2025	0.3727	0.4593	1.5
2025	2026	0.1104	0.136	1.5
2001	211	0.0	0.001	6
211	210	0.0312	0.6753	6
7	210	0.005	0.0344	6
3001	3002	0.0431	0.1204	4

continued . . .

i	j	$R_{i,j}$ **(p.u.)**	$X_{i,j}$ **(p.u.)**	$F_{i,j}^{p,+}$ **(MW)**
3002	3003	0.0601	0.1677	4
3003	3004	0.0316	0.0882	4
3004	3005	0.0896	0.2502	4
3005	3006	0.0295	0.0824	1.5
3006	3007	0.172	0.212	1.5
3007	3008	0.407	0.3053	1.5
3002	3009	0.1706	0.2209	1.5
3001	3020	0.291	0.3768	4
3020	3021	0.2222	0.2877	4
3021	3022	0.4803	0.6218	1.5
3021	3023	0.3985	0.516	**0.75**
3023	3024	0.291	0.3768	1.5
3023	3025	0.3727	0.4593	1.5
3025	3026	0.1104	0.136	1.5
3001	311	0.0	0.001	6
311	310	0.0312	0.6753	6
12	310	0.005	0.0344	6
4001	4002	0.0431	0.1204	4
4002	4003	0.0601	0.1677	4
4003	4004	0.0316	0.0882	4
4004	4005	0.0896	0.2502	4
4005	4006	0.0295	0.0824	1.5
4006	4007	0.172	0.212	1.5
4007	4008	0.407	0.3053	1.5
4002	4009	0.1706	0.2209	1.5
4001	4020	0.291	0.3768	4
4020	4021	0.2222	0.2877	4
4021	4022	0.4803	0.6218	1.5
4021	4023	0.3985	0.516	1.5
4023	4024	0.291	0.3768	1.5
4023	4025	0.3727	0.4593	1.5
4025	4026	0.1104	0.136	1.5
4001	411	0.0	0.001	6
411	410	0.0312	0.6753	6
30	410	0.005	0.0344	6

continued ...

i	j	$R_{i,j}$ **(p.u.)**	$X_{i,j}$ **(p.u.)**	$F_{i,j}^{p,+}$ **(MW)**

Table 5: Branch data for 102-Bus Case Study.

i	s	$SLACK$	D_i^p **(MW)**	D_i^q **(MVAr)**	$DispatchDA_i$ **(MW)**
1	TSO	TSO	0	0	36.2
2	TSO		9.85	0	49.1
3	TSO		2.4	0	
4	TSO		7.6	0	
5	TSO		0	0	
6	TSO		0	0	
7	TSO		10.95	0	
8	TSO		30	0	
9	TSO		0	0	
10	TSO		5.8	0	
11	TSO		0	0	
12	TSO		0	0	
13	TSO		0	0	14.13
14	TSO		6.2	0	
15	TSO		8.2	0	
16	TSO		3.5	0	
17	TSO		9	0	
18	TSO		3.2	0	
19	TSO		9.5	0	
20	TSO		2.2	0	
21	TSO		17.5	0	
22	TSO		0	0	21.24
23	TSO		3.2	0	13.82
24	TSO		8.7	0	
25	TSO		0	0	
26	TSO		3.5	0	
27	TSO		0	0	32.41

continued . . .

i	s	$SLACK$	D_i^p **(MW)**	D_i^q **(MVAr)**	$DispatchDA_i$ **(MW)**
28	TSO		0	0	
29	TSO		2.4	0	
30	TSO		0	0	
110	(interface)	DSO 1	0	0	
111	DSO 1		0	0	
1001	DSO 1		0	0	
1002	DSO 1		0.1	0.06	
1003	DSO 1		0.2	0.125	
1004	DSO 1		0.75	0.465	
1005	DSO 1		1.5	1.13	
1006	DSO 1		0.4	0.25	
1007	DSO 1		0.1	0.06	
1008	DSO 1		0.5	0.31	
1009	DSO 1		0.25	0.155	
1020	DSO 1		0.5	0.31	
1021	DSO 1		0.15	0.095	
1022	DSO 1		0.1	0.06	
1023	DSO 1		0.4	0.25	
1024	DSO 1		0.25	0.155	
1025	DSO 1		0.5	0.31	
1026	DSO 1		0.1	0.06	
210	(interface)	DSO 2	0	0	
211	DSO 2		0	0	
2001	DSO 2		0	0	
2002	DSO 2		0.1	0.06	
2003	DSO 2		0.2	0.125	
2004	DSO 2		0.75	0.465	
2005	DSO 2		1.5	1.13	
2006	DSO 2		0.4	0.25	
2007	DSO 2		0.1	0.06	
2008	DSO 2		0.5	0.31	
2009	DSO 2		0.25	0.155	
2020	DSO 2		0.5	0.31	
2021	DSO 2		0.15	0.095	

continued ...

