Getting Energy Conversion Right

New commands related to build unit PQ curves since SHOP 12

User meeting Hydro Scheduling, 13 – 14 March 2019

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SINTEF Energy Research

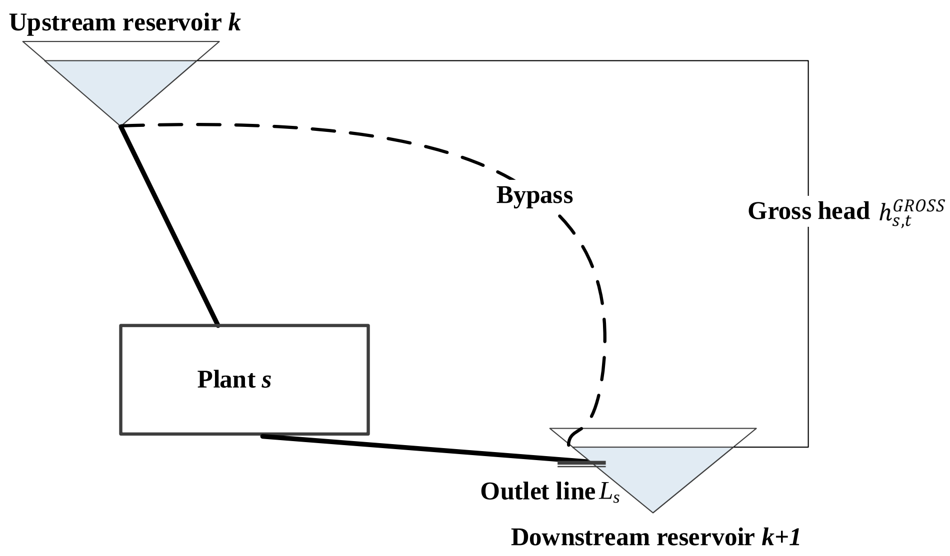
Outline

- Transition from plant-based to unit-based short-term hydro scheduling
- New commands related to build unit PQ curves
  - Determination of the unit PQ curve
  - Incorporation of power loss in shared penstock
  - Determination of the unit PQ curve without MIP
  - Determination of the unit PQ curve in abnormal situation
  - Printing of unit PQ curves
- New project proposal

Hydropower production function

Mathematical formulation

$$p_{s,t} = G \cdot \eta \cdot h_{s,t}^{GROSS} \cdot q_{s,t}$$



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Hydropower production function

Mathematical formulation

$$p_{i,s,t} = G \cdot \eta_{i,s}^{GEN}(p_{i,s,t}) \cdot \eta_{i,s}^{TURB}(h_{i,s,t}^{NET}, q_{i,s,t}) \cdot h_{i,s,t}^{NET} \cdot q_{i,s,t}$$

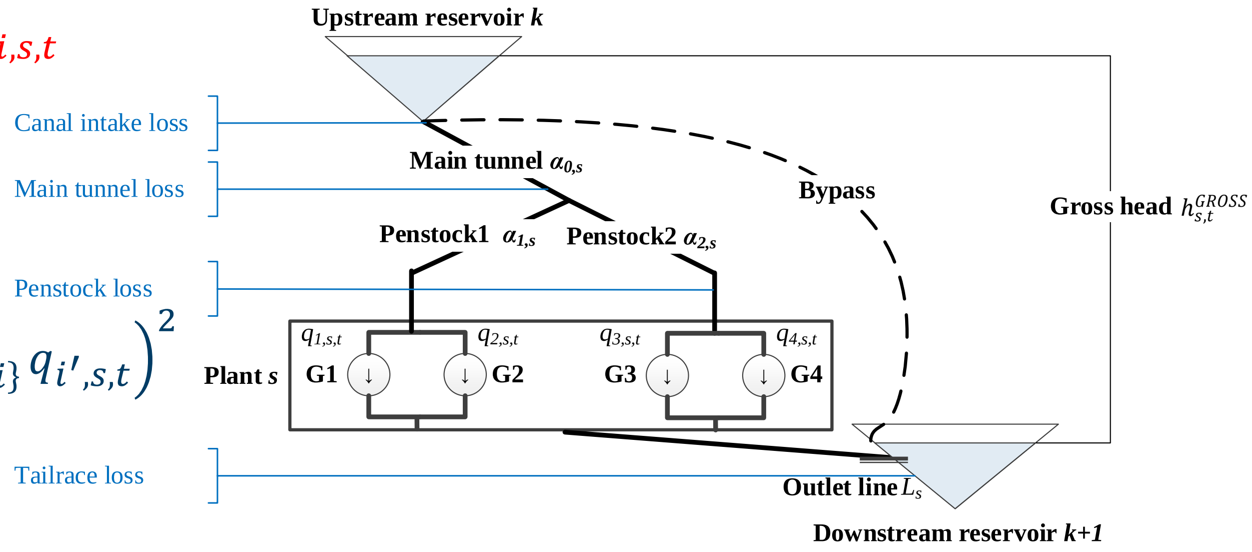
$$P_{i,t}^{MIN} \cdot \omega_{i,t} \leq p_{i,t} \leq P_{i,t}^{MAX} \cdot \omega_{i,t}$$

$$Q_{i,t}^{MIN}(h_{i,t}^{NET}) \cdot \omega_{i,t} \leq q_{i,t} \leq Q_{i,t}^{MAX}(h_{i,t}^{NET}) \cdot \omega_{i,t}$$

$$h_{i,s,t}^{NET} = h_{s,t}^{GROSS} - \sum_{n \in N_s | i \in I_{n,s}} \alpha_{n,s} \cdot \left(q_{i,s,t} + \sum_{i' \in I_{n,s} \setminus \{i\}} q_{i',s,t}\right)^2$$

$$-\Delta h_{s,t}^{INTAKE}\left(l_{k,t-1}(v_{k,t-1}), q_{k,t}^{TOTAL}\right)$$

$$-\Delta h_{s,t}^{TAIL}\left(l_{k+1,t-1}(v_{k+1,t-1}), q_{k,t}^{TOTAL}\right)$$



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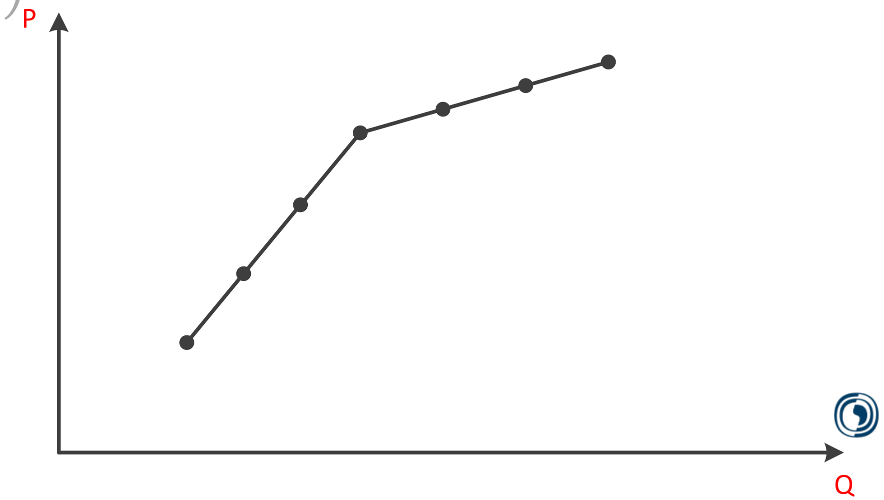
Hydropower production function

