Incorporating FACTS Set Point Optimization in Day-Ahead Generation Scheduling

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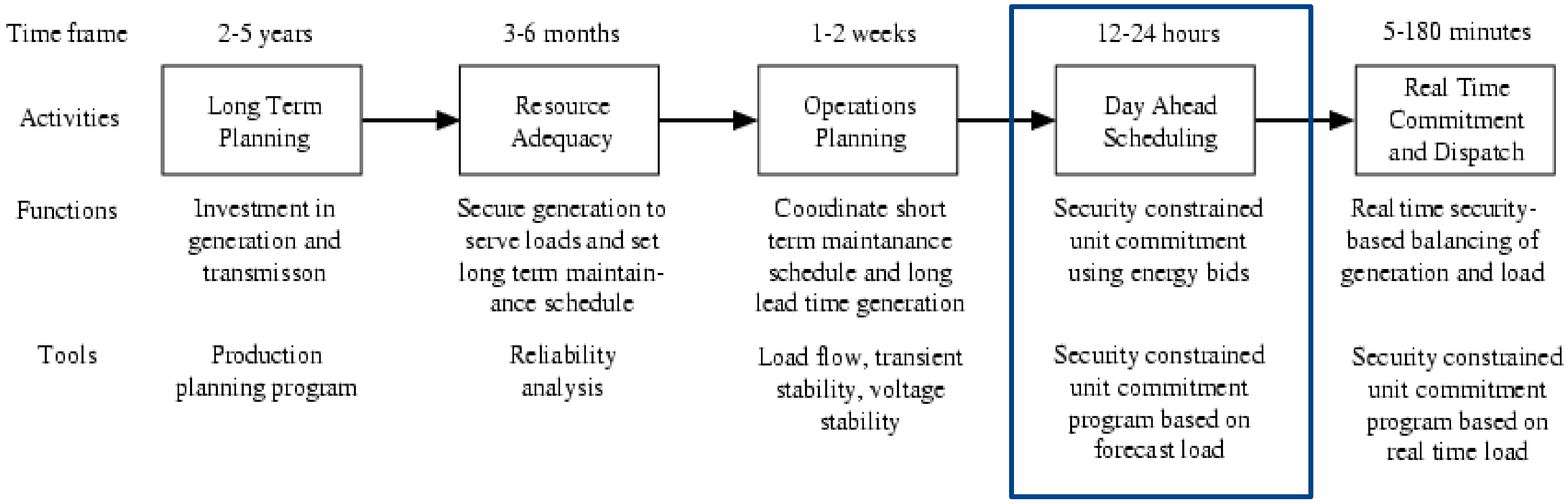
Outline

- Background
- Problem and Mathematical Formulation
- Solution Algorithms
- Preliminary Numerical Results
- Conclusions

Background

Introduction

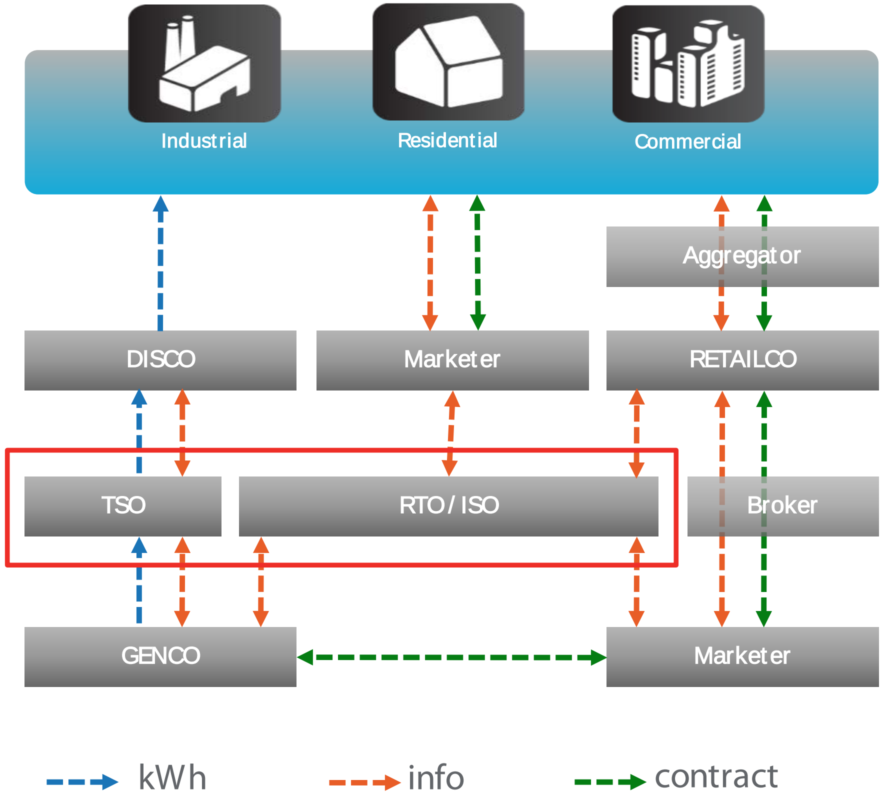
- Security and reliability functions of grid operators:

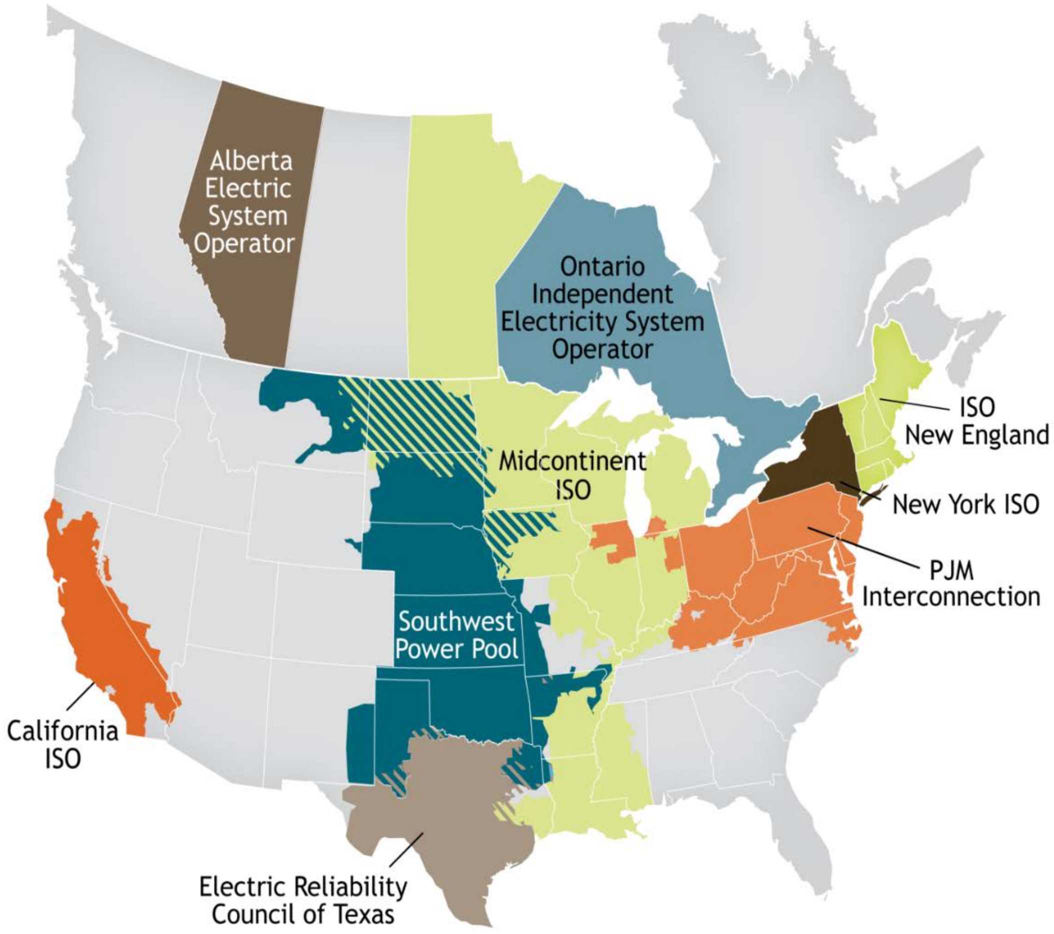


- Day-ahead generation scheduling is a typical business process of grid operators for markets and non-markets

Introduction (cont'd)

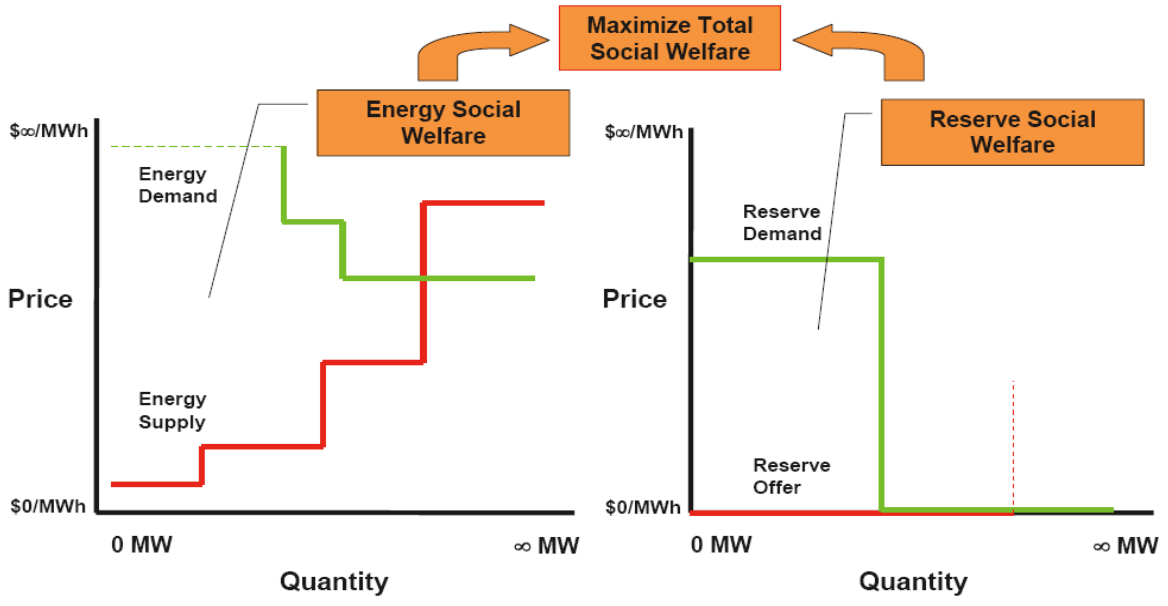
- RTOs/TSOs are reliant on wholesale market mechanism to optimally dispatch energy and ancillary services [3]

