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Updated and validated power flow model of the main continental European transmission network

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***Abstract*—The advent of liberalisation of the electricity market in Europe has seen the growth of cross-border trading of energy. Zhou & Bialek published in 2005 a paper outlining an approximate model which simulated the real network and could be used to analyse the effects of cross-border trades in a test environment. This paper presents an updated and validated model that includes the Balkan region that was not included in the original model. In addition the model was fully updated to replicate 2009 power flows. The final results are positive and show an overall correlation of over 95% when compared with the published cross-border flows from 2009. Power Transfer Distribution Factors were also calculated to show the problems of loop flows when considering large exporters or importers of energy. The database created in this project has been made available for public use by making it accessible from PowerWorld website http://www.powerworld.com/bialek. It is hoped that it will be used widely to analyse transmission constraints and functioning of the energy market in Europe.**

***Index Terms*—transmission networks, DC power flow analysis.**

I. INTRODUCTION

Availability of realistic models of transmission networks is of paramount importance for researchers studying technical and economic aspects of power system operation. However due to commercial and political sensitivity of making real network models available, few utilities in the world are making their network models widely available. This creates a particular problem for researchers wishing to study the operation of the Common European Market in Europe as any techno-economic analysis of how transmission constraints affect the market operation is impossible without having a realistic network model. To address those concerns, Zhou and Bialek have developed an approximate model of the main continental transmission network using publicly available information 1. The model reflected well the main characteristics of the network. It was developed using PowerWorld simulator and it was widely used by researchers and consultancies worldwide wishing to analyse operation of electricity markets in Europe and especially the effect of transmission constraints.

The initial simulation model was developed to cover what was then referred to as the 1st synchronous UCTE zone. One of the problems associated with creating such a model is the ever evolving transmission network in Europe; most significantly the re-connection of the Balkan area in 2004 and therefore needs to be updated consistently. This paper presents an updated and validated network model that includes the Balkans and replicates winter peak power flows in Europe in 2009 [2]. The model includes cross-border constraints on the main tie-lines in Europe.

The importance of research in this field is clear; the ENTSO-E transmission network constitutes one of the largest interconnected grid systems in the world. There is a need to produce a satisfactory benchmark model that could be used to test the impacts of different techniques on the networks operation and aid in the development of the internal energy market. This work is vital to improving the power transmission networks of Europe and preventing the problems blackouts and congestions bring to an ever expanding system.

II. UPDATING THE ORIGINAL MODEL

Several changes have been made to the original model published in 2005. Most importantly, a model the Balkan region has been developed following the same principles as those presented in [1] and connected to the rest of Europe. Secondly, re-appraisal and correction of the original model was undertaken as the model had been developed in 2000-2001. Thirdly, some errors in entering of reactance values have been discovered and these were corrected. The resulting model has 1494 buses, 2322 transmission lines, 570 power stations and 1092 loads. Figure 1. shows the model of the whole network while Figure 2. shows a zoom-in to Switzerland as an example.

It should be emphasized that the developed model was DC, i.e. it deals only with real power flows as no data was available regarding AVR and other voltage regulator settings. Secondly maximum capacities of only cross-border lines are included as it has been proven impossible to obtain capacities of internal lines in each country.

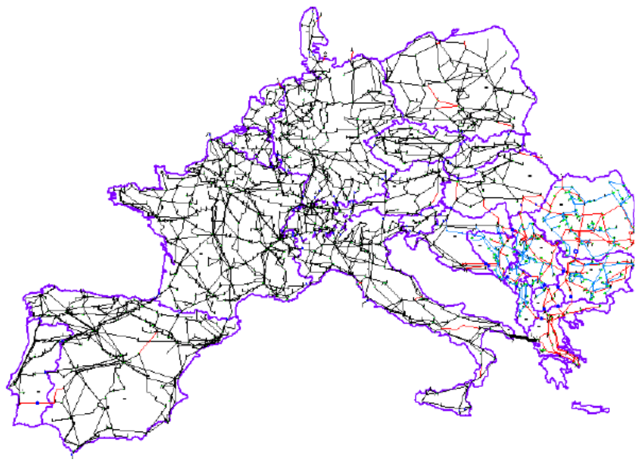

Figure 1. PowerWorld model of the main continental transmission network in Europe