Mathematical formulation

$$p_{i,s,t} = G \cdot \eta_{i,s}^{GEN}(p_{i,s,t}) \cdot \eta_{i,s}^{TURB}(h_{i,s,t}^{NET}, q_{i,s,t}) \cdot h_{i,s,t}^{NET} \cdot q_{i,s,t}$$
$$P_{i,t}^{MIN} \cdot \omega_{i,t} \leq p_{i,t} \leq P_{i,t}^{MAX} \cdot \omega_{i,t}$$
$$Q_{i,t}^{MIN}(h_{i,t}^{NET}) \cdot \omega_{i,t} \leq q_{i,t} \leq Q_{i,t}^{MAX}(h_{i,t}^{NET}) \cdot \omega_{i,t}$$

$$h_{i,s,t}^{NET} = h_{s,t}^{GROSS} - \sum_{n \in N_s | i \in I_{n,s}} \alpha_{n,s} \cdot \left(q_{i,s,t} + \sum_{i' \in I_{n,s} \setminus \{i\}} q_{i',s,t}\right)^2$$
$$-\Delta h_{s,t}^{INTAKE}\left(l_{k,t-1}(v_{k,t-1}), q_{k,t}^{TOTAL}\right)$$
$$-\Delta h_{s,t}^{TAIL}\left(l_{k+1,t-1}(v_{k+1,t-1}), q_{k,t}^{TOTAL}\right)$$

- SHOP is formulated as a **Mixed Integer Linear Programming (MILP)** model
- How to convert the **nonlinear** & **nonconvex** hydropower production function into a **concave piecewise linear** unit PQ curve?



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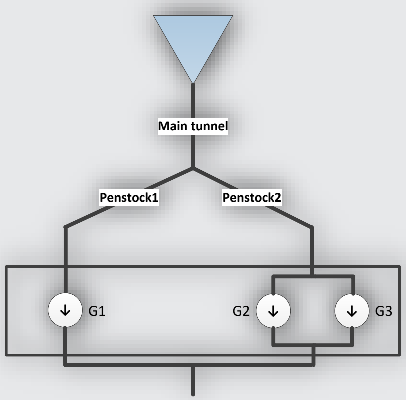
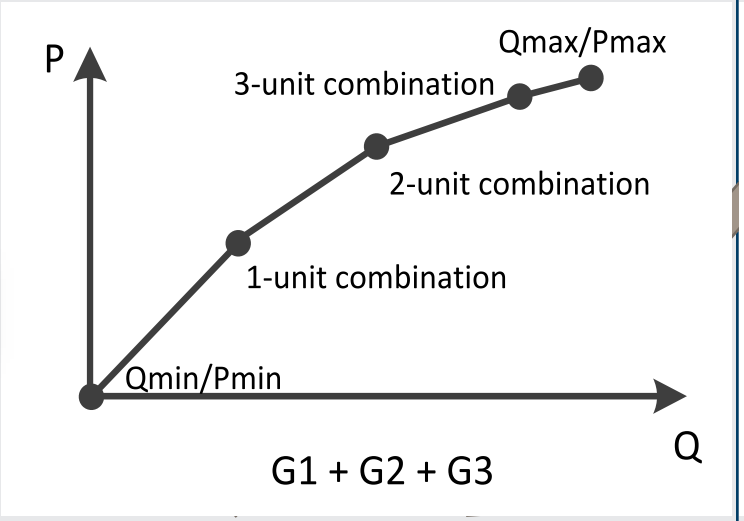
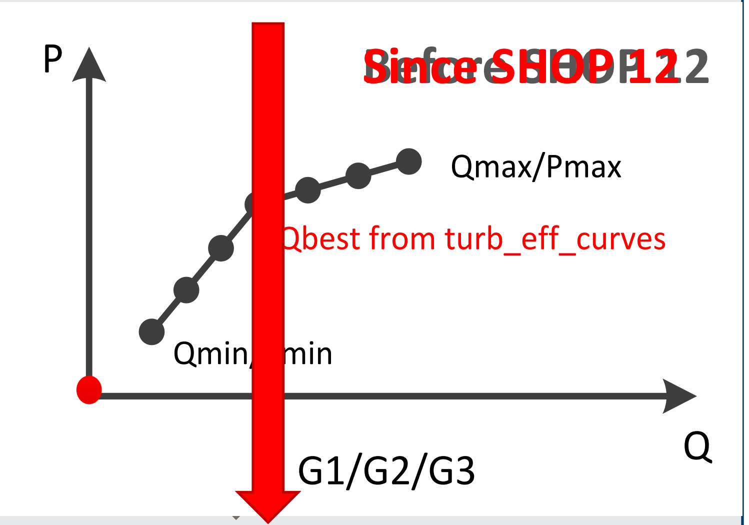
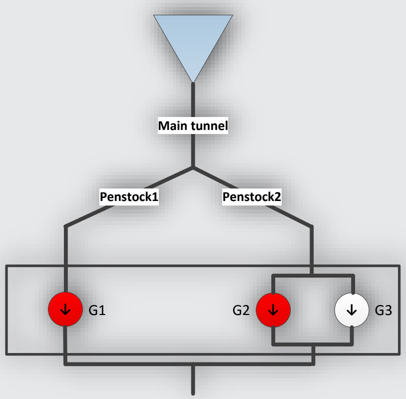
Full mode **(set code /full)**	**LP model**	**MIP model** (mip_flag/universal_mip as input data)
	• Built on PLANT level 	• Built on UNIT level 
Incremental mode **(set code /incr)**	**LP model**	**LP model** (reserve/gen discharge cost is used)
	• Built on PLANT level	• Built on UNIT level

Outline

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- New commands related to build unit PQ curves
  - Determination of the unit PQ curve
  - Incorporation of power loss in shared penstock
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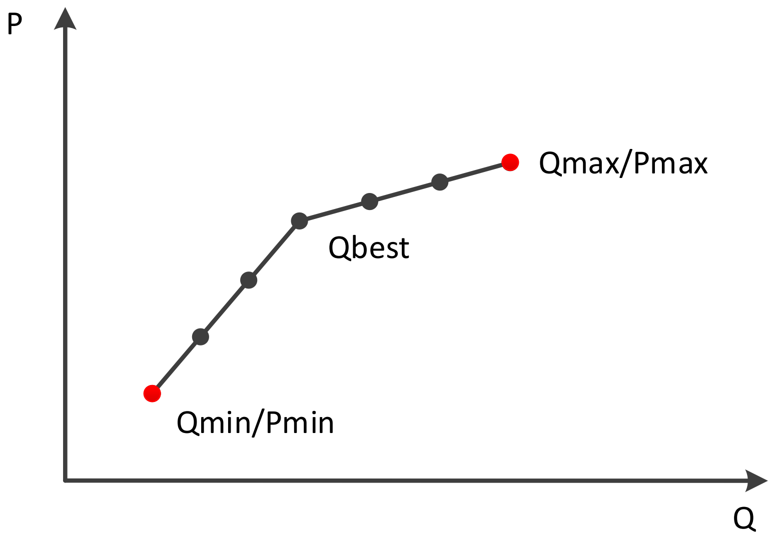
  - Determination of the unit PQ curve in abnormal situation
  - Printing of unit PQ curves
- New project proposal

Determination of the unit PQ curve

Command 1 (Default): Set build_pq_curve /unit_uploading /all_limits



- Pmin/Qmin
  - $Pmin = MAX\left(P(turb\_min),\ \ gen \rightarrow minprod,\ \ min\_p\_constr,\ \ P(min\_q\_constr)\right)$
  - $Qmin = Q(Pmin)$
- Pmax/Qmax
  - $Pmax = MIN\left(P(turb\_max),\ \ gen \rightarrow maxprod,\ \ max\_p\_constr,\ \ P(max\_q\_constr)\right)$
  - $Qmax = Q(Pmax)$