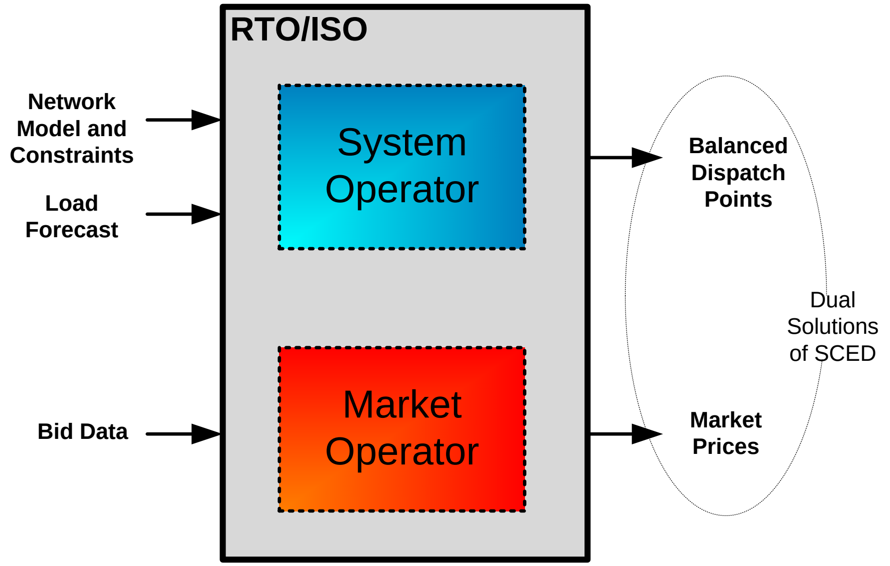




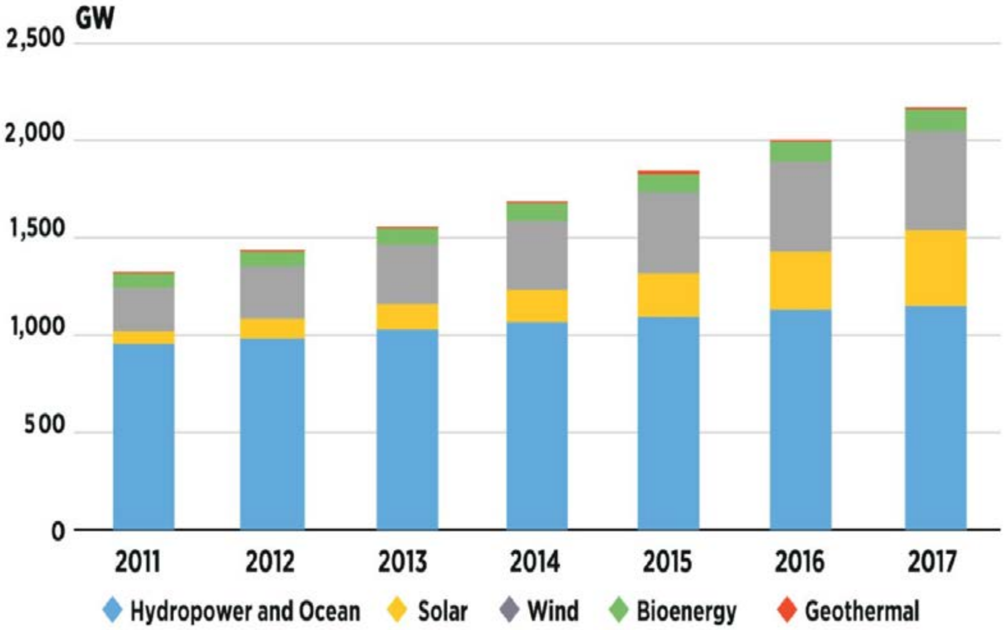
Wholesale Power Market Platform

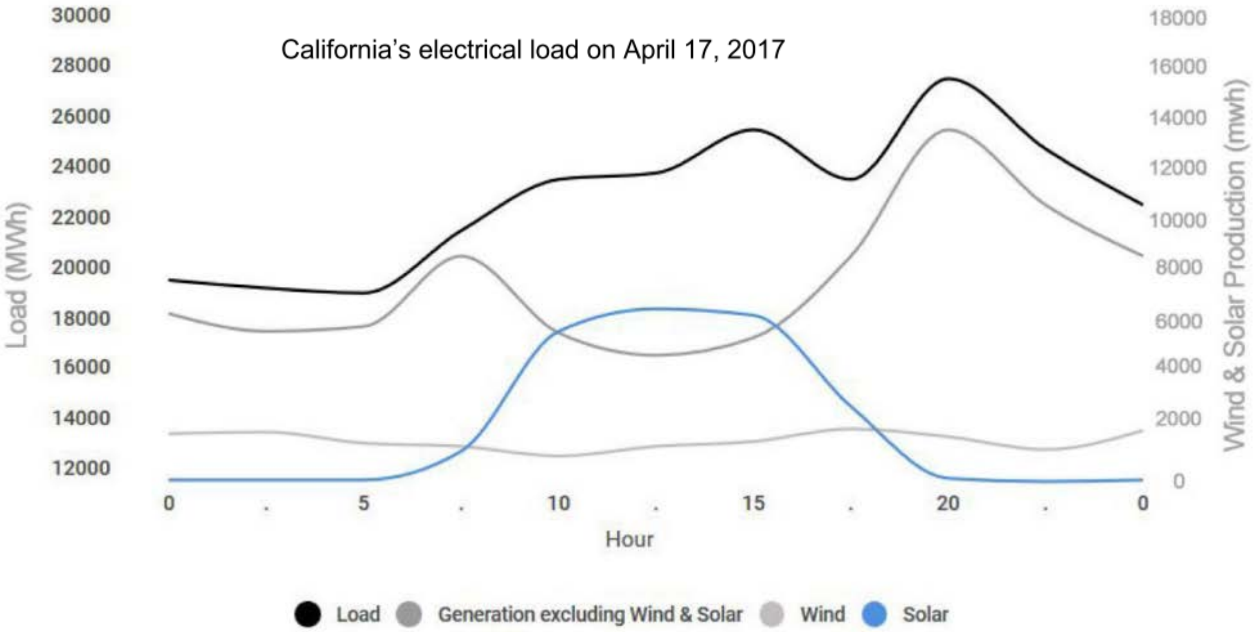
- In the beginning of this century, FERC pushed for a common market design framework called Standard Market Design or the so-called Wholesale Power Market Platform. Variation of such a model (LMP-based two-settlement system) has been adopted by all RTOs in the United States.
- As energy-only markets approached maturity, RTOs one after another enhanced their energy markets to incorporate clearing of ancillary services.
- A co-optimized approach of clearing energy and ancillary services simultaneously has been extensively accepted by ***all*** restructured electricity markets in USA.



