Smart Integration of RENewables

Optimalna ulaganja u prijenosnu mrežu korištenjem DC i AC modela prijenosne mreže te Bendersove dekompozicije

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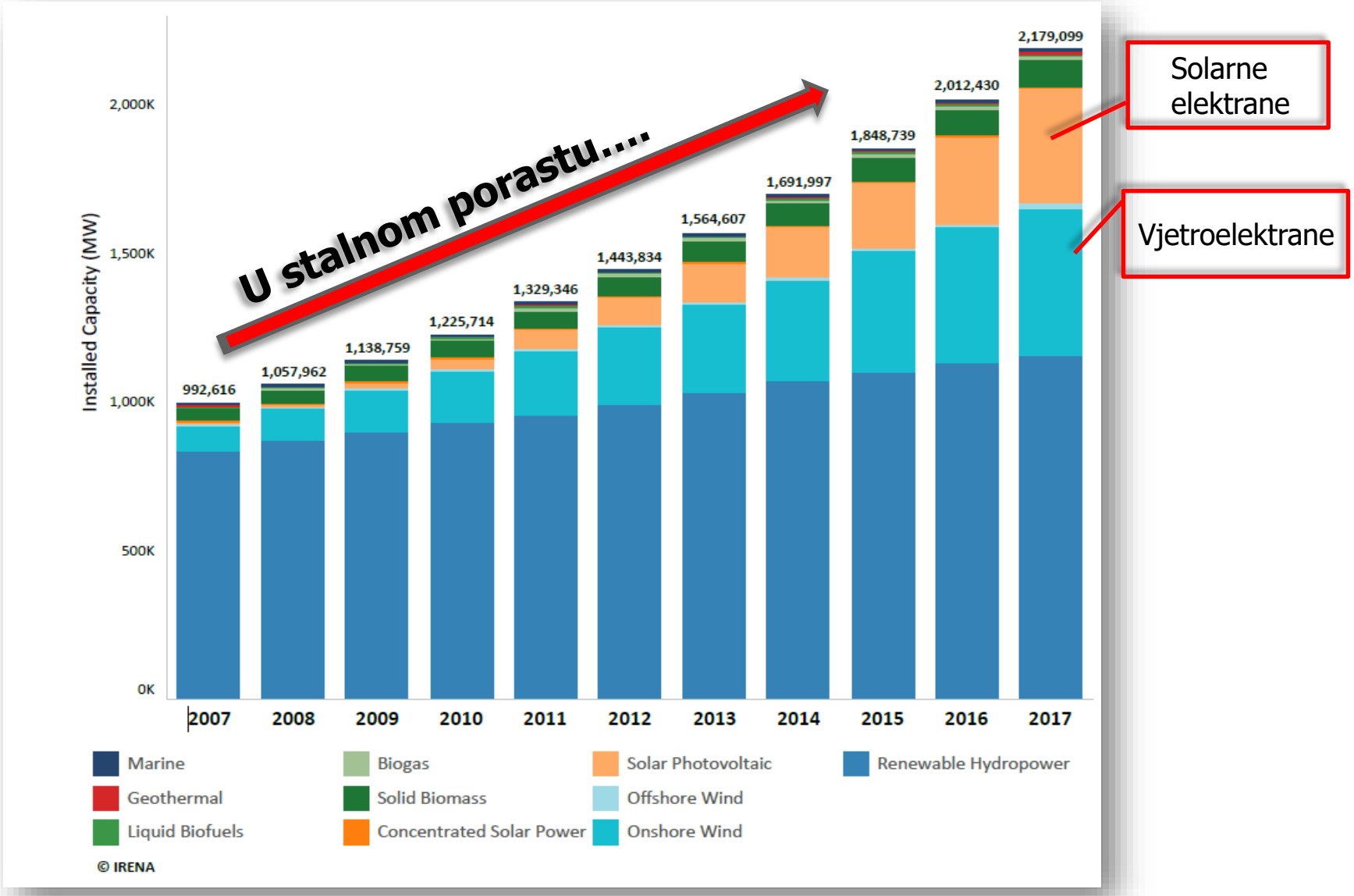
Sadržaj

- Uvod – motivacija
- Metodologija
- Benders dekomopozicija
- Studija slučaja
- Zaključak

Instalacija OIE u svijetu (2007.-2017.)



Aktualna situacija u EES-u

- Problematika:
  - Nepreciznost u predviđanju proizvodnje OIE
  - Smanjenje inercije u sustavu
  - Povećana potreba za pomoćnim uslugama – uravnoteženjem sustava
  - Povećanje zagušenja u mreži – odbacivanje proizvedene energije iz vjetra/sunca
  - Povećane rampe u sustavu
- Rješenje:
  - Gradnja fleksibilnih jedinica u mreži
  - Povećanje kapaciteta mreže
  - Instalacija spremnika energije, FACTS uređaja

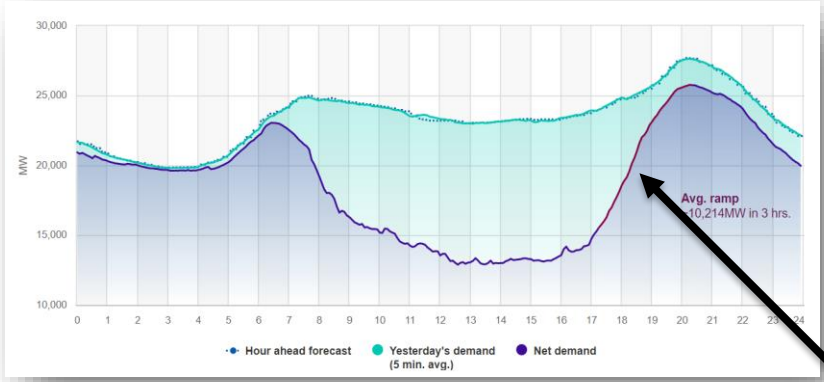
Moderni elektroenergetski sustav

Nesigurnost u predviđanju proizvodnje OIE

Odbačena energija vjetra

Inercija sustava

...