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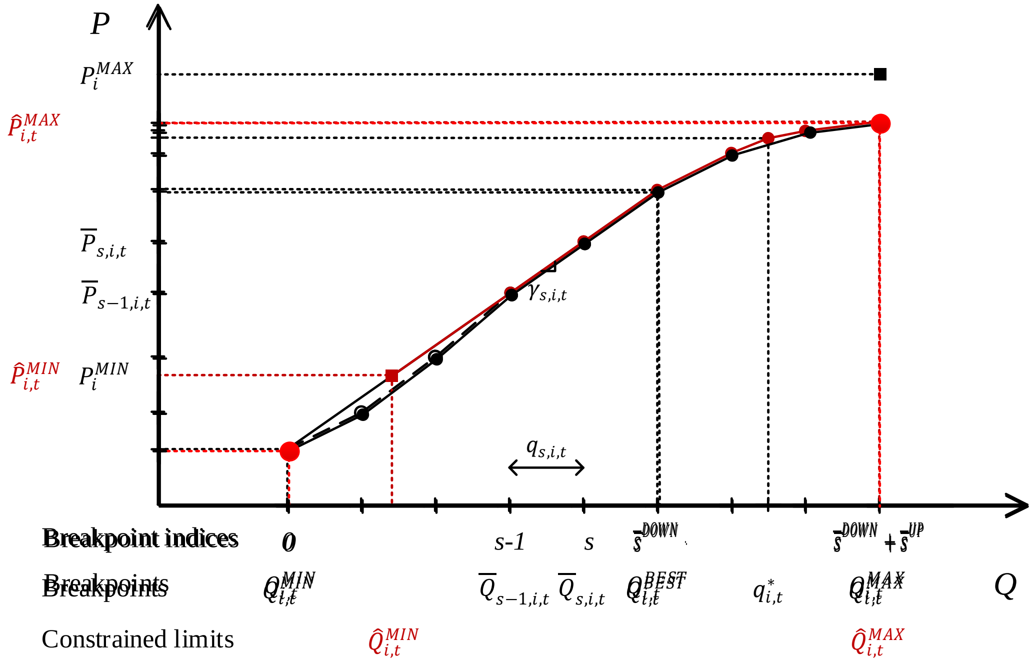
Determination of the unit PQ curve

Command 2: Set build_pq_curve /unit_uploading /turb_eff_curves



- *Step 2: Determinate the Head-dependent Minimum Water Discharge $Q_{i,t}^{MIN}$, Best Efficiency point $Q_{i,t}^{BEST}$ and Maximum Water Discharge $Q_{i,t}^{MAX}$ of the Unit*
  - *Only based on the head-dependent* ***turbine efficiency curves***
- …
- *Step 8: Define the Final Operating limits*
  - *Including all the* ***other limits*** *by linear interpolation*

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Determination of the unit PQ curve

Command 1 (Default): Set build_pq_curve /unit_uploading /all_limits

- When building PQ curve, all the limits ($P(turb\_min)$, $gen \rightarrow minprod$, min_p_constr, $P(min\_q\_constr)$) are taken into account at the same time. If there is a schedule, only one point will be built.
- It is suitable for those who want to run schedule or run on the limits.

Command 2: Set build_pq_curve /unit_uploading /turb_eff_curves

- PQ curve is first built according to the head-dependent turbine efficiency curves. Other limits are linear interpolated later.
- It is suitable for those who want to get the overview of the operation range.

Incorporation of power loss in shared penstock

Mathematical formulation

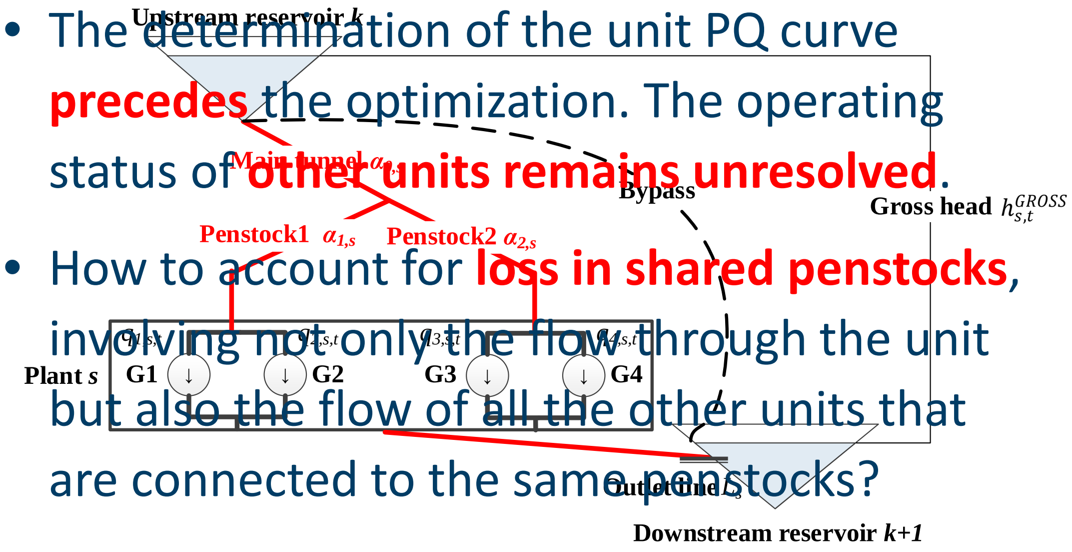
$$p_{i,s,t} = G \cdot \eta_{i,s}^{GEN}(p_{i,s,t}) \cdot \eta_{i,s}^{TURB}(h_{i,s,t}^{NET}, q_{i,s,t}) \cdot h_{i,s,t}^{NET} \cdot q_{i,s,t}$$

$$P_{i,t}^{MIN} \cdot \omega_{i,t} \leq p_{i,t} \leq P_{i,t}^{MAX} \cdot \omega_{i,t}$$

$$Q_{i,t}^{MIN}(h_{i,t}^{NET}) \cdot \omega_{i,t} \leq q_{i,t} \leq Q_{i,t}^{MAX}(h_{i,t}^{NET}) \cdot \omega_{i,t}$$

$$h_{i,s,t}^{NET} = h_{s,t}^{GROSS} - \sum_{n \in N_s | i \in I_{n,s}} \alpha_{n,s} \cdot \left(q_{i,s,t} + \sum_{i' \in I_{n,s} \setminus \{i\}} q_{i',s,t}\right)^2$$
$$- \Delta h_{s,t}^{INTAKE}\left(l_{k,t-1}(v_{k,t-1}), q_{k,t}^{TOTAL}\right)$$
$$- \Delta h_{s,t}^{TAIL}\left(l_{k+1,t-1}(v_{k+1,t-1}), q_{k,t}^{TOTAL}\right)$$

- The determination of the unit PQ curve **precedes** the optimization. The operating status of **other units remains unresolved**.
- How to account for **loss in shared penstocks**, involving not only the flow through the unit but also the flow of all the other units that are connected to the same penstocks?



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Incorporation of power loss in shared penstock

Command 1 (Default): Set power_loss /busbar

- First **excludes** the penstock loss in the PQ curve, causing over-estimated power generation for the given discharge.
- Then **subtracts** the sum of power loss for each unit, which is equal to the sum of power loss in each penstock, from the plant energy balance constraint, i.e. busbar.
- The sum of power loss in a shared penstock is a cubic function of the total flow through the penstock, which is approximated by a convex piecewise linear function.

Command 2: Set power_loss /pq /previous

$$h_{i,t}^{NET} = H_t^{GROSS} - \alpha_n \cdot \left(q_{i,t} + \sum_{i' \in I_n \setminus \{i\}} q_{i',t}\right)^2$$

- **Directly includes** penstock loss in the PQ curve of the unit.
- Uses the **optimal results obtained in the previous iteration**.