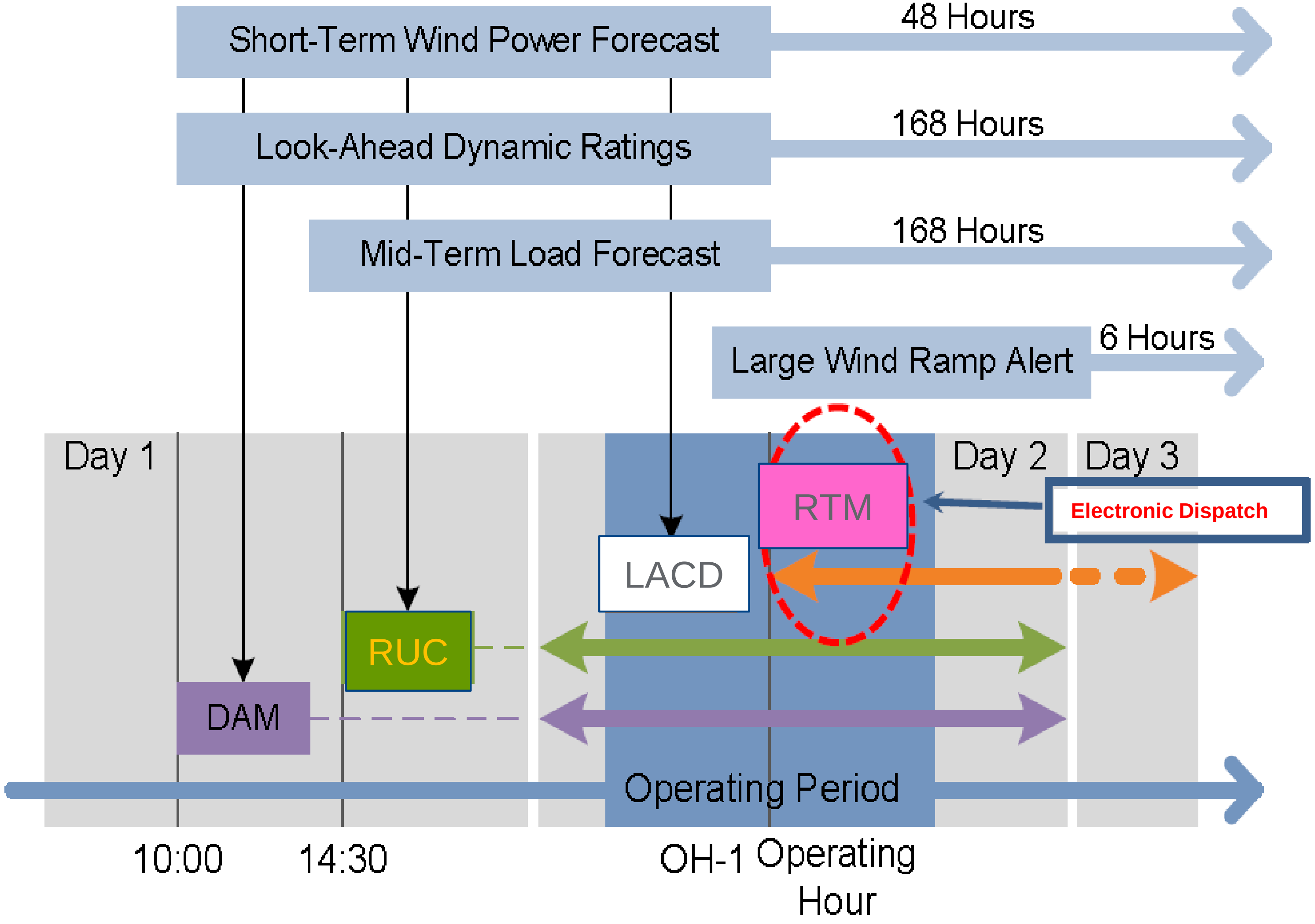


Growth of Renewable Power and High Ramp Net Load



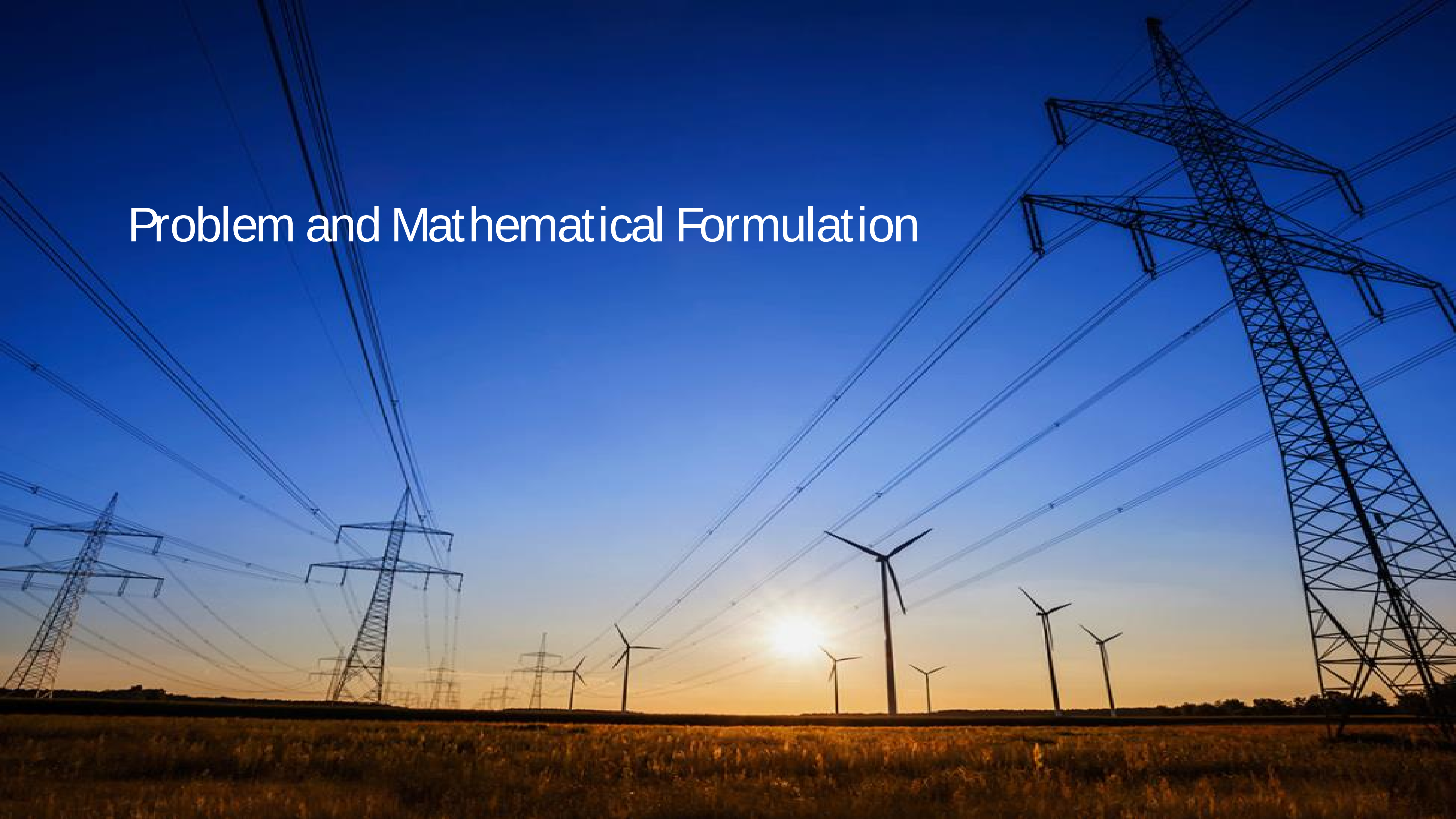


Smart Dispatch to Cope with Uncertainty of Renewable Power



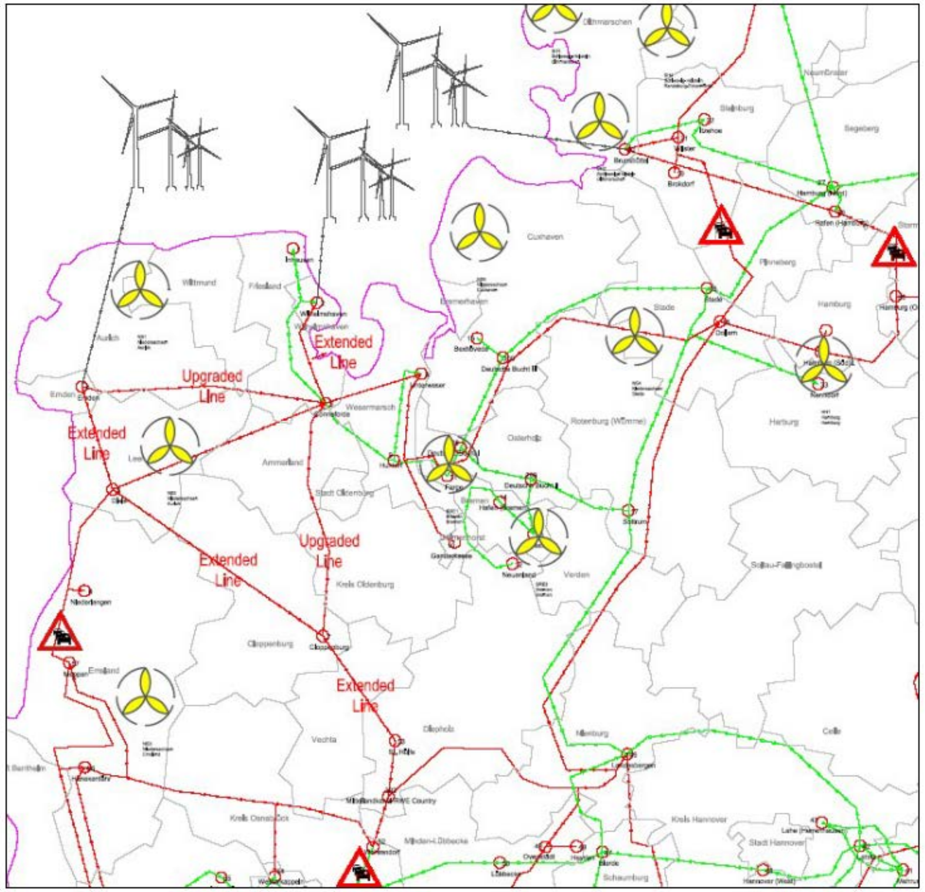
- Day-Ahead Market (DAM) process - provides functions for day-ahead bid data submission, market clearing, and market solution publishing.
- Reliability Unit Commitment (RUC) process - provides system operators a set of tools to revise the day-ahead unit commitment schedule as necessary in order to ensure that the forecasted load and operating reserve requirements will be met and the transmission system is reliable and secured.
- Look-Ahead Commitment and Dispatch (LACD) process – provides a forward-looking view of system operating conditions and recommend start-up/shut-down recommendation of fast-start resources to operators.
- Real-Time Market (RTM) process – provides market-clearing functions to balance generation and load, and meet reserve requirements based on actual real-time system operating conditions. The RTM process computes ex-ante pricing and provides the dispatch signals either MW or price back to the Market Participants.