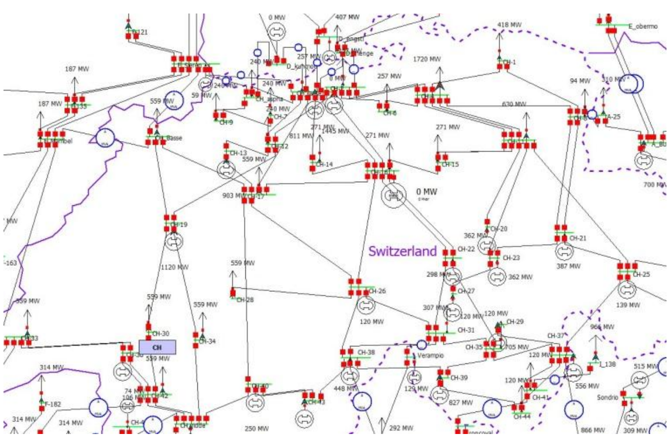

Figure 2. Zoom-in to Switzerland.

III. VALIDATION OF THE MODEL

The updated model was validated using the published ENTSO-E Winter Scenario and Monthly Statistics reports taking 16/12/2009 at 11:00 am as the reference day [3, 4] – see Figure 3. The data included only power flows across each country but did not include generation and demand in each country. ENTSOE 2009 Statistical Yearbook was therefore used to obtain the total load in each country. Then the total value of generation in each country was easily calculated having the value of net imports and exports. TABLE I. shows the resulting values. As the DC power flow model was used, transmission losses were not accounted for.

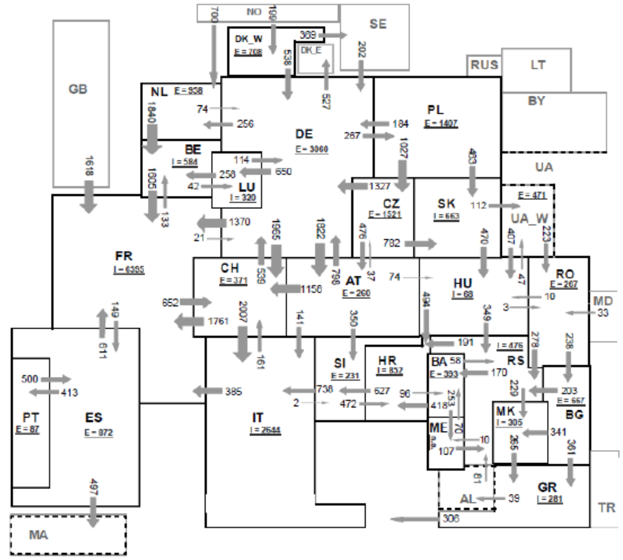

Figure 3. Published winter peak flows in 2009 day [4].

TABLE I. GENERATION AND DEMAND IN EACH COUNTRY.

Country	Winter Demand (MW)	Import (MW)	Export (MW)	Calculated Generation (MW)
Austria (AT)	9,343		260	9,603
Bosnia & Herzegovina (BA)	1,686		393	2,079
Belgium (BE)	12,727	584		12,143
Bulgaria (BG)	5,757		667	6,424
Switzerland (CH)	10,108		371	10,479
Czech Republic (CZ)	9,465		1,521	10,986
Germany (DE)	74,843		3,060	77,903
Denmark West (DK_W)	3,403		708	4,111
Spain (ES)	43,154		872	44,026
France (FR)	85,207	6,395		78,812
Greece (GR)	7,035	281		6,754
Croatia (HR)	2,669	852		1,817
Hungary (HU)	5,803	68		5,735
Italy (IT)	47,668	2,644		45,024
Luxembourg (LU)	828	320		508
Montenegro (ME)	542		262	804
FYROM (MK)	1,136	305		831
Netherlands (NL)	16,768		958	17,726
Poland (PL)	20,889		1,407	22,296
Portugal (PT)	8,324		87	8,411
Romania (RO)	7,413		267	7,680
Serbia (RS)	6,350	476		5,874
Slovenia (SI)	1,763		231	1,994
Slovakia (SK)	3,891	663		3,228