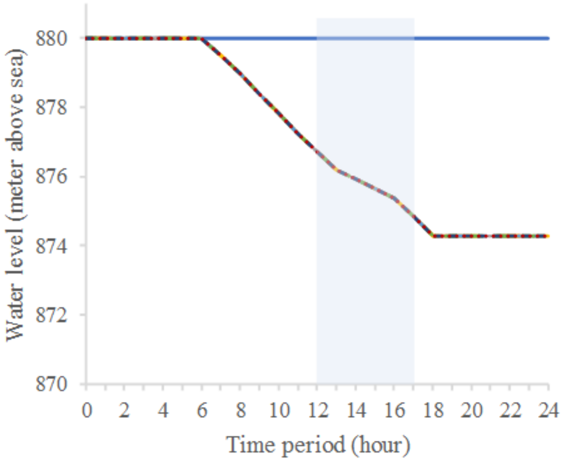
Command 3: Set power_loss /pq /proportional

$$\sum_{i \in I} p_{i,t} - \sum_{n \in N} \Delta p_{n,t} = p_t^{SELL}$$

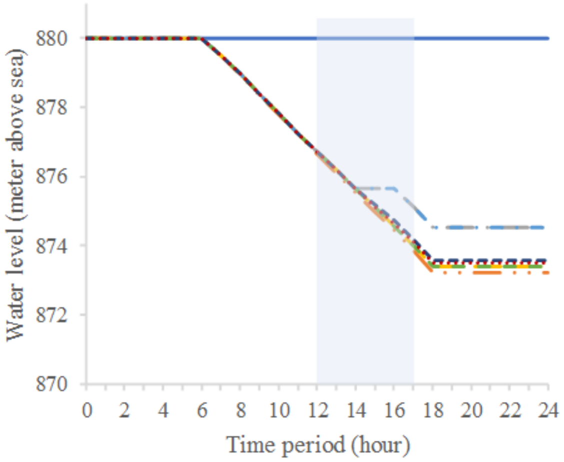
- **Directly includes** penstock loss in the PQ curve of the unit.
- Assumes that all the units connected to the same penstock always operate **at the same fraction** of their allowable capacity range.

Numerical results – Comparison of Methods

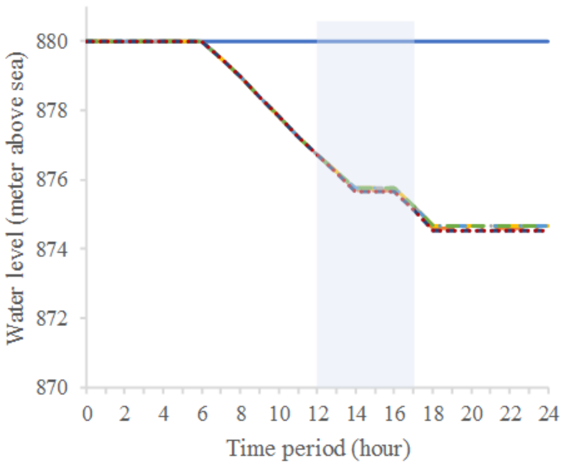
Command 1

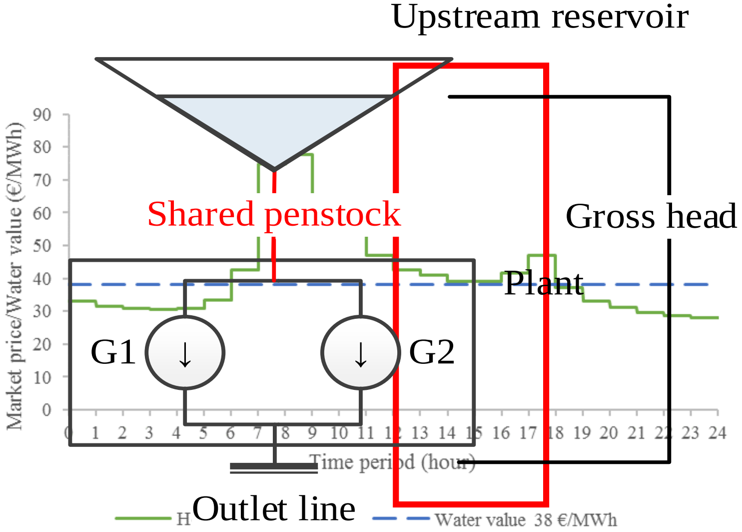


Command 2



Command 3





Command 1 (Default)			Command 2			Command 3		
Production Revenue	Reservoir Value	Total Profit	Production Revenue	Reservoir Value	Total Profit	Production Revenue	Reservoir Value	Total Profit
109,365.24	156,070.49	**265,435.73**	117,588.81	147,118.76	**264,707.57**	105,467.63	159,807.10	**265,274.73**

Command 1 gives the best result

Command 2 causes flip-flop

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Incorporation of power loss in shared penstock

Command 1 (Default): Set power_loss /busbar

- Gives **better** optimization result but potentially might **increase computational time**, since the unit penstock loss should be introduced to unit energy balance constraints to improve accuracy, especially when delivering reserves

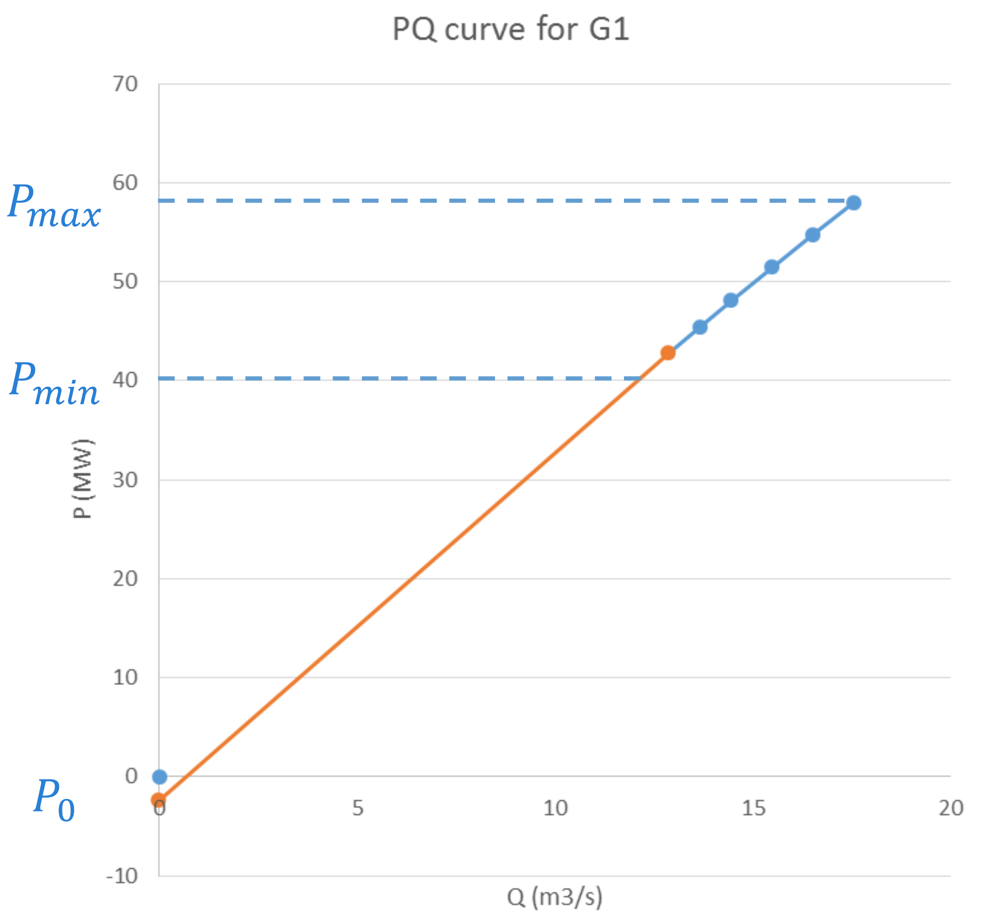
Command 2: Set power_loss /pq /previous

- When the predicted market price for electricity is **close** to the water value at the end of the scheduling horizon, the power production is likely to **oscillate** between iterations