Rampa unutar 3 sata:
10 214 MW

Pogonske i investicijske odluke

LINE

FACTS

ENERGY STORAGE

Fleksibilnost EES-a

Pojam fleksibilnosti u EES-a

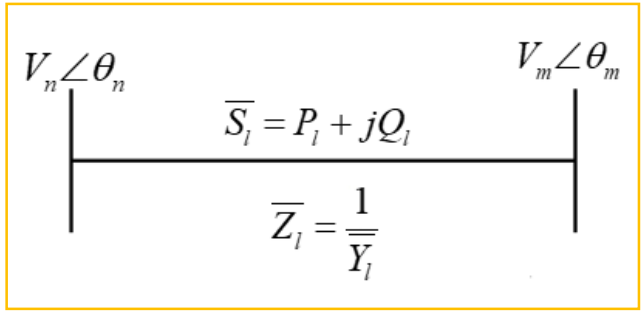
- Sposobnost sustava da odreagira na promjene u proizvodnji i potrošnji
  - Veća važnost porastom proizvodnje iz OIE
- Obuhvaća sve razine EES-a:
  - Fleksibilnost u proizvodnji
    - Elektrane koje mogu brzo mijenjati proizvodnju
    - Spremnici energije
  - Fleksibilnost u prijenosu/distribuciji
    - Povećanje prijenosne moći interkonekcijskih vodova
    - Pametna tehnologija za bolju iskoristivost prijenosnih vodova: FACTS uređaji
  - Fleksibilnost na strani potrošnje
    - Mikromreža, odziv potrošnje, spremnici energije

AC OPF modeliranje

- Tok snage po vodu:

$$\overline{S}_l = \overline{V}_n \cdot \overline{I}_l^* = \overline{V}_n \cdot \left(\frac{\overline{V}_n - \overline{V}_m}{\vec{Z}_l} \right)^* = |V_n| \angle \theta_n \cdot \left(|Y_l| \cdot |V_n| \angle -\theta_n - \vartheta_l - |Y_l| \cdot |V_m| \angle -\theta_m - \vartheta_l \right)$$

$$= |Y_l| \cdot |V_n|^2 \angle -\vartheta_l - |Y_l| \cdot |V_n| \cdot |V_m| \angle \theta_n - \theta_m - \vartheta_l$$



- Radna i jalova snaga:

$$P_l = Re\{S_l\},\ Q_l = Im\{S_l\}$$

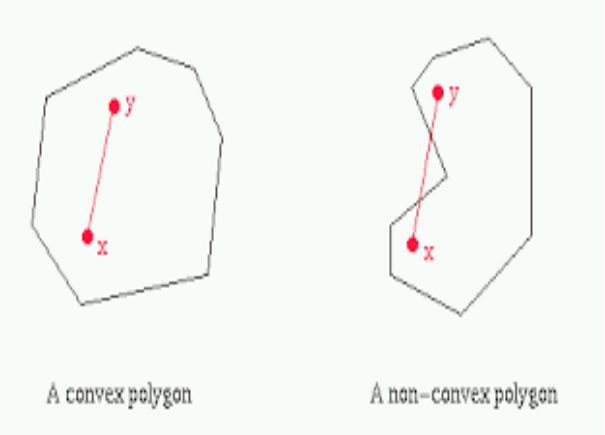
- Predstavlja stvarne prilike u EES-u:
  - Iznosi struje, napona, gubitka
- **Ali**: nelinearni i nekonveksni problemi

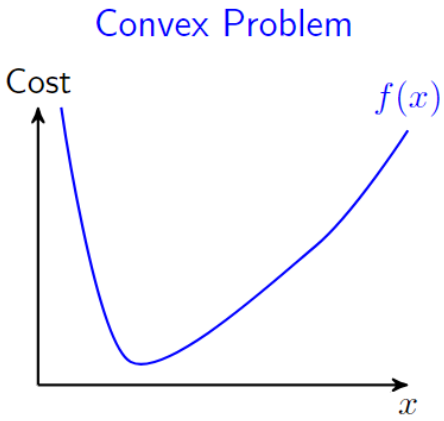
$$P_{t,l} = Y_l \left[V_{t,n}^2 \cdot \cos(\vartheta_l) - V_{t,n} \cdot V_{t,m} \cdot \cos(\theta_{t,n} - \theta_{t,m} - \vartheta_l) \right] \quad \forall \{n,m\} \in l \in \Omega^L, \forall t \in \Omega^T$$

$$Q_{t,l} = -Y_l \left[V_{t,n}^2 \cdot \sin(\vartheta_l) + V_{t,n} \cdot V_{t,m} \cdot \sin(\theta_{t,n} - \theta_{t,m} - \vartheta_l) \right] \quad \forall \{n,m\} \in l \in \Omega^L, \forall t \in \Omega^T$$

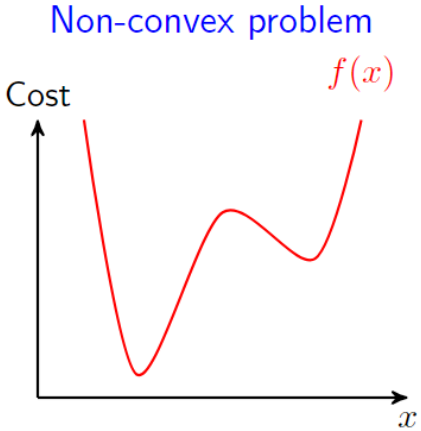
Konveksni vs. nekonveksni problemi

- Konveksni problemi – garantiraju globalno optimalno rješenje
- Nekonveksni problem – daju lokana rješenja
- Konveksnim relaksacijama se transformiraju modeli OPF u konveksne:
  - Semi-Definite Program (SDP)
  - Više scenarija/reprezentativnih dana