Once the generation and demand data were entered into the model, generations in individual power stations were manipulated, within their generation limits, to obtain as close as possible cross-border flows to those observed in practice and shown in Figure 3.

The resulting accuracy of replicating the actual cross-border power flows was excellent reaching the average of 95%. Comparison between individual cross-border flows for each interface is shown in Figure 4. Percentage accuracy between the published and obtained cross-border flows is illustrated in Figure 5.

From	To	Model	ENTSO-E	% Accuracy
P	E	86.9	87	100%
E	MA	497	497	100%
E	F	461.5	462	100%
GB	F	1618	1618	100%
B	F	1489.1	1472	99%
NO	NL	700	700	100%
NO	DK_W	199	199	100%
NL	B	1855.1	1840	99%
LU	B	217.6	216	99%
D	F	1258.4	1349	93%
D	CH	1624.3	1426	88%
D	AT	921.8	1024	90%
D	LU	537.6	536	100%
D	PL	77.2	83	93%
D	NL	197.8	213	93%
D	DK_E	527	527	100%
SE	D	202	202	100%
CH	F	1141.6	1109	97%
CH	I	1933.3	1846	95%
DK_W	SE	369	369	100%
DK_W	D	538	538	100%
CZ	D	1344.2	1327	99%
CZ	AT	402.8	439	92%
CZ	SK	787.6	782	99%
PL	CZ	1013.2	1027	99%
PL	SK	470.6	463	98%
AT	CH	1076.1	1158	93%
AT	I	135.4	141	96%
AT	SI	296.4	350	85%
AT	HU	76.9	74	96%
I	F	426.8	385	90%
SI	I	696	736	95%
SK	HU	482.8	470	97%
SK	UA_W	112	112	100%
HU	HR	568.8	494	87%
HU	RS	290	349	83%
UA_W	HU	360	360	100%
UA_W	RO	223	223	100%
HR	SI	168.4	155	92%
RO	HU	8	7	88%
RO	BG	283.2	238	84%
RO	RS	230.8	278	83%
MD	RO	33	33	100%
RS	MK	232.2	229	99%
RS	HR	143.9	191	75%
RS	BA	117.6	112	95%
BA	HR	308.6	322	96%
BA	ME	202.2	183	91%
ME	RS	116.2	97	83%
BG	RS	250.8	203	81%
BG	GR	357.9	361	99%
BG	MK	341.5	341	100%
MK	GR	268.3	265	99%
GR	AL	39	39	100%
AL	RS	81	81	100%

Figure 4. Cross-border flows in the model and in ENTSO-E data.

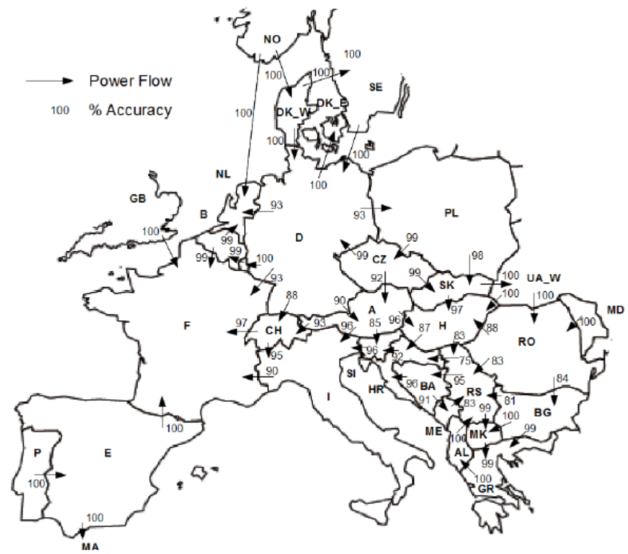

Figure 5. Cross-border power flows and percentage accuracy of simulation.