Command 3: Set power_loss /pq /proportional

- Can avoid the flip-flop problem but suggests the units to **operate in the same pattern**

Determination of the unit PQ curve without MIP



In a MIP model, binary variables are used.

$$p = P_0 \cdot \gamma_t + \sum_{seg} \frac{dP}{dQ}_{seg} \cdot q_{seg}$$

$$p \geq P_{min} \cdot \gamma_t$$

$$p \leq P_{max} \cdot \gamma_t$$

$$\gamma_t \in \{0, 1\}$$

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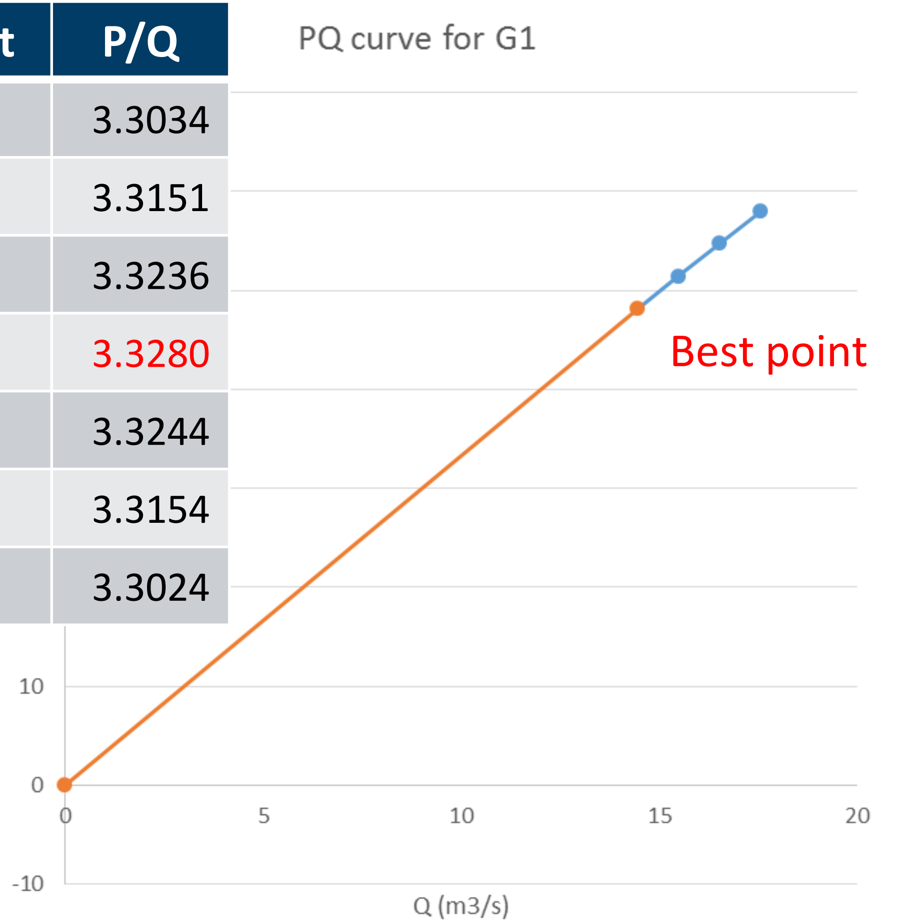
Determination of the unit PQ curve without MIP

Point	P/Q
1	3.3034
2	3.3151
3	3.3236
4	3.3280
5	3.3244
6	3.3154
7	3.3024



In a LP model, binary variables are relaxed!

$$p = P_0 \cdot \gamma_t + \sum_{seg} \frac{dP}{dQ}_{seg} \cdot q_{seg}$$

$$p \geq P_{min} \cdot \gamma_t$$

$$p \leq P_{max} \cdot \gamma_t$$

~~$\gamma_t \in \{0,1\}$~~ $0 \leq \gamma_t \leq 1$

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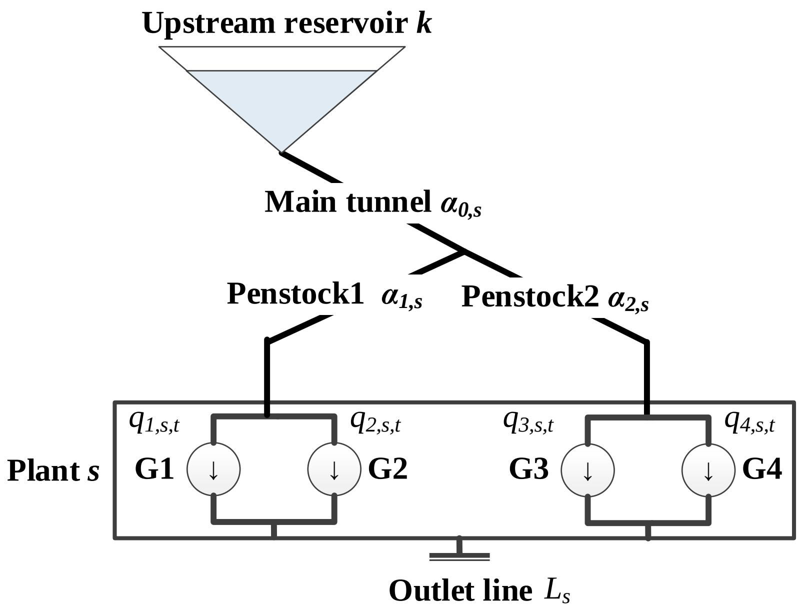
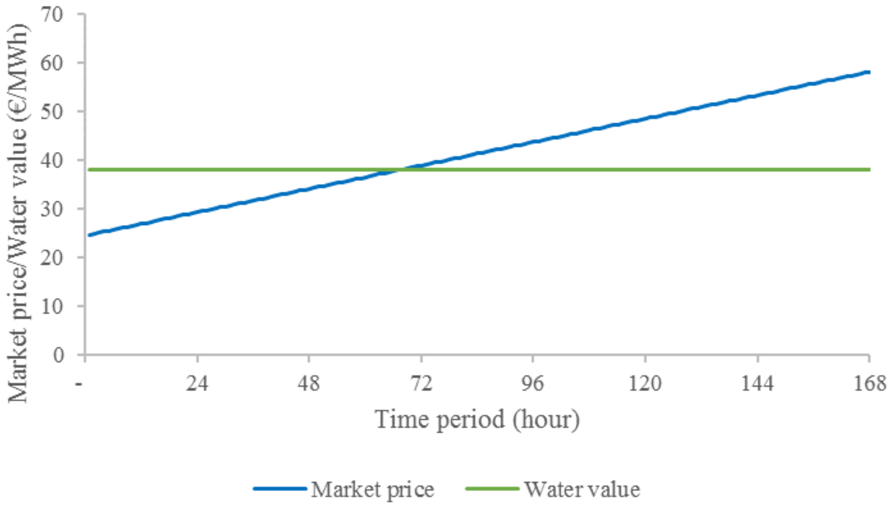
Determination of the unit PQ curve without MIP