One global minimum



Several local minima

DC OPF modeli

- Kut razlike dvaju kutova napona – mali
- Linearizacija – razvoj sinus funkcije u Taylor red oko nule
  - Uzima u obzir samo radnu snagu
  - Nema gubitaka
  - Iznos nazivnog napona
- Linearni, konveksni modeli

$$loss \approx 0 \quad \rightarrow \quad p_{d,t,nm} = p_{d,t,mn} = p_{d,t,l} = v_{d,t,n} \cdot v_{d,t,m} \cdot B_l \cdot \sin\theta_{d,t,l}$$

$$\sin\theta_{d,t,l} \approx \theta_{d,t,l} \quad \rightarrow \quad p_{d,t,l} = v_{d,t,n} \cdot v_{d,t,m} \cdot B_l \cdot \theta_{d,t,l}$$

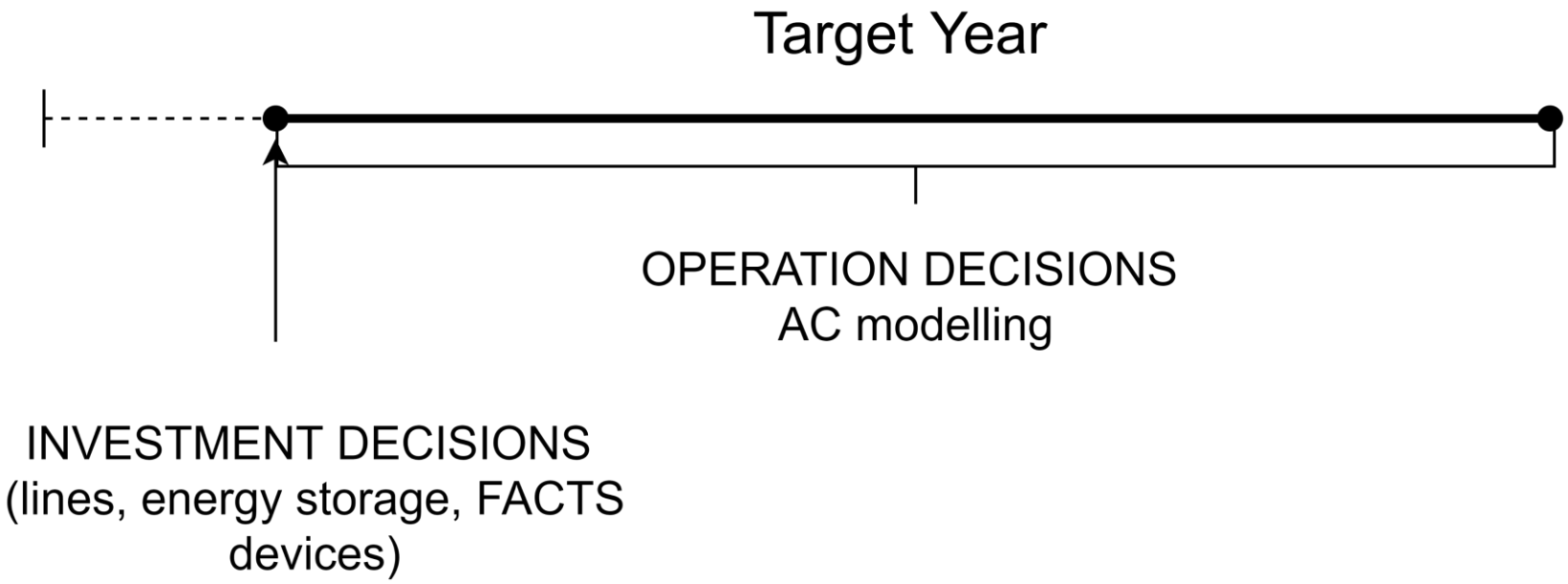
$$v_{d,t,n} \cdot v_{d,t,m} \approx 1 \rightarrow p_{d,t,l} = B_l \cdot \theta_{d,t,l}$$

$$R \ll X \rightarrow B_l \approx \frac{1}{X_l} \rightarrow p_{d,t,l} = \frac{\theta_{d,t,l}}{X_l}$$

$$\boxed{p_{d,t,l} = B_l \cdot \left(\theta_{d,t,n} - \theta_{d,t,m}\right) \qquad \forall \{n,m\} \in l, \forall t \in \Omega^T, \forall d \in \Omega^D}$$

Investicijski modeli

- Ideja rada:
  - Istražiti u kojoj mjeri dolazi do pogrešnih investicijskih odluka prilikom modeliranja samo DC modela mreže u odnosu na AC model mreže koji u obzir uzima gubitke, iznose amplitude napona



Koraci u istraživanju

- **Riješiti investicijski model u jednom koraku – nemoguće za velike modele (MINLP)**
- **Linearizacija AC jednadžbi tokova snaga → Linearizirani AC OPF (MILP) :**
  Benders dekompozicija: glavni (MIP), podproblemi (LP)
- **Benders dekompozicija TEP AC OPF cjelovitog modela (MINLP):**
  glavni (MIP), podproblemi (NLP)
- **Usporedbna DC i AC investicijskih modela koristeći Benders dekompoziciju**

Linearizacija AC OPF modela

- Konveksifikacija modela – razvoj funkcija sin i cos u Taylor red oko nule
- Admitancija $Y_l = G_l + \mathrm{j}B_l$
- Iznos amplitude napona: $v_{t,i} = 1 + \Delta v_{t,i}$

$$p_{d,t,l}^{(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) = G_l \cdot \left(\Delta v_{d,t,n}^{(\upsilon)} - \Delta v_{d,t,m}^{(\upsilon)}\right) + B_l \cdot \theta_{d,t,l}^{(\upsilon)} \quad \forall \{n,m\} \in l \in \Omega^{L^{\mathrm{EX}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$q_{d,t,l}^{(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) = -B_l^{sh} \cdot \left(1 + 2\Delta v_{d,t,n}^{(\upsilon)}\right) + B_l \cdot \left(\Delta v_{d,t,n}^{(\upsilon)} - \Delta v_{d,t,m}^{(\upsilon)}\right) - G_l \cdot \theta_{d,t,l}^{(\upsilon)}$$

$$\forall \{n,m\} \in l \in \Omega^{L^{\mathrm{EX}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