i	s	$SLACK$	D_i^p **(MW)**	D_i^q **(MVAr)**	$DispatchDA_i$ **(MW)**
2022	DSO 2		0.1	0.06	
2023	DSO 2		0.4	0.25	
2024	DSO 2		0.25	0.155	
2025	DSO 2		0.5	0.31	
2026	DSO 2		0.1	0.06	
310	(interface)	DSO 3	0	0	
311	DSO 3		0	0	
3001	DSO 3		0	0	
3002	DSO 3		0.1	0.06	
3003	DSO 3		0.2	0.125	
3004	DSO 3		0.75	0.465	
3005	DSO 3		1.5	1.13	
3006	DSO 3		0.4	0.25	
3007	DSO 3		0.1	0.06	
3008	DSO 3		0.5	0.31	
3009	DSO 3		0.25	0.155	
3020	DSO 3		0.5	0.31	
3021	DSO 3		0.15	0.095	
3022	DSO 3		0.1	0.06	
3023	DSO 3		0.4	0.25	
3024	DSO 3		0.25	0.155	
3025	DSO 3		0.5	0.31	
3026	DSO 3		0.1	0.06	
410	(interface)	DSO 4	0	0	
411	DSO 4		0	0	
4001	DSO 4		0	0	
4002	DSO 4		0.1	0.06	
4003	DSO 4		0.2	0.125	
4004	DSO 4		0.75	0.465	
4005	DSO 4		1.5	1.13	
4006	DSO 4		0.4	0.25	
4007	DSO 4		0.1	0.06	
4008	DSO 4		0.5	0.31	
4009	DSO 4		0.25	0.155	

continued ...

i	s	$SLACK$	D_i^p (MW)	D_i^q (MVAr)	$DispatchDA_i$ (MW)
4020	DSO 4		0.5	0.31	
4021	DSO 4		0.15	0.095	
4022	DSO 4		0.1	0.06	
4023	DSO 4		0.4	0.25	
4024	DSO 4		0.25	0.155	
4025	DSO 4		0.5	0.31	
4026	DSO 4		0.1	0.06	

Table 6: Bus data for 102-Bus Case Study

k	i	s	P_k^- (MW)	P_k^+ (MW)	Bid_k^{dw} (€/MWh)	Bid_k^{up} (€/MWh)
KT2	2	TSO	60	60	21	21
KT22	22	TSO	70	70	35	35
KT27	27	TSO	50	50	48	48
KT23	23	TSO	40	40	25	25
KT13	13	TSO	45	45	55	55
K1009	1009	DSO 1	1	1	34	68
K1020	1020	DSO 1	1	1	59	118
K1021	1021	DSO 1	1	1	41	81
K1022	1022	DSO 1	1	1	33	66
K1024	1024	DSO 1	1	1	56	111
K1025	1025	DSO 1	1	1	67	134
K2004	2004	DSO 2	1	1	68	136
K2008	2008	DSO 2	1	1	47	93
K2009	2009	DSO 2	1	1	65	130
K2022	2022	DSO 2	1	1	74	147
K2025	2025	DSO 2	1	1	71	141
K3004	3004	DSO 3	1	1	73	146
K3005	3005	DSO 3	1	1	52	104
K3007	3007	DSO 3	1	1	38	75
K3009	3009	DSO 3	1	1	44	88

continued . . .

k	i	s	P_k^- **(MW)**	P_k^+ **(MW)**	Bid_k^{dw} **(€/MWh)**	Bid_k^{up} **(€/MWh)**
K4002	4002	DSO 4	1	1	45	89
K4003	4003	DSO 4	1	1	37	73
K4020	4020	DSO 4	1	1	72	143
K4023	4023	DSO 4	1	1	50	99
K4026	4026	DSO 4	1	1	29	57
K3025	3025	DSO 3	0	3	220	439
K1006	1006	DSO 1	0	3	64	128

Table 7: FSP data for the 102-Bus Case Study