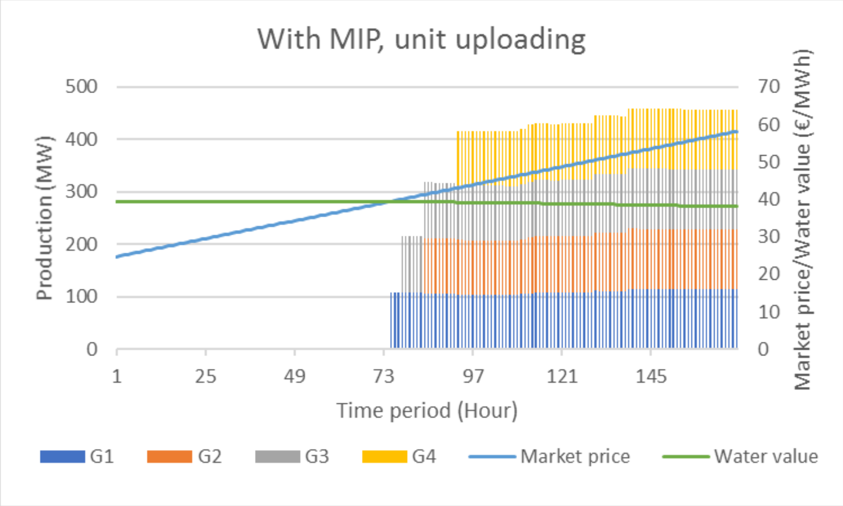


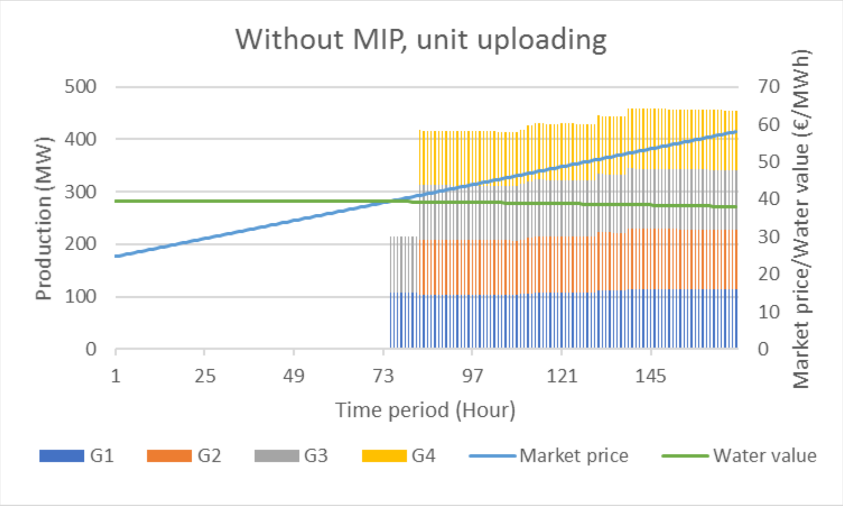


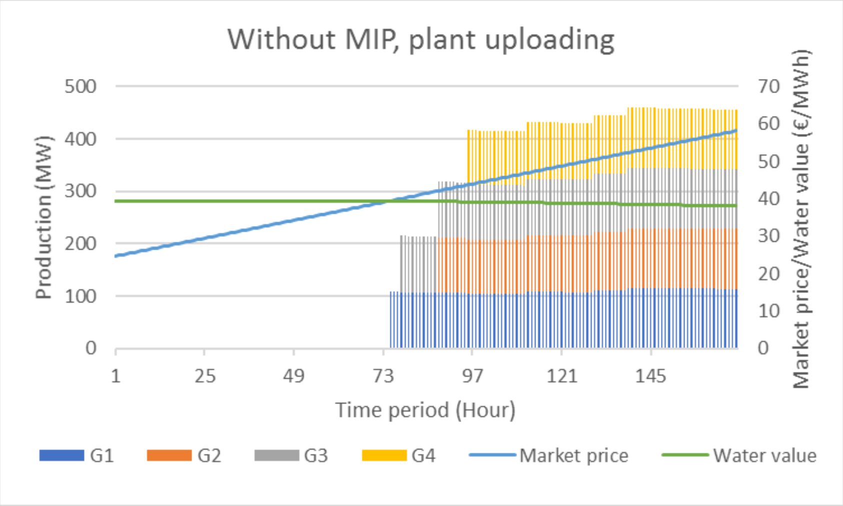
Determination of the unit PQ curve without MIP