- Razvojem cos funkcije u Taylor red, drugi član reda predstavlja kvadratnu funkciju $\theta_{d,t,l}^2$

Linearizacija $\theta^2_{d,t,l}$ po dijelovima

- Podrazumijeva (2G) linearnih blokova i toliko varijabli
- Ili (G+2)
- Formulacija:

$$(\theta^{(\upsilon)}_{d,t,l})^2 = \sum_g K_g \cdot \Delta\theta^{(\upsilon)}_{d,t,l,g}$$

Aproksimacija kvadratne krivulje pravcima

$$\left|\theta^{(\upsilon)}_{d,t,l}\right| = \theta^{+(\upsilon)}_{d,t,l} + \theta^{-(\upsilon)}_{d,t,l}$$

$$\theta^{(\upsilon)}_{d,t,l} = \theta^{+(\upsilon)}_{d,t,l} - \theta^{-(\upsilon)}_{d,t,l}$$

$$\sum_g \Delta\theta^{(\upsilon)}_{d,t,l,g} = \theta^{+(\upsilon)}_{d,t,l} + \theta^{-(\upsilon)}_{d,t,l}$$

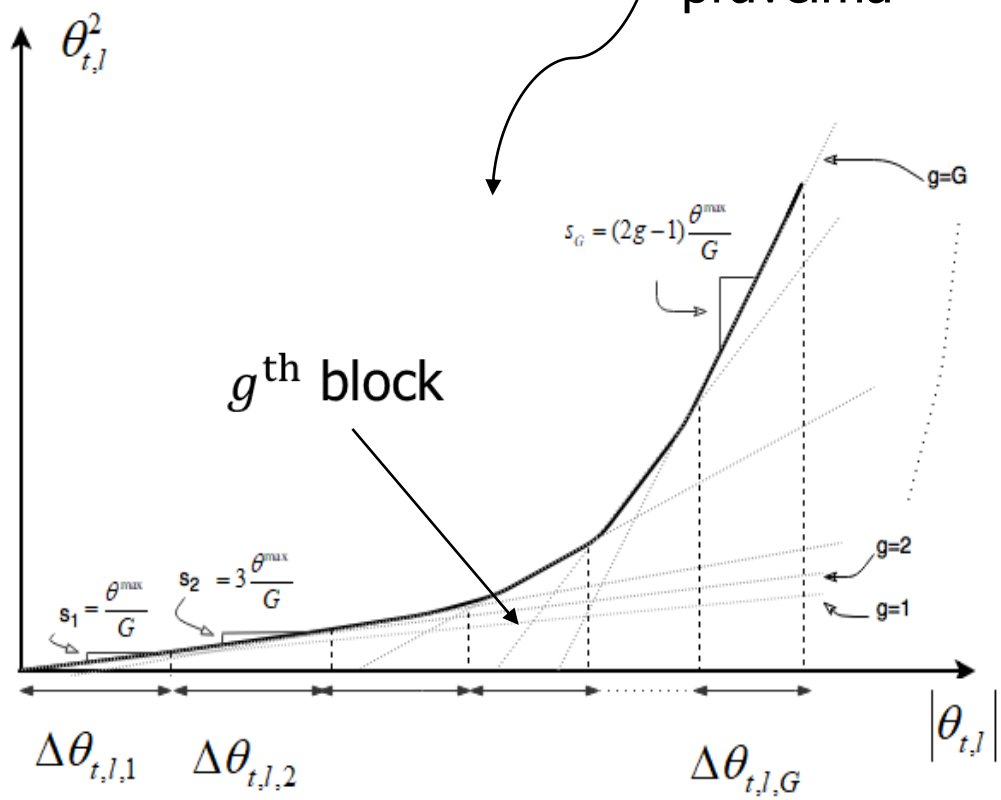
$$0 \le \Delta\theta^{(\upsilon)}_{d,t,l,g} \le \frac{\theta^{\max}}{G}$$

$$pls^{(\upsilon)}_{d,t,l} = G_l \cdot \sum_g K_g \cdot \Delta\theta^{(\upsilon)}_{d,t,l,g}$$

$$qls^{(\upsilon)}_{d,t,l} = -B_l \cdot \sum_g K_g \cdot \Delta\theta^{(\upsilon)}_{d,t,l,g}$$

$$\forall g \in \Omega^G, \forall l \in \Omega^L, \forall t \in \Omega^T, \forall d \in \Omega^D$$