Problem and Mathematical Formulation

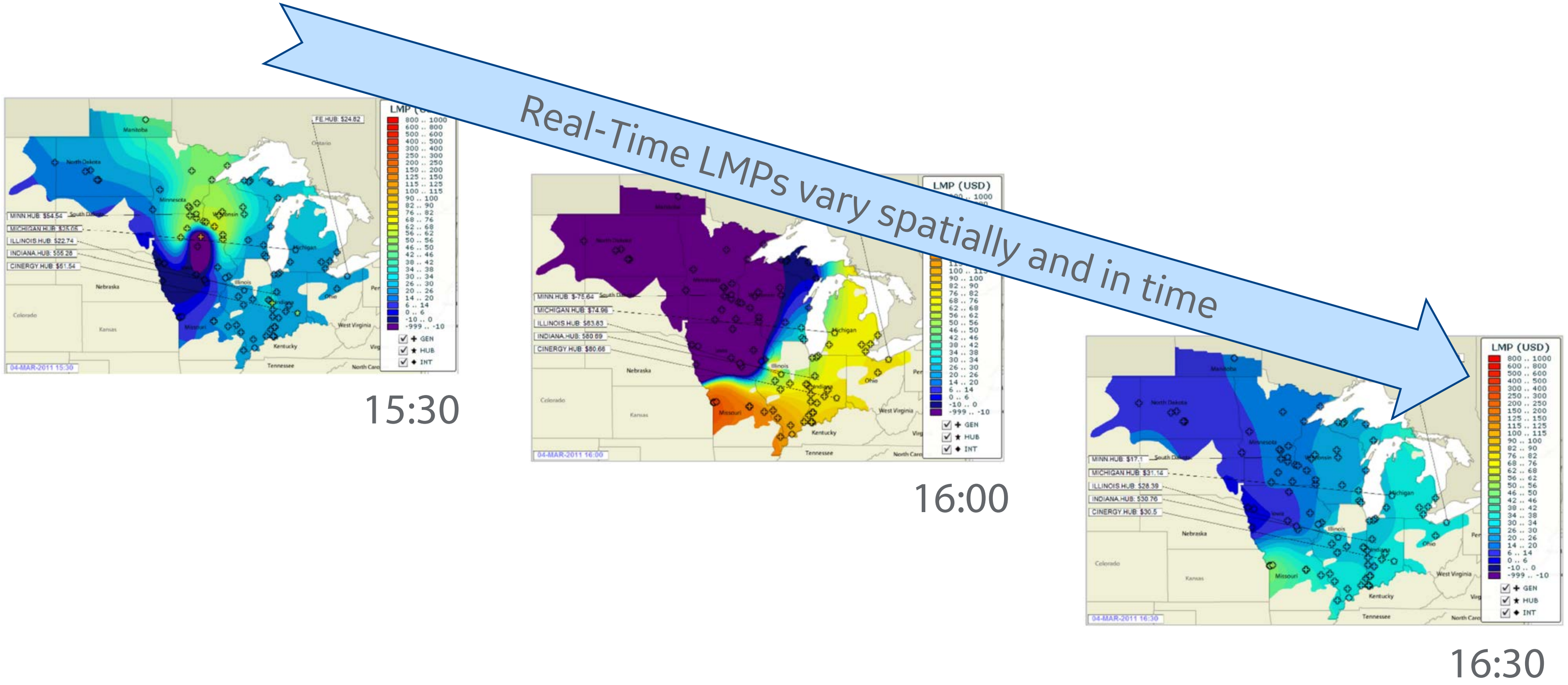


Transmission Congestion

- The increase in renewable generation connected to the grid has exacerbated the problem of transmission congestion considerably
  - o Copper-plate assumption
  - o Loop flow problem



Transmission Congestion Leads to High Production Cost



Source: PJM

- Due to transmission constraints, the economic merit order dispatch is not feasible
- Some low-cost units have to decrease their production, while some high-cost units have to increase their generation
- Production costs increase by the order of billions of dollars annually due to transmission congestion in USA

Solutions to Transmission Congestion

- Market-based congestion management
  - Locational pricing and dynamic pricing
  - Transmission constraints need to be considered under the framework of SCUC/SCED
- Dynamic line ratings
- Optimal transmission switching
- FACTS control
  - Transmission including FACTS are traditionally treated as non-dispatchable asset in the network
  - Co-optimizing transmission and generation dispatch has the potential to further maximize the market surplus

Basic Unit Commitment & Economic Dispatch Model

$$\min \sum_{g,t} (u_{gt}\chi_{gt}(p_{gt}) + \varsigma_{gt}(u_{g(t-1)}, u_{gt}))$$

subject to

$$(\lambda_t) \qquad \sum_g p_{gt} = l_t + p_t^{loss}, \qquad \forall t$$

$$(\alpha_t \geq 0) \qquad \sum_g r_{gt} \geq \underline{r}_t, \qquad \forall t$$

$$u_{gt}\underline{p}_{gt} \leq p_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$p_{gt} + r_{gt} \leq u_{gt}\overline{p}_{gt}, \qquad \forall g,t$$

$$0 \leq r_{gt} \leq u_{gt}\overline{r}_{gt}, \qquad \forall g,t$$

$$(\mu_{kt}) \qquad \underline{f}_{kt} \leq f_{kt} \leq \overline{f}_{kt}, \qquad \forall k,t$$

$$f_{kt} = B_k(\theta_{mt} - \theta_{nt}), \qquad \forall k,t$$

$$(\lambda_{mt}) \qquad p_{gmt} - l_{mt} - p_{mt}^{loss} = \sum_{k \in line_m^{fr}} f_{kt} - \sum_{k \in line_m^{to}} f_{kt}, \qquad \forall m,t$$

$$|p_{gt} - p_{g(t-1)}| \leq u_{gt}R_{gt}, \qquad \forall g,t$$

$$\underline{\theta} \leq \theta_{mt} \leq \overline{\theta}, \qquad \forall m,t$$

$$(\mathbf{u}, \mathbf{p}, \mathbf{r}) \in \Gamma.$$

- Alternative Transmission flow model

$$f_{kt} = \sum_g a_{kgt} p_{gt}, \qquad \forall k,t$$

(Power Transfer Distribution Factor-PTDF model)

- Location marginal price (LMP)

$$LMP_{gt} = \lambda_t - \lambda_t \frac{\partial p_t^{loss}}{\partial p_{gt}} - \sum_k a_{kgt}\mu_{kt}$$

  - Promoted by FERC, LMP methodology is proven to be an effective mechanism to relieve transmission congestion and to achieve market efficiency
  - LMP is the foundation for market-based congestion management

Concept of FACTS Set Point Optimization

Motivation:

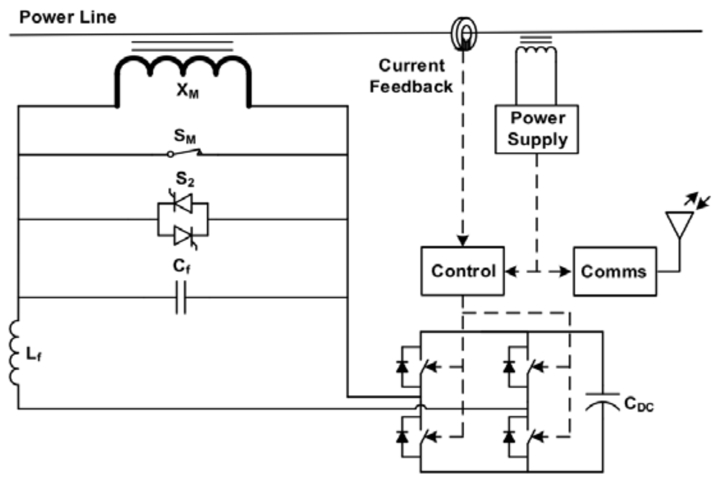
- Further improve social welfare in market clearing by changing line impedances

Control of transmission not fully utilized today

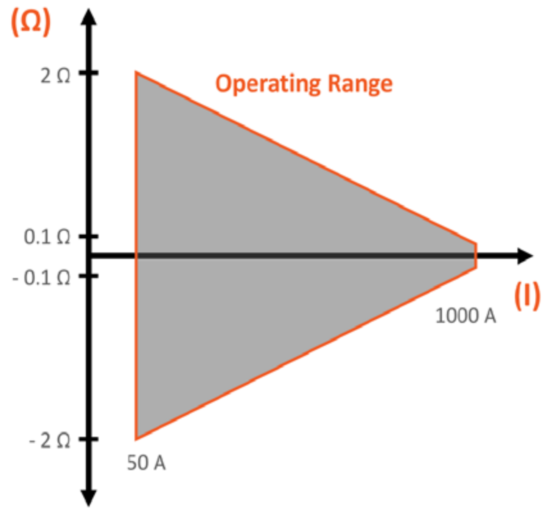
- Transmission assets are treated as static in the short term
- Current transmission control only for reliability purposes:
  1. Operators change transmission assets' states on ad-hoc basis
  2. Special Protection Schemes (SPSs)
- Alternative to topology control (discrete) [1][2] – less disturbing

Flow control via FACTS ARPA-e GENI projects on "Distributed Power Flow Control" [4]

Incorporate state of transmission assets into generation dispatch co-optimization