Command 1: Set build_pq_curve /plant_uploading /all_limits

Command 2: Set build_pq_curve /plant_uploading /turb_eff_curves



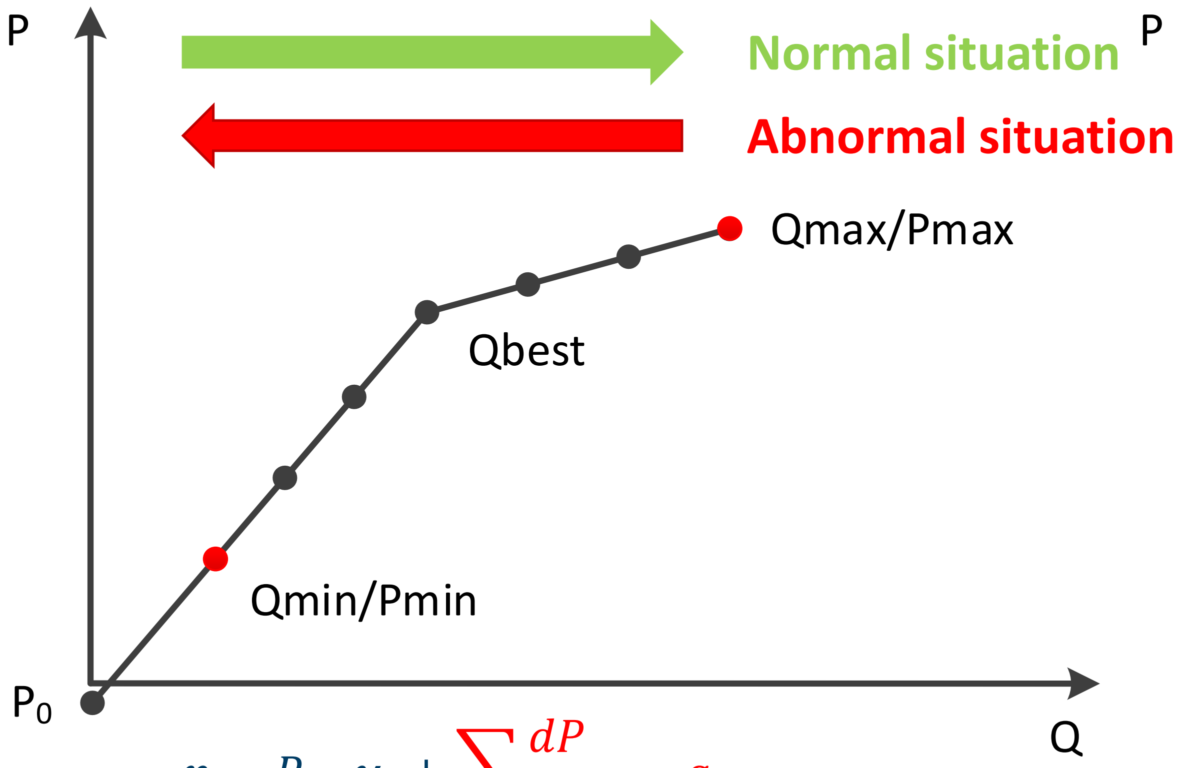


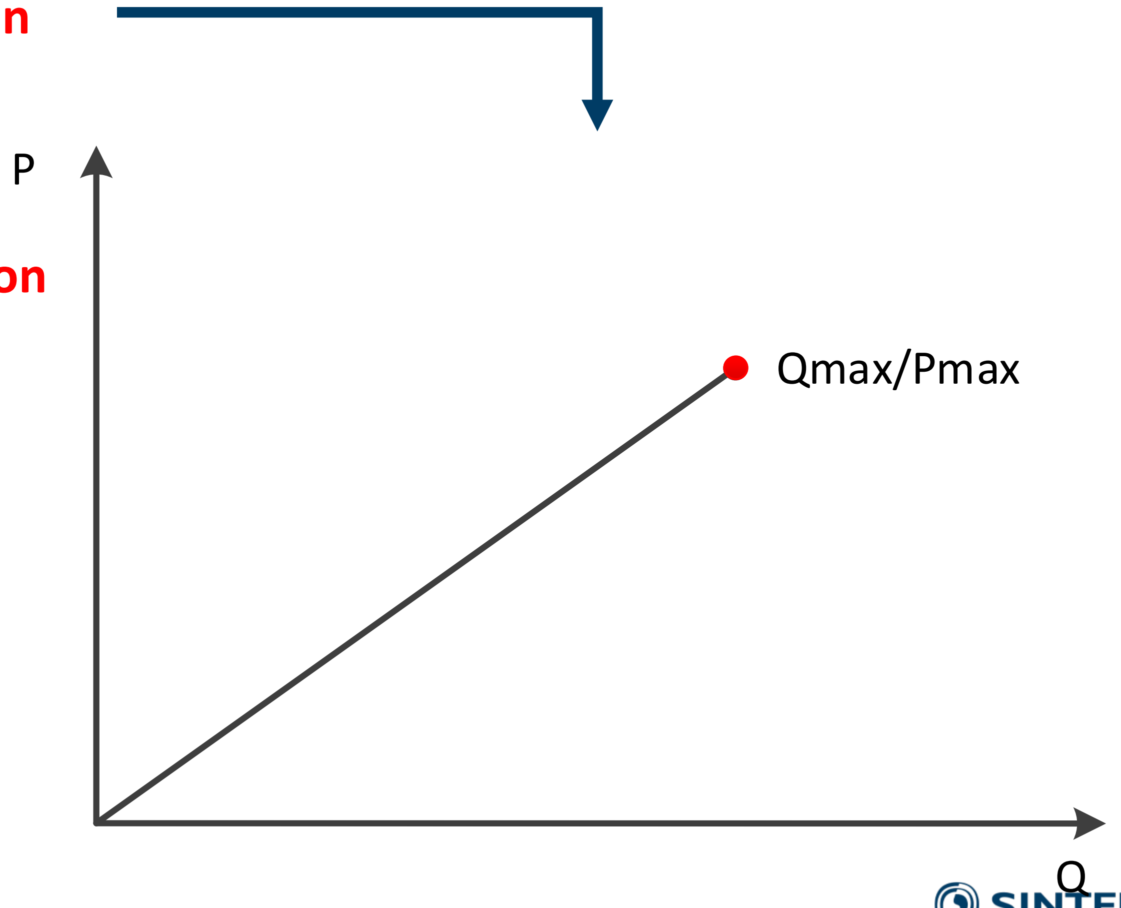


MIP	Build_pq_curve	Full_1	Full_2	Full_3	Full_4	Full_5	Incr_1	Incr_2	Incr_3	Total Time
With MIP	Unit_uploading	0.98	1.63	1.36	1.27	1.30	0.04	0.04	0.02	6.64 sec
Without MIP	Unit_uploading	0.22	0.22	0.11	0.10	0.11	0.05	0.04	0.03	0.88 sec
Without MIP	Plant_uploading	0.15	0.08	0.06	0.06	0.07	0.05	0.04	0.03	0.54 sec

Determination of the unit PQ curve in abnormal situation

Command 1 (Default): Set simple_pq_recovery /on
Command 2: Set simple_pq_recovery /off





$$p = P_0 \cdot \gamma_t + \sum_{seg} \frac{dP}{dQ}_{seg} \cdot q_{seg}$$

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Printing of unit PQ curves

Command: print pqcurves /<option> (<filename.xml>)

/<option>	Comment
/all	Print all three types of PQ curves
/original	Print PQ curves calculated based on turbine efficiency curves
/convex	Print PQ curves after convexification
/final	Print PQ curves after extending to Q=0

- The PQ curves can be written on xml format for **each unit** at **each time step** for **each iteration**
- If no filename is given by the user, the file will be saved with the default file "**pq_curves_full_mode_iter1.xml**" where the mode and the iteration number depend on the very next iteration
- How many **points** of the PQ curves will be printed out relies on 1) **how the PQ curves are built;** 2) the number of segments defined by the user (Default: set nseg /up 3; set nseg /down 3)

Printing of unit PQ curves (When G1 has schedule 100 MW)

Command 1 (Default): Set build_pq_curve /unit_uploading /all_limits

- When building PQ curve, all the limits ($P(turb\_min)$, $gen \rightarrow minprod$, min_p_constr, $P(min\_q\_constr)$) are taken into account at the same time. **If there is a schedule, only one point will be built.**
- It is suitable for those who want to run schedule or run on the limits.

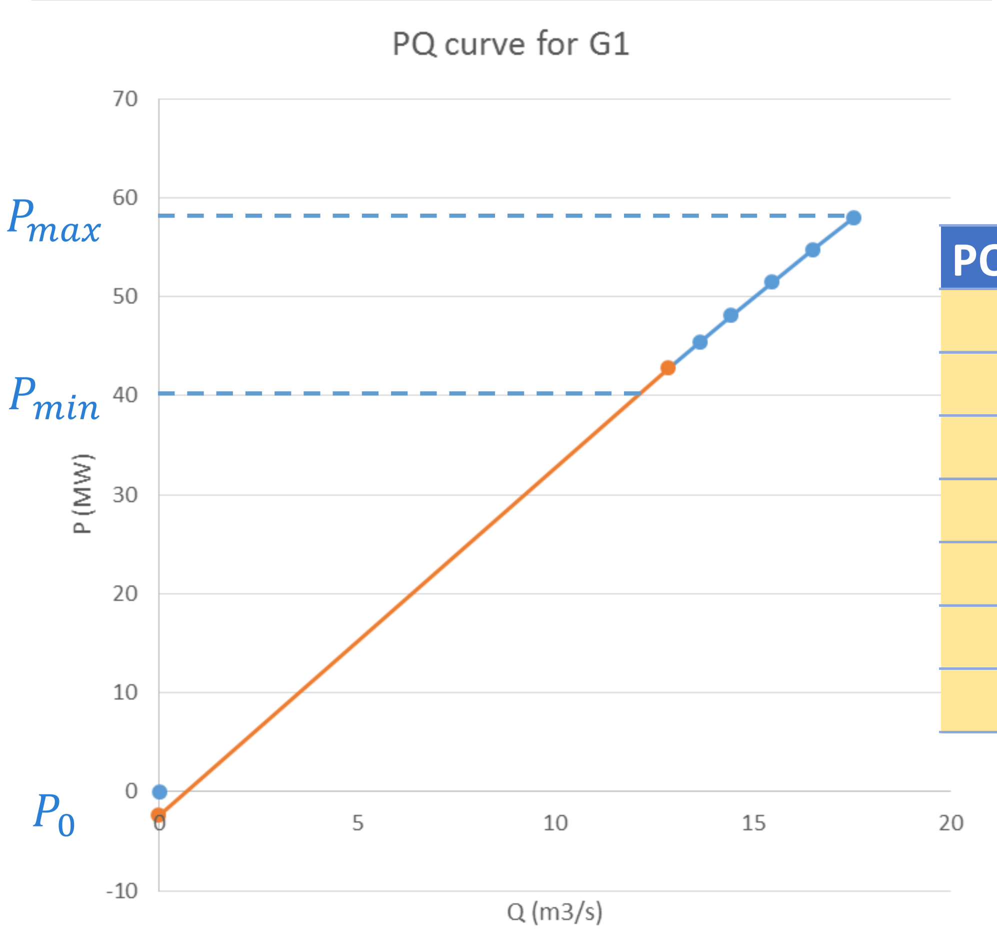
Time_period	Date	Plant_name	Unit_type	Unit_no	Needle_comb_no	PQ_curve_type	Q	P	dPdQ	Energy_Equivalent
75	2019 1/4 02:00	PLANT001	GEN	1	1	Original	47.90	100.00	0.00	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	47.90	100.00	0.00	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	0.00	0.00	0.00	0.00
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	47.90	100.00	2.09	0.58

```
GENERATOR turb_eff_curves PLANT001        1
#Id;Number;Reference;Pts;X_unit;Y_unit
 16650       1     180.000        3 M3/S %
#  x_value;    y_value;
 28.12      85.8733
 30.45      87.0319
 32.78      88.0879
 35.11      89.0544
 37.45      89.9446
 39.78      90.7717
 42.11      91.5488
 44.44      92.2643
 46.77      92.8213
 49.10      93.1090
 51.43      93.2170
 53.76      93.0390
 56.10      92.6570
 58.83      92.1746
```