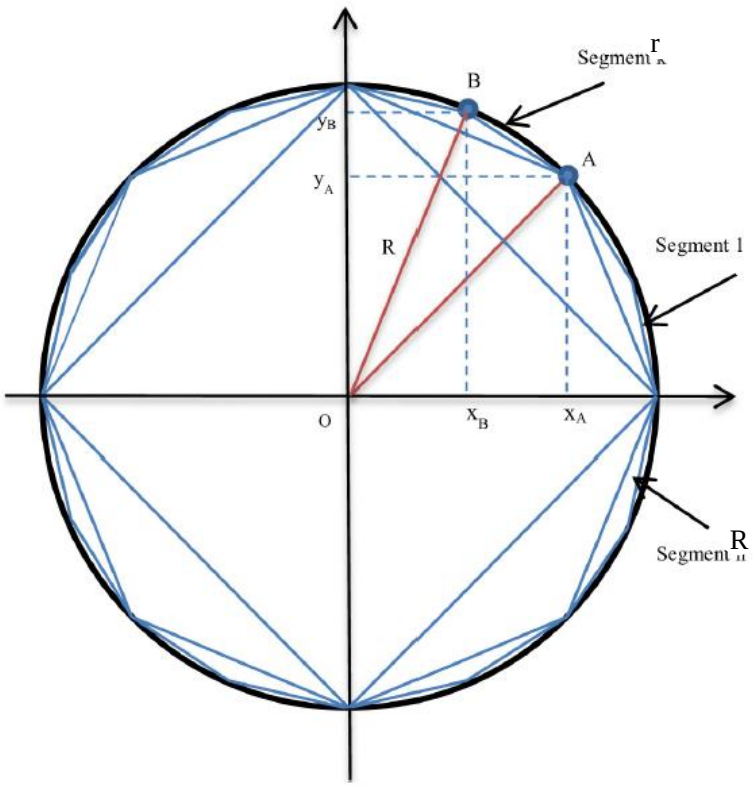
$$K_g = (2g-1) \cdot \frac{\theta^{max}}{G} \qquad \forall g \in \Omega^G$$



Linearizacija ograničenja tokova snaga

- Nelinearnost: $\left(p_{d,t,l}^{(\upsilon)}\right)^2+\left(q_{d,t,l}^{(\upsilon)}\right)^2 \le \left(S_l^{\max}\right)^2 \quad l\in\Omega^L, \forall t\in\Omega^T, \forall d\in\Omega^D$
- Područje rješenja kružnice je moguće aproksimirati pomoću r-konveksnog poligona*:

$$\left(\sin\left(\frac{360^\circ\cdot r}{R}\right)-\sin\left(\frac{360^\circ}{R}(r-1)\right)\right)\cdot p_{d,t,l}^{(\upsilon)}$$
$$-\left(\cos\left(\frac{360^\circ\cdot r}{R}\right)-\cos\left(\frac{360^\circ}{R}(r-1)\right)\right)\cdot q_{d,t,l}^{(\upsilon)}$$
$$-S_l^{\max}\cdot\sin\left(\frac{360^\circ}{R}\right)\le 0 \quad \forall r\in\Omega^R, l\in\Omega^L, \forall t\in\Omega^T, \forall d\in\Omega^D$$



*Izvor: *Akbari, T., and Bina, M. T. (2014). A linearized formulation of AC multi-year transmission expansion planning: A mixed-integer linear programming approach. Electric Power Systems Research, 114, 93-100.*

Direktni pristup

- Funkcija cilja:
  - » Pogonski troškovi + Investicijski troškovi
- Ograničenja:
  - » AC jednadžbe tokova snaga
  - » Ograničenja na minimalne i maksimalne tokove snaga
  - » Ograničenja na minimalne i maksimalne kutove
  - » Ograničenja na minimalne i maksimalne iznose napona
  - » Ograničenja generatora, spremnika energije, serijskih FACTS uređaja

Investicijski modeli

- Direktni pristup je moguć jedino za linearne modele
  - Funkcija cilja sadrži **Pogonske troškove i Investicijske troškove**
- AC full OPF investicijski modeli
  - MINLP – nije moguće za riješiti
  - Rješenje – Benders dekompozicija

Funkcija cilja

$$\underset{x_1,\ldots,x_n;\,y_1,\ldots,y_m}{\text{minimize}} \quad \sum_{i=1}^{n} c_i\, x_i + \sum_{j=1}^{m} d_j\, y_j$$