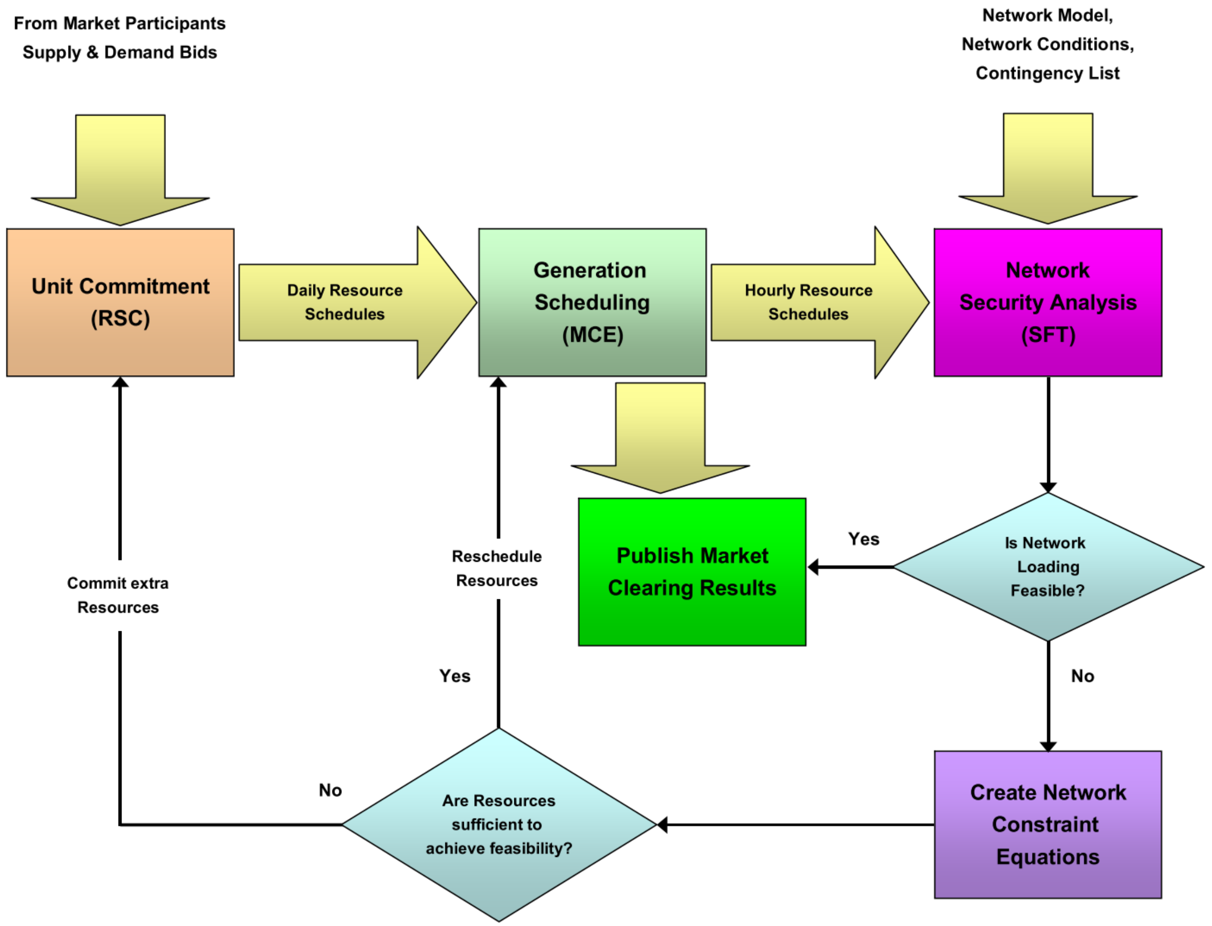


Source: https://www.smartwires.com



Challenges of FACTS Control in Optimization

- FACTS devices can achieve control functions such as voltage regulation, system damping, and power flow control.
- FACTS control seem to be a viable way to leverage grid controllability for enhancing system efficiency.
- The problem of SCUC with FACTS control is a Mixed Integer nonlinear programming (MINLP) problem.
- The problem of SCED with FACTS control is a nonlinear programming (NLP) problem.



$$f_{kt} = B_k(\theta_{mt} - \theta_{nt}), \qquad \forall k, t$$

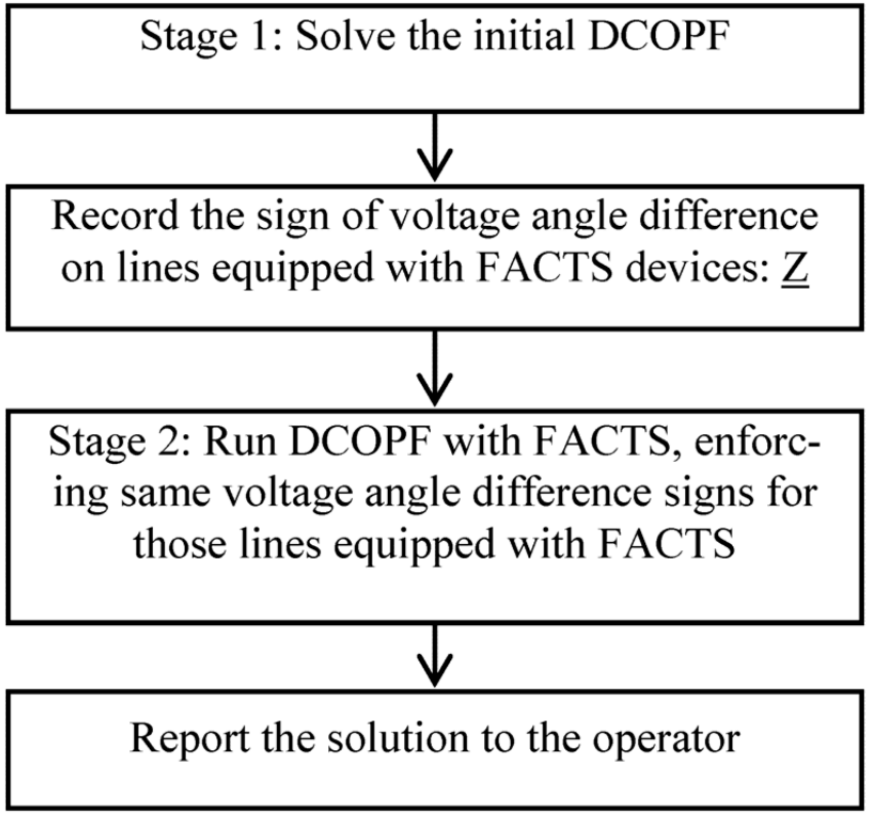
Both are decision variables in the DC load flow equations

Solution Algorithms

Two-stage LP-based Solution Algorithm [5]

$$F_k - B_k(\theta_n - \theta_m) = 0$$

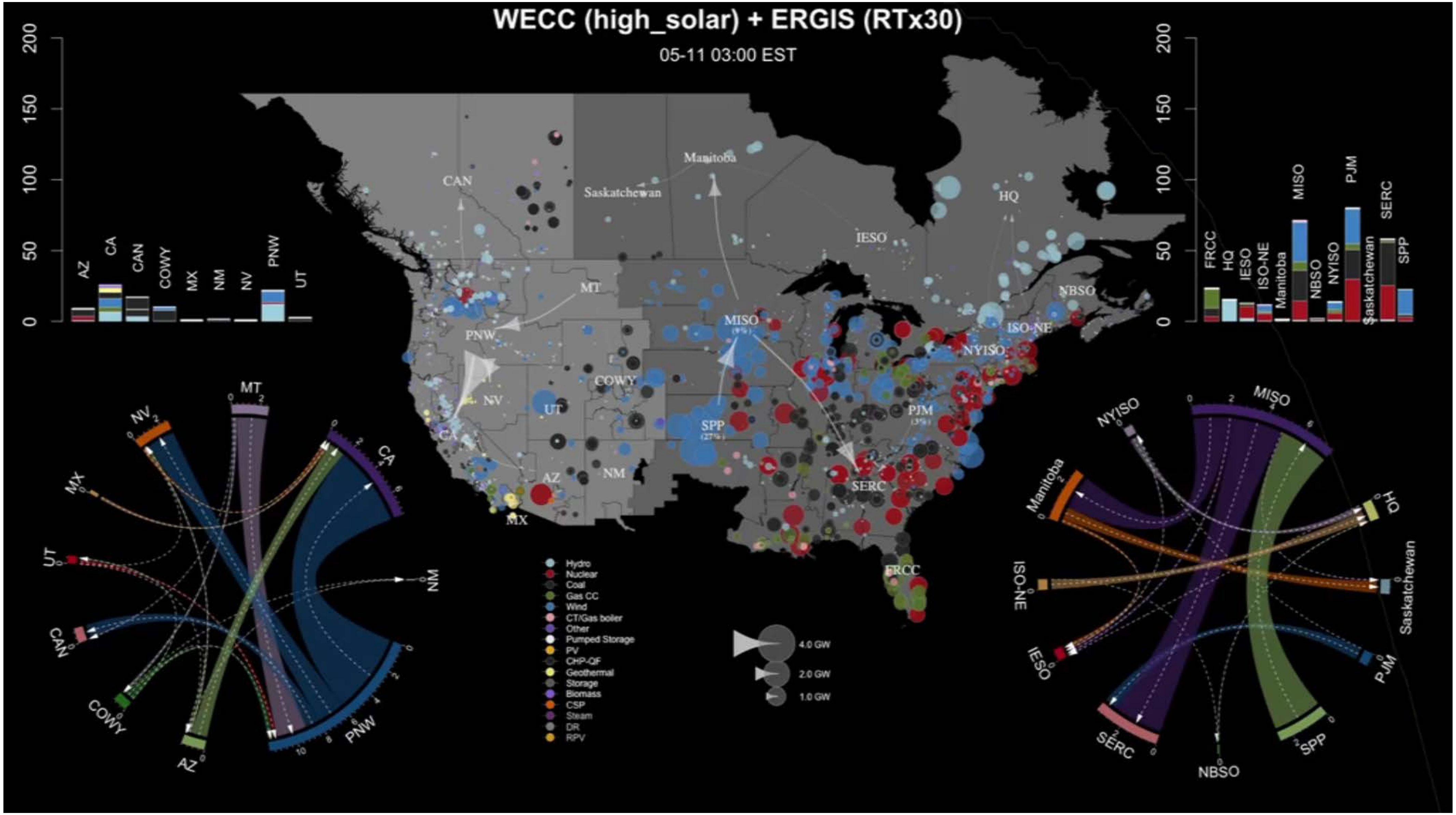
$$
\begin{aligned}
& z_{\bar{k}} B_{\bar{k}}^{\min}(\theta_n - \theta_m) - (1 - z_{\bar{k}})M \le F_{\bar{k}} && \forall \bar{k} \\
& (1 - z_{\bar{k}}) B_{\bar{k}}^{\max}(\theta_n - \theta_m) - z_{\bar{k}} M \le F_{\bar{k}} && \forall \bar{k} \\
& z_{\bar{k}} B_{\bar{k}}^{\max}(\theta_n - \theta_m) + (1 - z_{\bar{k}})M \ge F_{\bar{k}} && \forall \bar{k} \\
& (1 - z_{\bar{k}}) B_{\bar{k}}^{\min}(\theta_n - \theta_m) + z_{\bar{k}} M \ge F_{\bar{k}} && \forall \bar{k} \\
& \theta_n + (1 - z_{\bar{k}})M \ge \theta_m && \forall \bar{k} \\
& \theta_m + z_{\bar{k}} M \ge \theta_n && \forall \bar{k} \\
& z_{\bar{k}} \in \{0, 1\} \\
& M \gg Max\left\{F_{\bar{k}} + B_k(\theta_m - \theta_n)\right\}.
\end{aligned}
$$