Time_period	Date	Plant_name				PQ_curve_type	Q	P	dPdQ	Energy_Equivalent
75	2019 1/4 02:00	PLANT001				Original	28.12	54.33	0.00	0.54
75	2019 1/4 02:00	PLANT001				Original	35.89	72.11	2.29	0.56
75	2019 1/4 02:00	PLANT001				Original	43.66	90.28	2.34	0.57
75	2019 1/4 02:00	PLANT001				Original	47.90	100.00	2.29	0.58
75	2019 1/4 02:00	PLANT001				Original	51.43	107.63	2.16	0.58
75	2019 1/4 02:00	PLANT001				Original	53.90	112.51	1.98	0.58
75	2019 1/4 02:00	PLANT001				Original	56.36	117.11	1.86	0.58
75	2019 1/4 02:00	PLANT001				Original	58.83	121.62	1.83	0.57
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	28.12	54.33	0.00	0.54
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	43.66	90.28	2.31	0.57
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	47.90	100.00	2.29	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	51.43	107.63	2.16	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	53.90	112.51	1.98	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	56.36	117.11	1.86	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Convex	58.83	121.62	1.83	0.57
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	0.00	-10.72	0.00	0.00
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	30.57	60.00	2.31	0.55
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	43.66	90.28	2.31	0.57
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	47.90	100.00	2.29	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	51.43	107.63	2.16	0.58
75	2019 1/4 02:00	PLANT001	GEN	1	1	Final	53.90	112.51	1.98	0.58
75	2					Final	56.36	117.11	1.86	0.58
75	2					Final	57.94	120.00	1.83	0.58

```
GENERATOR attributes PLANT001        1
Id        Type      Penstock      Nom_prod      Min_prod      Max_prod      Start_cost
24839     0         1             120.000       60.000        120.000       180
```

Printing of unit PQ curves (When MIP is used)



PQ_curve_type	Q	P	dPdQ	Energy_Equivalent
Final	0.00	-10.99	0.00	0.00
Final	30.43	60.00	2.33	0.55
Final	43.66	90.85	2.33	0.58
Final	51.43	108.41	2.26	0.59
Final	53.90	113.36	2.01	0.58
Final	56.36	118.04	1.89	0.58
Final	57.42	120.00	1.86	0.58

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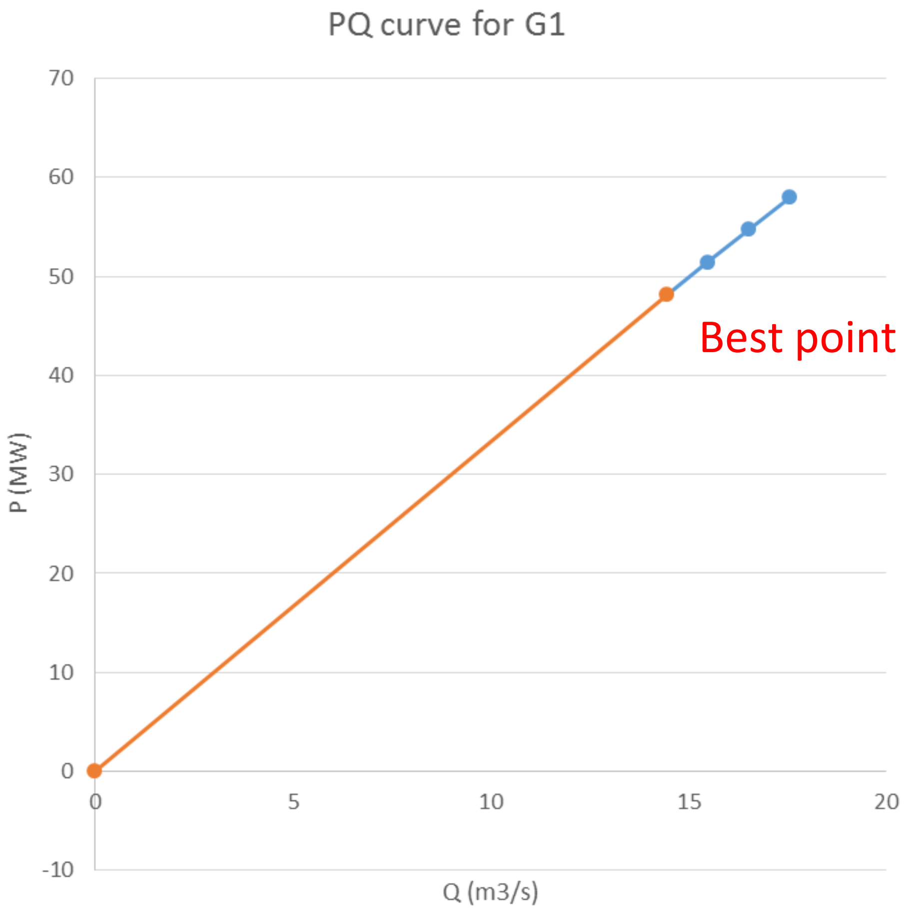
Printing of unit PQ curves (When MIP is relaxed)



PQ_curve_type	Q	P	dPdQ	Energy_Equivalent
Final	0.00	0.00	0.00	0.00
Final	51.43	108.41	2.11	0.59
Final	53.90	113.36	2.01	0.58
Final	56.36	118.03	1.89	0.58
Final	57.42	120.00	1.86	0.58

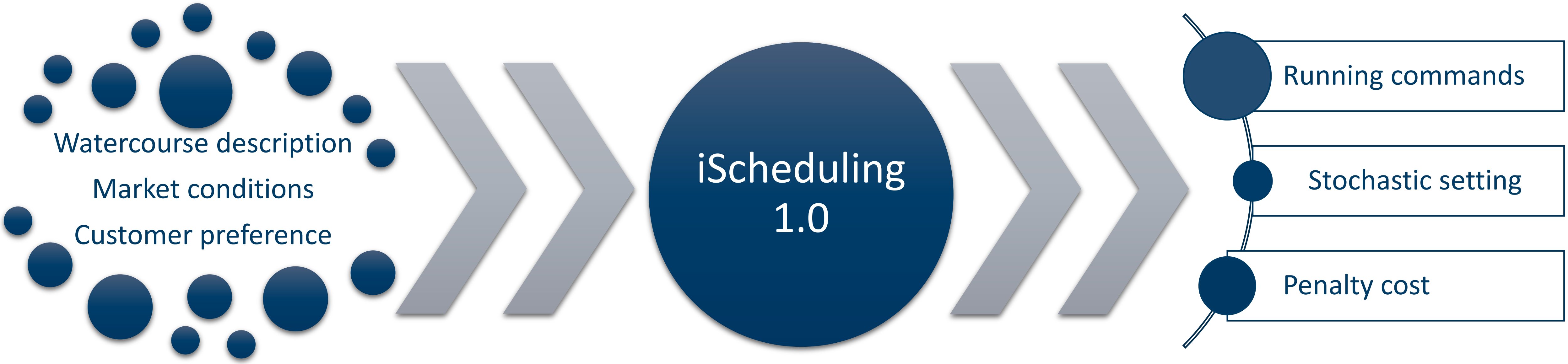
Outline

- Transition from plant-based to unit-based short-term hydro scheduling
- New commands related to build unit PQ curves
  - Determination of the unit PQ curve
  - Incorporation of power loss in shared penstock
  - Determination of the unit PQ curve without MIP
  - Determination of the unit PQ curve in abnormal situation
  - Printing of unit PQ curves
- New project proposal

New project proposal

Input data

Suggested setting



A Case-dependent Intelligent Scheduling System

SINTEF

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