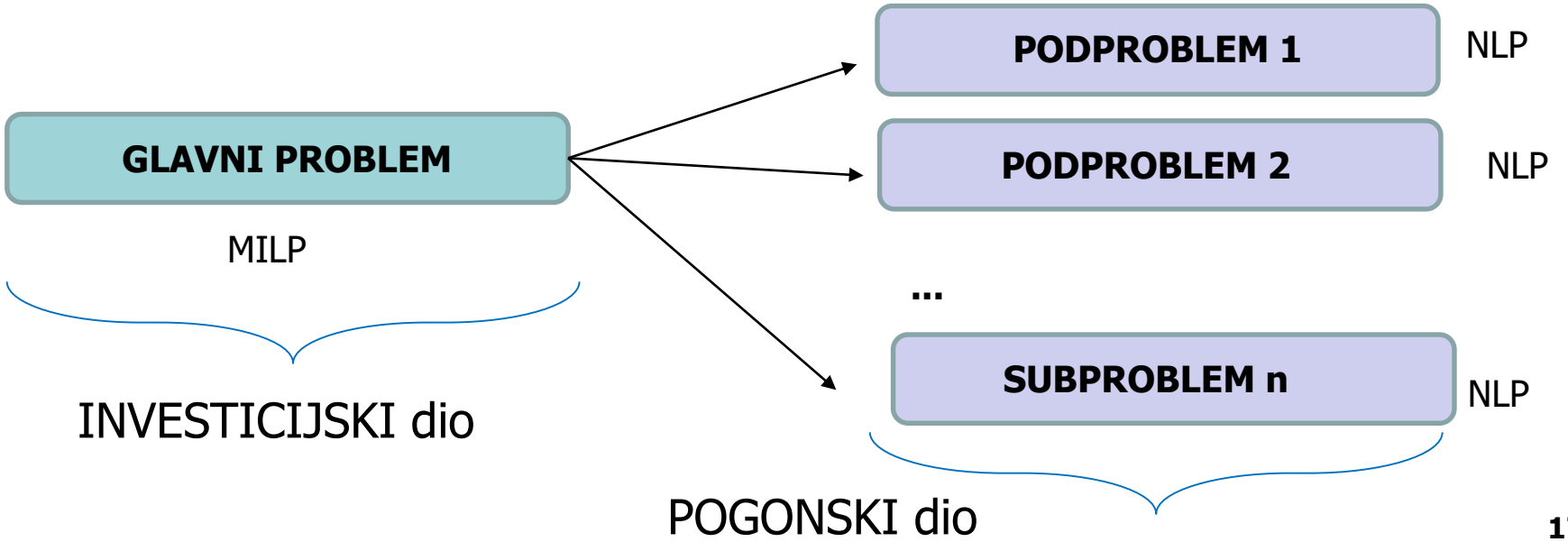
Ograničenja

$$\begin{aligned} \sum_{i=1}^{n} a_{\ell i}\, x_i + \sum_{j=1}^{m} e_{\ell j}\, y_j &\leq b^{(\ell)}; \quad \ell = 1,\ldots,q \\ 0 \leq x_i &\leq x_i^{\text{up}}; \quad i = 1,\ldots,n \\ 0 \leq y_j &\leq y_j^{\text{up}}; \quad j = 1,\ldots,m\,, \end{aligned}$$

Komplicirajuće varijable

Benders dekomopozicija

- Iteracijski problem
- Omogućuje jednostavniji proračun velikih modela
- Problemi s kompliciraćim varijablama ili kompliciraćim ograničenjima:
  - Originalni problem se dekomponira prema *n* reprezentativnih dana u kojima se kompliciraće varijable fiksiraju prema vrijednostima dobivenim iz glavnog problema
- Struktura AC full OPF:



Benders rezovi (engl. "cuts")

- Dekompozicija:

$$\underset{x_1,\ldots,x_n,\alpha}{\text{minimize}} \quad \sum_{i=1}^{n} c_i\, x_i + \alpha$$

Glavni problem

Prema ograničenjima:

$$\begin{aligned}
\alpha &\geq \sum_{j=1}^{m} d_j\, y_j^{(k)} + \sum_{i=1}^{n} \lambda_i^{(k)} (x_i - x_i^{(k)}) \\
0 &\leq x_i \leq x_i^{\text{up}}; \quad i = 1,\ldots,n \\
\alpha &\geq \alpha^{\text{down}},
\end{aligned}$$

$$\underset{y_1,\ldots,y_m}{\text{minimize}} \quad \sum_{j=1}^{m} d_j\, y_j$$

Podproblemi

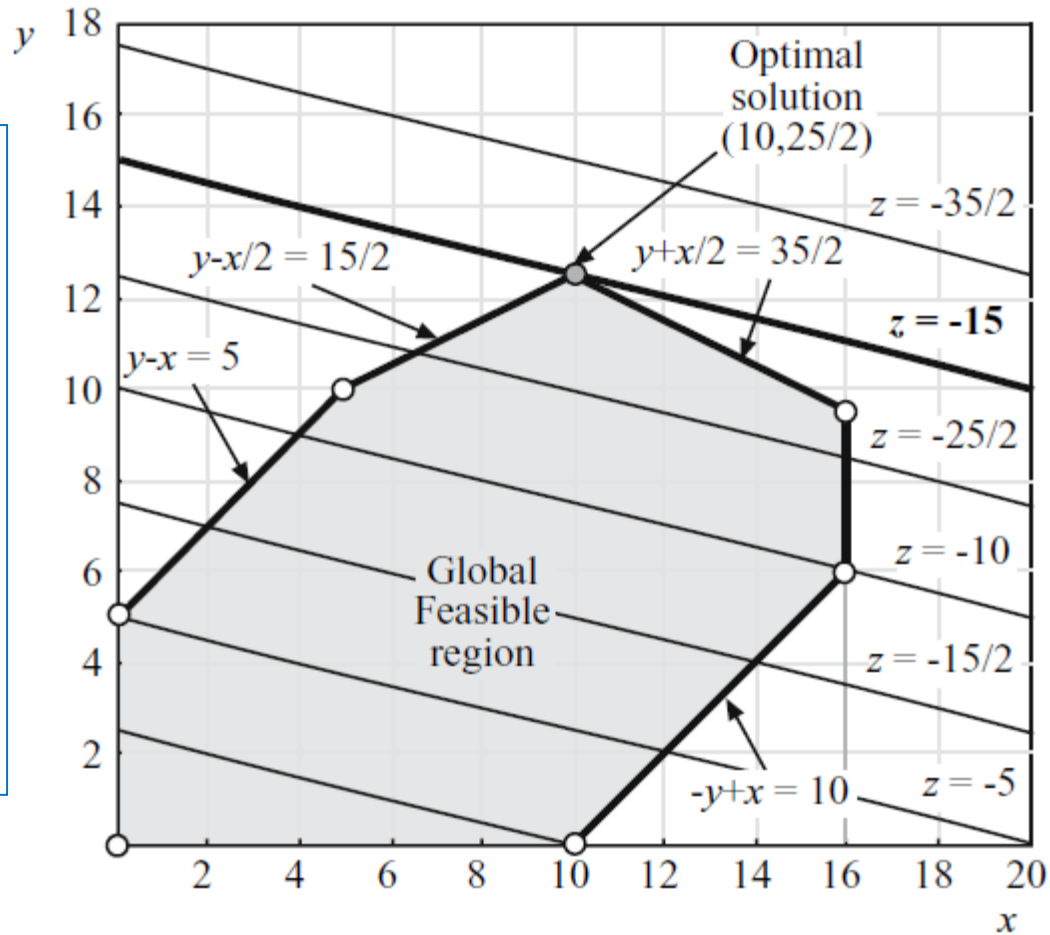
Prema ograničenjima:

$$\begin{aligned}
\sum_{i=1}^{n} a_{\ell i}\, x_i + \sum_{j=1}^{m} e_{\ell j}\, y_j \leq b^{(\ell)} \quad &; \quad \ell = 1,\ldots,q \\
0 \leq y_j \leq y_j^{\text{up}} \quad &; \quad j = 1,\ldots,m \\
x_i = x_i^{(k)} : \lambda_i \quad &; \quad i = 1,\ldots,n\,.
\end{aligned}$$