Assumption: The flow directions of all FACTS lines are known or can be pre-determined from the initial DCOPF

Positive voltage angle difference enforces $z_{\bar{k}}$ to take 1 as its value, while negative voltage angle difference set to $z_{\bar{k}}$ to 0.

Power Flow Direction Changes in Power Grids with Significant Renewable Penetration [6]



Proposed Solution Algorithm

NLP ⇒ LP1 + LP2

B_k frozen (LP1 → LP2)

θ_{nt} frozen (LP2 → LP1)

LP1

$$\min \sum_{g,t} (u_{gt}\chi_{gt}(p_{gt}) + \varsigma_{gt}(u_{g(t-1)}, u_{gt}))$$

subject to

$$\begin{aligned}
&(\lambda_t) && \sum_g p_{gt} = l_t + p_t^{loss}, && \forall t \\
&(\alpha_t \ge 0) && \sum_g r_{gt} \ge \underline{r}_t, && \forall t \\
& && u_{gt}\underline{p}_{gt} \le p_{gt} \le u_{gt}\overline{p}_{gt}, && \forall g,t \\
& && p_{gt} + r_{gt} \le u_{gt}\overline{p}_{gt}, && \forall g,t \\
& && 0 \le r_{gt} \le u_{gt}\overline{r}_{gt}, && \forall g,t \\
&(\mu_{kt}) && \underline{f}_{kt} \le f_{kt} \le \overline{f}_{kt}, && \forall k,t \\
& && f_{kt} = B_k(\theta_{mt} - \theta_{nt}), && \forall k,t \\
&(\lambda_{mt}) && p_{gmt} - l_{mt} - p_{mt}^{loss} = \sum_{k \in line_m^{fr}} f_{kt} - \sum_{k \in line_m^{to}} f_{kt}, && \forall m,t \\
& && |p_{gt} - p_{g(t-1)}| \le u_{gt}R_{gt}, && \forall g,t \\
& && \underline{\theta} \le \theta_{mt} \le \overline{\theta}, && \forall m,t \\
& && (\mathbf{u}, \mathbf{p}, \mathbf{r}) \in \Gamma.
\end{aligned}$$

LP2

$$\min \sum_{g,t} (u_{gt}\chi_{gt}(p_{gt}) + \varsigma_{gt}(u_{g(t-1)}, u_{gt}))$$

subject to

$$\begin{aligned}
&(\lambda_t) && \sum_g p_{gt} = l_t + p_t^{loss}, && \forall t \\
&(\alpha_t \ge 0) && \sum_g r_{gt} \ge \underline{r}_t, && \forall t \\
& && u_{gt}\underline{p}_{gt} \le p_{gt} \le u_{gt}\overline{p}_{gt}, && \forall g,t \\
& && p_{gt} + r_{gt} \le u_{gt}\overline{p}_{gt}, && \forall g,t \\
& && 0 \le r_{gt} \le u_{gt}\overline{r}_{gt}, && \forall g,t \\
&(\mu_{kt}) && \underline{f}_{kt} \le f_{kt} \le \overline{f}_{kt}, && \forall k,t \\
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& && |p_{gt} - p_{g(t-1)}| \le u_{gt}R_{gt}, && \forall g,t \\
& && \underline{\theta} \le \theta_{mt} \le \overline{\theta}, && \forall m,t \\
& && (\mathbf{u}, \mathbf{p}, \mathbf{r}) \in \Gamma.
\end{aligned}$$

Proposed Solution Algorithm (cont'd)

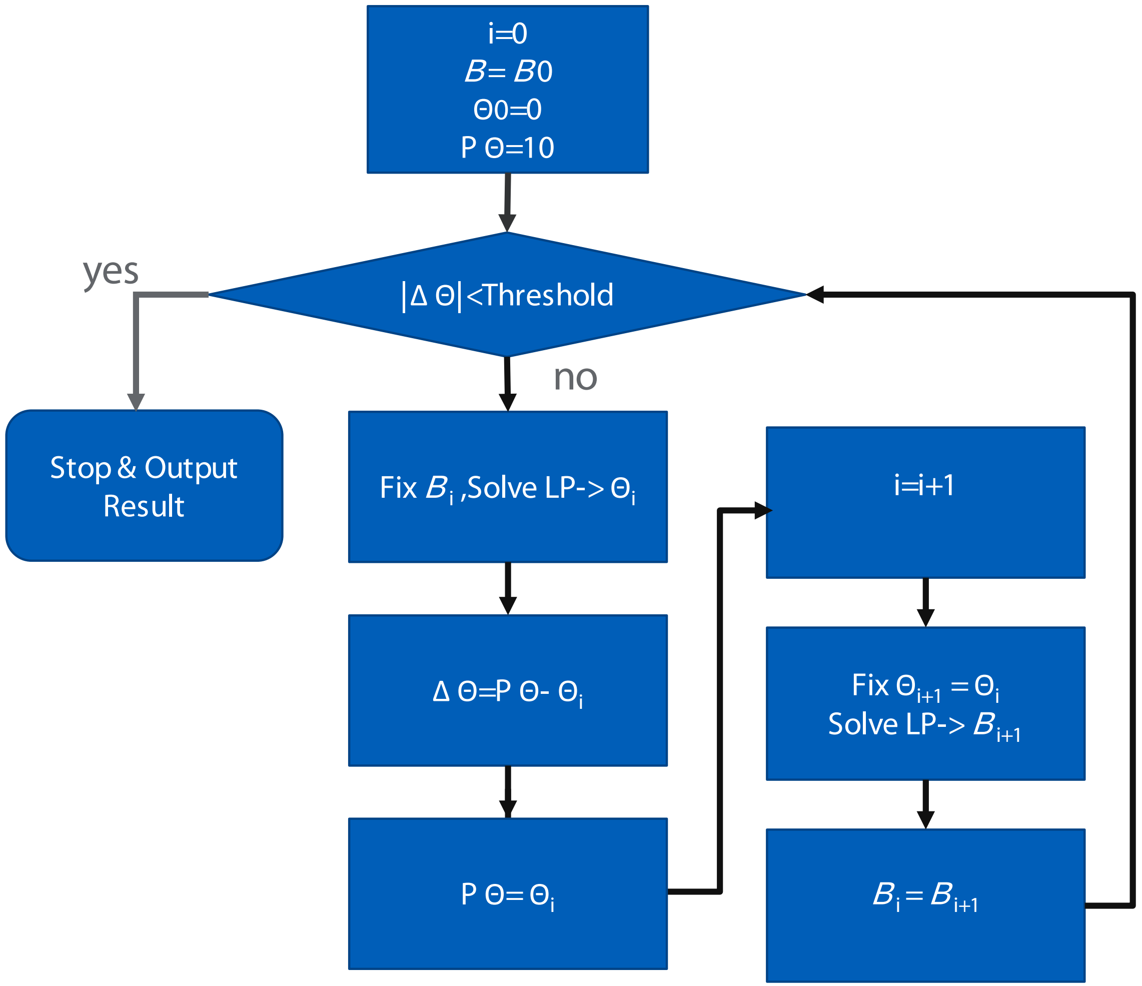
Solve two LP problems iteratively until they converge to one solution

i) LP1: Fixed *B*, solve LP and get Θ

ii) LP2: Fixed Θ , solve LP and get *B*

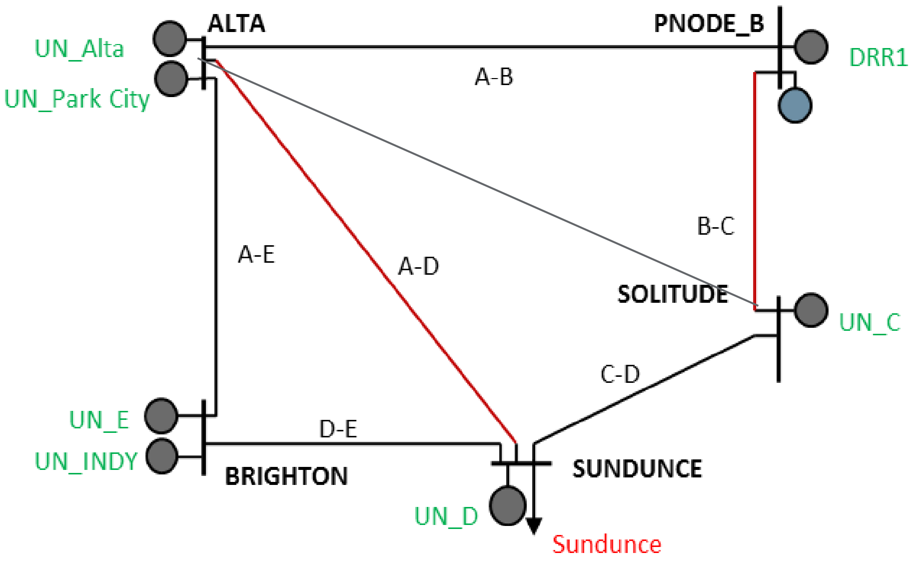
Step to solve mathematical model

1) Fixed *B* at normal admittance, solve LP1 and obtain Θ
2) Fixed Θ, solve LP2 and get a new *B*
3) Fixed *B* at new *B*, solve LP1 again and get new Θ
4) Repeat step 2) - 3), until Δ Θ (difference between two iterations) approaches 0