IV. POWER FLOW DISTRIBUTION FACTORS

Power Transfer Distribution Factors are one of the fundamental tools used to assess congestion management in a meshed network. They indicate the sensitivity of individual transmission lines in a system to a node-to-node transaction. The values are represented as a percentage of change in physical power flow experienced if a particular power is sent from a specified source to sink. The subsequent interconnection capacities have to be held in reserve for that transaction to take place 15. Bilateral transactions may be agreed by two separate countries however given the meshed nature of transmission networks the physical power transfer of power may involve several independent countries during transportation of the power exchanged. Power flows through third-countries are often referred to as loop flows.

PTDFs are quite useful to understand the effect a given country-to-country transaction has on third countries. They can also be useful for a simplified power system modelling when each country is modelled as a zone and only cross-border interfaces are represented without explicit modeling of transmission networks in each country. PTDFs can be then used to model the effect of loop flows without using the full transmission network model.

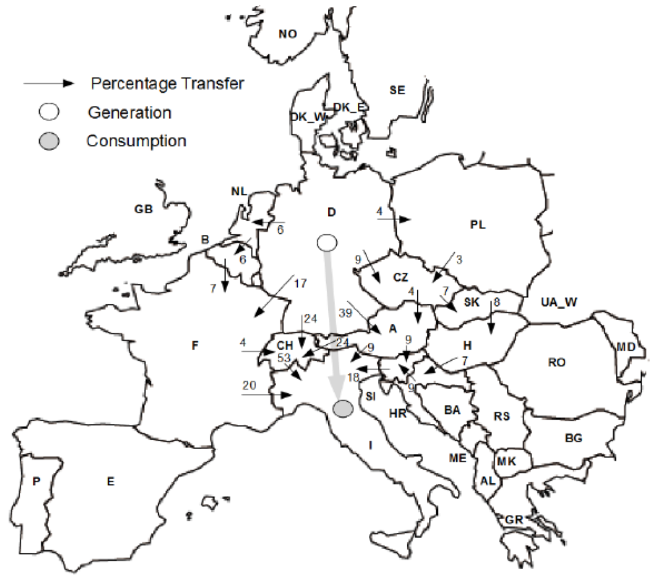

Figure 6. PTDFs for a Germany-Italy transaction

The developed power flow model of Europe was used to calculate a number of PTDFs for transactions originating and terminating in different countries. As an example, Figure 6. shows PTDFs for a Germany-Italy transaction with the numbers indicating a percentage flow through a given border. TABLE II. shows examples of PTDFs for a number of different transactions.

TABLE II. PTDFS FOR DIFFERENT COUNTRY-TO-COUNTRY TRANSACTIONS

Germany - Italy	
Name	% PTDF
A-CH	24.2
A-CZ	-4.4
A-D	-38.7
A-I	9.2
A-SV	9.4
B-F	6.9
B-NL	-5.8
CH-D	-24.3
CH-F	-4.6
CH-I	53.1
CRT-H	-7.1
CRT-SV	8.8
CZ-D	-8.7
CZ-PL	-2.6
CZ-SK	6.8
D-F	17.2
D-NL	5.8
D-PL	4.2
F-I	19.5
H-SK	-8.4
I-SV	-18.2

Germany - France	
Name	% PTDF
A-CH	13.8
A-CZ	-3
A-D	-13.7
B-F	25.2
B-Lx	-4.1
B-NL	-21.1
CH-D	-16.1
CH-F	22
CH-I	7.9
CRT-H	-2.1
CRT-SV	2.7
CZ-D	-3.7
CZ-SK	2.4
D-F	38.8
D-Lx	4.1
D-NL	21.1
D-PL	2.6
F-I	-14
H-SK	-3.2
I-SV	-4.5