Objašnjenje

- Originalni problem – skup rješenja

$$
\begin{array}{lrcl}
\underset{x,y}{\text{minimize}} & & z = -y - x/4 & \\
 & y \quad -x & \leq & 5 \\
 & y \quad -\frac{1}{2}x & \leq & \frac{15}{2} \\
 & y \quad +\frac{1}{2}x & \leq & \frac{35}{2} \\
 & -y \quad +x & \leq & 10 \\
 & 0 & \leq & x \leq 16 \\
 & y & \geq & 0\,.
\end{array}
$$



Benders dekompozicija

- 1. iteracija

$$\begin{array}{lll} \underset{x,\alpha}{\text{minimize}} & & -\frac{1}{4}x+\alpha \\ & 0 \le x \le 16 & \\ & -25 \le \alpha. & \end{array}$$

GLAVNI

PODPROBLEM

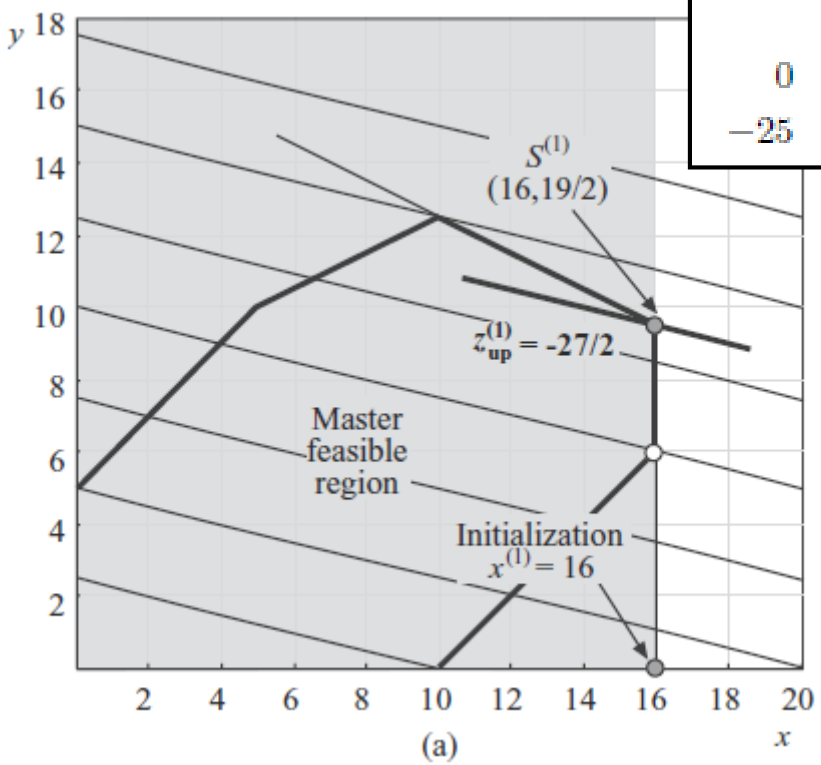
$$\begin{array}{lll} \underset{y}{\text{minimize}} & & z=-y \\ & y-x \le 5 & \\ & y-\frac{1}{2}x \le \frac{15}{2} & \\ & y+\frac{1}{2}x \le \frac{35}{2} & \\ & -y+x \le 10 & \\ & y \ge 0 & \\ & x = 16 \ : \ \lambda\,. & \end{array}$$

$$x^{(1)} = 16$$

$$y^{(1)} = \frac{19}{2}$$

$$z^{\text{up}} = \frac{-27}{2}$$

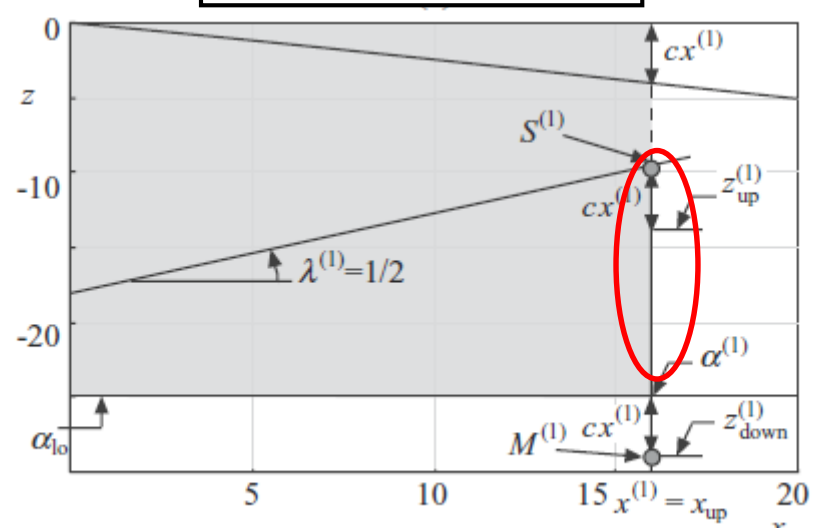
$$z^{\text{down}} = -29$$



(a)

$$z^{(\nu)}_{\text{up}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \sum_{j=1}^{m} d_j\, y_j^{(\nu)}$$