Preliminary Numerical Results

Test Cases---5 Bus System



Objective comparison

Before FACTS Opt.	After FACTS Opt.	Cost Savings ($/hr)
28947.18	27186.53	1760.65

Cleared Generation comparison

Unit	Cleared Generation after (MW)	Cleared Generation before (MW)	Unit Price ($/MWh)
TARE_ALTA_UN_PARKCITY_Steam	110	110	185
TARE_SOLITUDE_UN_C_Steam	229.14	311.03	24
TARE_BRIGHTON_UN_E_Steam	534.86	452.97	2.5

Admittance comparison

Transmission Lines	Adjusted admittance	Min Admittance	Admittance (mho)
SUNDANCE_230 KV_D-E_LN	-1348	-1348	-1037
ALTA_230 KV_A-B_LN	-1348	-1348	-1037
ALTA_230 KV_A-D_LN	-378	-1348	-1037
ALTA_230 KV_A-E_LN	-1037	-1348	-1037
PNODE_B_230 KV_B-C_LN	-386	-1348	-1037
SOLITUDE_230 KV_C-D_LN	-107	-1348	-1037
ALTA_230 KV_A-C_LN	-1348	-1348	-1037

Transmission flow comparison

Transmission Lines	Transmission Flow (after) (MW)	Transmission Flow (before) (MW)	Transmission Line Limits(MW)
SUNDANCE_230 KV_D-E_LN	-354.86	-298.42	500
ALTA_230 KV_A-B_LN	168.3	167.64	310
ALTA_230 KV_A-D_LN	33.86	118.42	530
ALTA_230 KV_A-E_LN	-180	-180	180
PNODE_B_230 KV_B-C_LN	-23.04	-23.69	300
SOLITUDE_230 KV_C-D_LN	2.62	-25.51	400
ALTA_230 KV_A-C_LN	87.84	143.93	380

Test case- 37,000-bus, 47,000-branch Test System

- 370 dispatchable generation units
- 28 transmission lines violated/binding at limits

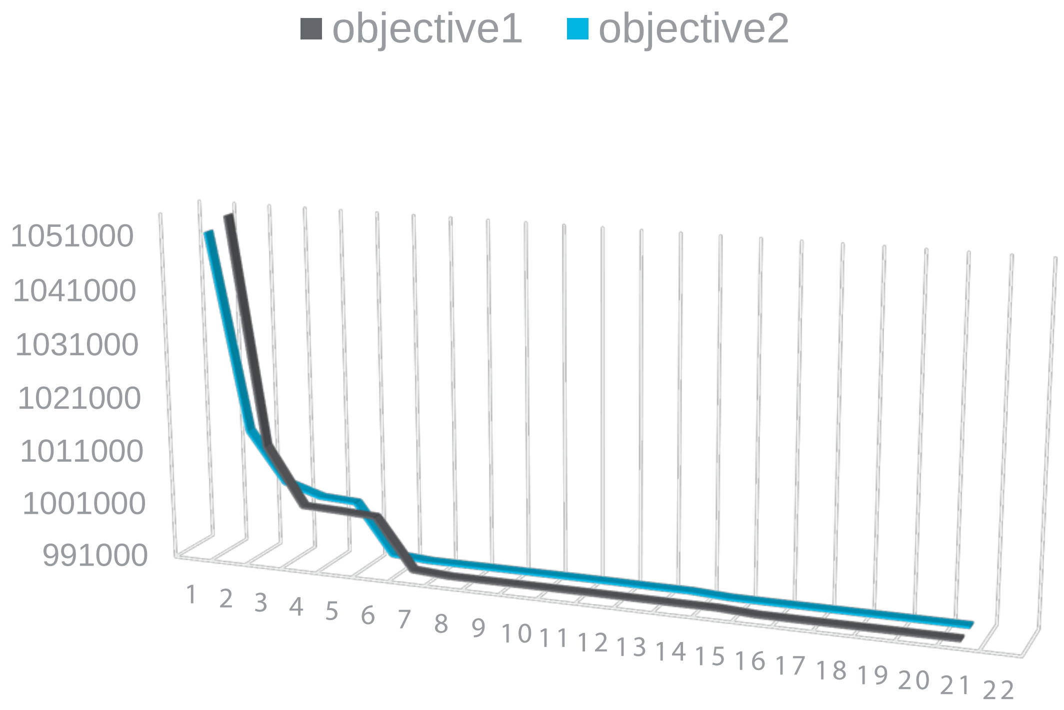
Objective comparison:

	Objective($/hr)	Total Offer Cost($/hr)	Violation Cost($/hr)
Before FACTS Optimization	15,642,372.87	1,071,201.70	14,571,170.17
After FACTS Optimization	991628.73	991628.73	0
FACTS Optimization Cost Savings	14,650,744.14	79,572.97	14,571,170.17

Test case- 37,000-bus, 47,000-branch Test System (cont'd)

Solution Iteration

iteration	Objective1 (fix B)	Objective2 (fix Θ)	$\lvert \Theta_i - \Theta_{i-1} \rvert$	$\lvert \Theta_{mn(i)} - \Theta_{mn(i-1)} \rvert$
0	15642372.87	1050294.11		
1	1061344.93	1013514	4.855	6.66
2	1013034	1004291	2.129	0.851
3	1002416	1002166	1.939	0.178
4	1002163	1001804	0.869	0.066
5	1001799	992647	0.757	0.846
6	992616	992151	0.875	0.844
7	992151	992144	0.862	0.844
8	992144	992143	0.91	0.837
9	992143	992143	0.238	0.001
10	992143	992141	1.055	0.837
11	992135	992122	1.429	0.837
12	992086	992062	1.811	0.837
13	992055	992054	0.64	0.826
14	992054	991670	1.322	0.831
15	991658	991632	0.637	0.01
16	991632	991629	0.527	0.003
17	991629	991629	0.495	0.826
18	991629	991629	0.832	0.832
19	991629	991629	0.468	0.832
20	991629	991629	0.000	0.000



Test case- 37,000-bus, 47,000-branch Test System (cont'd)

Admittance Comparison

Max/Min Admittance is about (+/-)30% of admittance

Transmission lines	Adjusted admittance	Min Admittance	Max Admittance	Admittance (mho)
SQBUTTE_SQBUTSQBUT23_4_1_LN	1303200	701723	1303200	1002462
ROCHSTR_ROCHST_622QB15_1_LN	1303200	701723	1303200	1002462
SQBUTTEW_SQBUTSQBUT23_1_1_LN	1303200	701723	1303200	1002462
SYCAMOR_SYCAMSYCAM34_1_S_LN	1303148	701695	1303148	1002421
SQBUTTEW_SQBUTCENTE23_2_1_LN	1303085	701723	1303200	1002462
HIWAY106_HIWAYHIWAY69_2_S_LN	1233166	701723	1303200	1002462
ROXF_ROXF_WRR_1_A_LN	1220231	701723	1303200	1002462
BVR_CH_BVR_CBVR_C69_1_S_LN	1198744	701723	1303200	1002462
ROCK_IS_ROCK_ROCK_16_1_S_LN	1197328	701723	1303200	1002462
HAZLTON_HAZLTON99534_1_S_LN	1193047	701723	1303200	1002462
CORYDON_CORYDCORYD69_1_S_LN	1187093	701723	1303200	1002462
RUSHUPA_RUSHURUSHN23_1_1_LN	1186271	701723	1303200	1002462
AUDUBON_AUDUBAUDUB23_1_1_LN	1174870	701723	1303200	1002462
KIPPRD_KIPPRVEVAY13_1_1_LN	1076645	637930	1184727	911329
OTTOWATP_IP-1516_2_LN	651600	350862	651600	501231
WHITE_WHITEBRKNG34_1_1_LN	651600	350862	651600	501231
LKST_MER-WAT-2_G_LN	651600	350862	651600	501231
LAPOINTE_Y-43_4_4_LN	592364	318965	592364	455664
HAYWARD_HAYWARD66716_1_S_LN	1114840	701723	1303200	1002462
TILDEN_T_IP-1476_NE_LN	1110849	701723	1303200	1002462
WRSN_WRSN-MASN-4_A_LN	1105106	701723	1303200	1002462
LAKEFLD_LAKEFLAKEF34_1_S_LN	1102918	701723	1303200	1002462
TAZE_CE_TAZEW4525TIE_1_1_LN	501231	280689	521280	400985
EATH_TAP_WLWD-GRAY-1_B_LN	434400	233908	434400	334154
SQIN_SQIN_BT_A_LN	1098138	701723	1303200	1002462
WLWD_WLWD-GRAY-2_A_LN	587730	350862	651600	501231
HAYWARD_HAYWARD66369_1_S_LN	1080124	701723	1303200	1002462
FT_INDUS_FI_STERLING_1_LN	347579	190169	353171	271670
…...	…	..	..	..