Germany - Slovakia	
Name	% PTDF
A-CH	-2
A-CZ	11.2
A-D	-20.1
A-H	11
BA-CRT	-2.2
B-F	4.9
B-NL	-4.8
CH-D	-4.2
CH-F	-4.5
CH-I	6.7
CRT-H	7.9
CRT-SV	-10.6
CZ-D	-33.2
CZ-PL	-15.9
CZ-SK	60.4
D-F	3.6
D-NL	4.8
D-PL	34
F-I	3.9
H-SK	21.5
I-SV	10.1
PL-SK	18.1

Spain - Italy	
Name	% PTDF
A-CH	4.6
A-CZ	-2.7
A-D	-16.1
A-I	6.9
A-SV	6.8
B-F	-11
B-Lx	2.4
B-NL	8.6
CH-D	-4.9
CH-F	-31.9
CH-I	41.5
CRT-H	-4.8
CRT-SV	6
CZ-D	-5.3
CZ-SK	4.5
D-F	-18.3
D-Lx	-2.4
D-NL	-8.6
D-PL	3
E-F	100
F-I	38.8
H-SK	-5.6
I-SV	-12.9

Poland - Croatia	
Name	% PTDF
A-CH	4.5
A-CZ	-20.4
A-D	-19.7
A-H	4.2
A-I	3.1
A-SV	28.3
BA-CRT	15.9
BA-ME	-11.7
BA-RS	-4.1
B-F	3.5
BG-RO	-3.7
BG-RS	2
B-NL	-3.2
CH-D	-7.1
CH-F	-3.1
CH-I	14.7
CRT-H	-33.4
CRT-SV	-51.8
CZ-D	-5.9
CZ-PL	-40.2
CZ-SK	25.7
D-F	5.2
D-NL	3.2
D-PL	-41.5
F-I	5.6
H-SK	-44
I-SV	23.5
PL-SK	18.2
RO-H	-6.7
RO-RS	3
RS-H	-8.1
RS-ME	11.7

Bulgaria - Belgium	
Name	% PTDF
A-CH	8.6
A-CZ	2.6
A-D	25.4
A-H	-21.7
A-SV	-15.2
BA-CRT	37.6
BA-ME	-21.8
BA-RS	-15.8
B-F	-44.4
BG-GR	12.9
BG-RO	56.8
BG-RS	30.3
B-Lx	-8.9
B-NL	-46.7
CH-D	2.8
CH-F	18.8
CH-I	-13
CRT-H	9.9
CRT-SV	40.9
CZ-D	24.7
CZ-PL	8.6
CZ-SK	-30.7
D-F	12.7
D-Lx	8.9
D-NL	46.7
D-PL	-15.3
F-I	-13
GR-MK	12.9
H-SK	37.4
I-SV	-25.6
MK-RS	12.9
PL-SK	-6.7
RO-H	40.1
RO-RS	16.7
RS-CRT	13.1
RS-H	9.2
RS-ME	21.8

Denmark - France	
Name	**% PTDF**
A-CH	13.3
A-CZ	-3.9
A-D	-12
B-F	28.1
B-Lx	-3.4
B-NL	-24.7
CH-D	-15.1
CH-F	21
CH-I	7.3
CRT-H	-2.4
CRT-SV	3
CZ-D	-4
CZ-PL	-2.6
CZ-SK	2.7
D-DK	-100
D-F	37
D-Lx	3.4
D-NL	24.7
D-PL	3.8
F-I	-13.8
H-SK	-3.9
I-SV	-4.8

V. Conclusions

This paper has presented an updated and validated model of the main European transmission network that includes the Balkan region that was not included in the original model published in 2005. In addition the model was fully updated to replicate the actual 2009 power flows in Europe. The final results show an overall correlation of over 95% when compared with the published cross-border flows from 2009. Power Transfer Distribution Factors were also calculated to show the problems of loop flows when considering large exporters or importers of energy.

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