Test case- 37,000-bus, 47,000-branch Test System(cont'd)

Branch flow comparison

Before FACTS Optimization:

Transmission Lines	Limits (MW)	Flow (MW)
ALMA2_ALMAWABAC16_1_1_LN	105	105
ARROWHD_TR7_TR7_XF	68	-68
BAILLY_138_U8_A_LN	300	300
BNE_JCT_BNE_JAMES11_1_1_LN	20	20
BR_GR_PN_BR_GRPONTI34_1_1_LN	115	115
BUTTEDES_43021_43_LN	60	60
CANIFF_P3_P3_PS	300	300
CBLUFFS_R922_TR922_XF	172	-172
COFFEEN_IP-4551_COFY_A_LN	315	315
CULLEY_CULLEGRAND13_1_1_LN	100	107
DUNKARD_DUNKALTV13_1_1_LN	60	60
EDWARDS2_EDWD_KEYS_1397_A_LN	68	68
FRANCESC_FRANCPETER34_1_1_LN	430	-434
GOOSECRK_IP-4575_1_LN	290	298
HAZLTON_HAZLTBLKHA16_1_1_LN	48	48
I_FALLS_10TR_IFAL10TR_PS	270	270
MGN_35351_35_LN	185	185
MILAN3_MILANAJ_MA34_1_1_LN	195	-195
PETERSBU_PETERTHOMP34_1_1_LN	448	453
PLYMOUT2_13819_A_LN	115	-115
PORTUNIO_PORTUZIMME34_1_1_LN	500	-504
SANDLAKE_SAL_WAU_SA_LN	10	10
SCHAHFER_34508_A_LN	225	232
SCHAHFER_34516_A_LN	106	107
SIOUXCY_U1A1_KU1A1_XF	135	-135
SUB_92_SUB_9HILLS34_1_1_LN	175	175
WMIDDLET_6997_69_LN	12	12
LONEROCK_TX00_LOR_PH_SHFT0_PS	49	-49

After FACTS Optimization:

Transmission Lines	Limits (MW)	Flow (MW)
ALMA2_ALMAWABAC16_1_1_LN	105	105
BNE_JCT_BNE_JAMES11_1_1_LN	20	20
BR_GR_PN_BR_GRPONTI34_1_1_LN	115	115
CANIFF_P3_P3_PS	300	300
COLUMPSI_1_2_1_SAME2_XF	81	81
COLUMPSI_1_3_1_SAME3_XF	81	81
CULLEY_CULLEGRAND13_1_1_LN	100	100
DUFF_DUFFDUBOIS_1_A_LN	170	170
HENNEPIN_IP-1556_1_LN	107	107
PINE0000_62101_62_LN	27	27
PINE0000_62201_62_LN	27	27
FLORNCE_62103_62_LN	93	93
OAKRDG_X-91_1_LN	341	341
BELLTAP_BELLTVANBT69_1_1_LN	6860	6860
ANDOVE_ANDOVDCRK69_1_1_LN	6860	6860
ELENDLE_ELENDOAKGL69_1_1_LN	44	44
BIXB_BIXBRIVER69_1_1_LN	6860	6860
MAPLEDPC_MAPLEMAPLE16_1_1_LN	67	67

Before FACTS Optimization: 7 transmission lines are violated their limits, 21 transmission lines are binding at limits.

After FACTS Optimization: 18 transmission lines are binding at limits.

Test case- 37,000-bus, 47,000-branch Test System (cont'd)

Unit	Cleared Generation (before) MW	Cleared Generation (after) MW	Reduced MW	Price ($/MW)
MP_BOS_115_2_04Steam	30	33.75	-3.75	70.03
OTP_HOOT_LK_2_04Steam	32	32.14	-0.14	53.98
WPS_PULLIAM_7_04Steam	91.1	93.47	-2.37	39.63
WPS_PULLIAM_6_04Steam	34.6	45.05	-10.45	37.59
NSP_BLK_DOG_4_04Steam	122.19	137.85	-15.66	33.9
WPS_LAKEFRON_7_04Steam	40.38	48	-7.62	30.94
WPS_WESTON_1_04Steam	20	51	-31	25.87
AMIL_VERMILIO_5_04Steam	70.01	82.39	-12.38	25.57
MEC_NEALN_5_04Steam	269.97	270	-0.03	25.27
IPL_16STOUTN_3_04Steam	101.23	103	-1.77	25.21
WPS_JOU_WPS1_2_04Steam	56	91.99	-35.99	24.61
WPS_WESTON_2_04Steam	44	79	-35	23.37
ALTE_EDGEWATE_1_04Steam	155.61	195.7	-40.09	21.91
ALTW_LANSING_4_04Steam	136	196	-60	20.99
FE_MANSFLD2_3_04Steam	350	509.57	-159.57	20.65
FE_MANSFLD2_2_04Steam	550	764	-214	20.35
FE_MANSFLD2_1_04Steam	550	765.48	-215.48	20.33
DECO_STCLAIR3_4_04Steam	95	104.49	-9.49	19.32
MP_TAC_HBR_1_04Steam	38	45.6	-7.6	18.65
WPS_JOU_WPS_2_04Steam	160.26	161	-0.74	17.76
MEC_NEALS_2_04Steam	169	239.3	-70.3	16.7
AMIL_HENNEPIN_4_04Steam	200.85	201.18	-0.33	16.25
MEC_NEALN_6_04Steam	356.58	368	-11.42	14.96
…	…	…	…	…

Unit	Cleared Generation (before) MW	Cleared Generation (after) MW	Increased MW	Price ($/MW)
…..	..	..	..	..
CONS_ADA2_2_04Steam	22.35	16.1	6.25	29.57
DPC_ALMA2_4_04Steam	370	301.9	68.1	28.04
CIN_EBEND_6_04Steam	414	400.52	13.48	26.47
CIN_BECKJORD_5_04Steam	233	113	120	23.97
HE_RATTS_1_04Steam	120	85	35	23.18
CONS_CAMPBEL4_17_04Steam	559.81	513	46.81	21.02
MEC_JOU_MEC_2_04Steam	351	341.38	9.62	20.37
AMMO_RUSH_IS_4_04Steam	342.01	303	39.01	19.94
AMMO_RUSH_IS_3_04Steam	560	550.1	9.9	19.92
SIGE_WARRICKW_8_04Steam	114.05	114	0.05	19.25
AMIL_DUCK_CRK_2_04Steam	410	290	120	19.19
CIN_WABASHR_5_04Steam	85	84.42	0.58	19.05
MP_TAC_HBR_3_04Steam	41.02	38.18	2.84	18.65
HE_MEROM_1_04Steam	483.09	469.14	13.95	18.46
AMIL_HAVANA_12_04Steam	339.85	309	30.85	17.92
ALTW_BRLGTN_5_04Steam	185	120	65	17.37
DECO_MONROE4_4_04Steam	460	400	60	16.64
DECO_MONROE4_3_04Steam	678	642.13	35.87	16.44
MEC_LOUISA_2_04Steam	536.11	411	125.11	15.47
AMIL_BALDWIN_4_04Steam	591	580.72	10.28	14.91
ALTW_JOU_ALT2_3_04Steam	34	28	6	13.69
ALTW_JOU_ALT2_4_04Steam	30	24	6	13.02

FACTS set point optimization allowing generation to shift from more expensive units to cheaper units

Conclusions

Conclusions

- This presentation discussed transmission flow control using FACTS in power system operations.
- A basic dispatch model with co-optimization of energy, ancillary services and FACTS set points is presented.
- Using an iterative linear programming approach, the nonlinear (bilinear) programming problem of generation scheduling based on a DC load flow formulation is solved. No assumption of line flow direction for FACTS is required.
- Preliminary simulation results have been presented to demonstrate hourly generation dispatch combined with FACTS set point optimization in day-ahead could reduce congestion cost, lower production cost and improve market efficiency.
- Studies and evaluation of impact of production costs to the selection of FACTS candidates are desirable in energy and ancillary services co-optimization markets.
- More studies are needed to investigate its impact of real-time market, reliability unit commitment, reliability assessment and revenue adequacy of FTR market.

References

1. Jun Wu, Kwok W. Cheung, "On Selection of Transmission Line Candidates for Optimal Transmission Switching in Large Power Networks", *2013 IEEE/PES General Meeting, Vancouver, BC, Canada.*

2. J. David Fuller et al, "Fast Heuristics for Transmission Line Switching", *IEEE Trans. on Pwr Sys. Vol 27, Issue 3, pp. 1377-1386. (2012)*

3. Joe H. Chow, Robert deMello, Kwok W. Cheung, "Electricity Market Design: An Integrated Approach to Reliability Assurance"", *Invited Paper, IEEE Proceeding (Special Issue on Power Technology & Policy: Forty Years after the 1965 Blackout), vol.93, no. 11, pp.1956-1969, November 20*05.

4. ARPA-e Distributed Power Flow Control Project (2012-2014) https://arpa-e.energy.gov/?q=slick-sheet-project/distributed-power-flow-control

5. M. Sahraei-Ardakani and K. W. Hedman, "A Fast LP Approach for Enhanced Utilization of Variable Impedance Based FACTS Devices," IEEE Trans. Power Syst., vol. 31, no. 3, pp. 2204–2213, May 2016.

6. National Renewable Energy Laboratory, The Interconnections Seam Study and the North American Renewable Integration Study https://youtu.be/YcgvGe2sN8Y

Thank you!

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