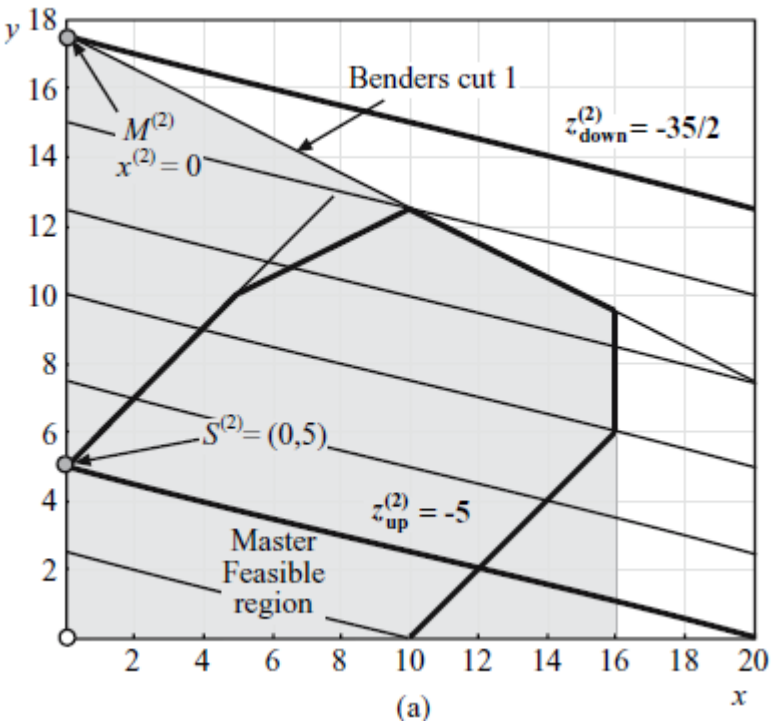
$$z^{(\nu)}_{\text{down}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \alpha^{(\nu)}\,.$$



(b)

Benders dekompozicija

- 2. iteracija

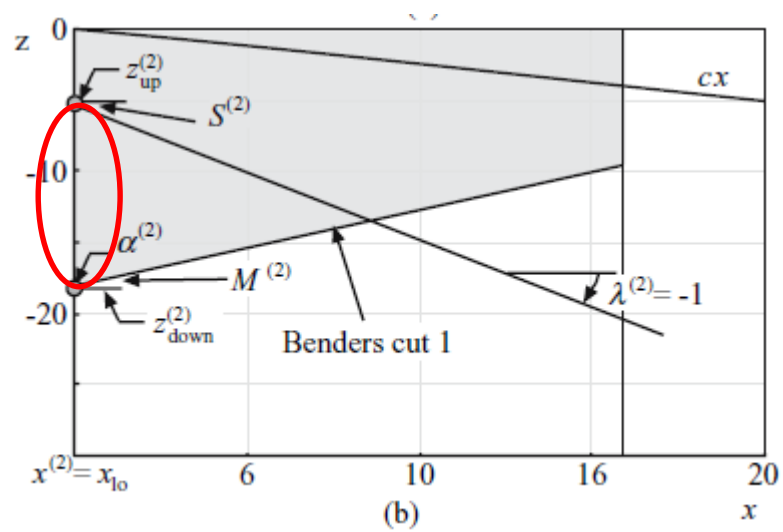


$$\begin{aligned} \underset{x,\alpha}{\text{minimize}} \quad & -\frac{1}{4}x + \alpha \\ -\frac{19}{2} + \frac{1}{2}(x-16) &\le \alpha \\ 0 \le x &\le 16 \\ -25 \le \alpha, & \end{aligned}$$

GLAVNI

Benders rez

$$x^{(2)} = 0$$
$$y^{(2)} = 5$$
$$z^{\text{up}} = -5$$
$$z^{\text{down}} = -\frac{35}{2}$$



$$z^{(\nu)}_{\text{up}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \sum_{j=1}^{m} d_j\, y_j^{(\nu)}$$

$$z^{(\nu)}_{\text{down}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \alpha^{(\nu)} .$$

Benders dekompozicija

- 3. iteracija

GLAVNI

$$\underset{x,\alpha}{\text{minimize}} \quad -\frac{1}{4}x + \alpha$$

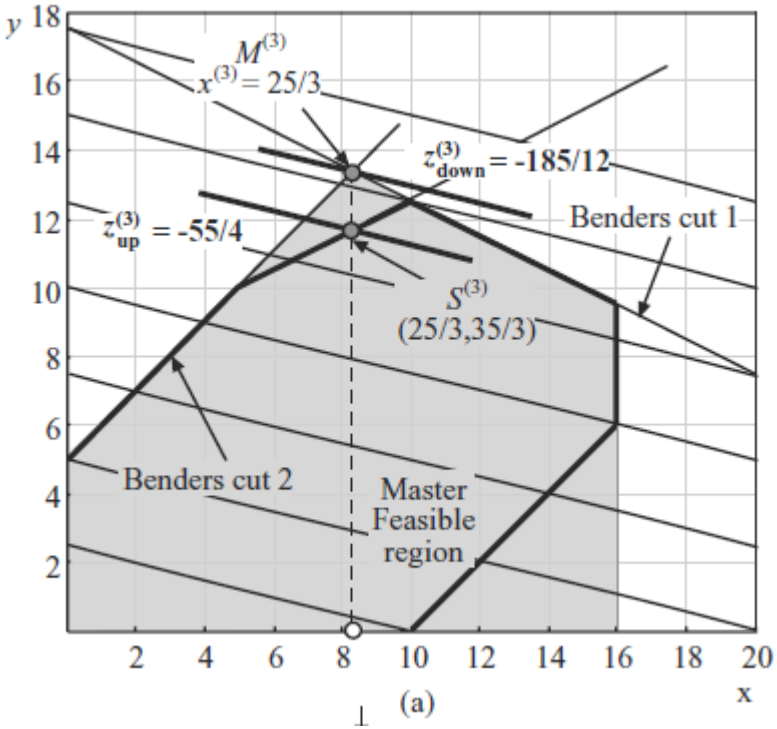
$$\begin{aligned} -\frac{19}{2} + \frac{1}{2}(x-16) &\le \alpha \\ -5-(x-0) &\le \alpha \\ 0 \le x &\le 16 \\ -25 &\le \alpha\,, \end{aligned}$$

$$x^{(3)} = \frac{25}{3}$$

$$y^{(3)} = \frac{35}{3}$$

$$z^{\text{up}} = -\frac{55}{4}$$

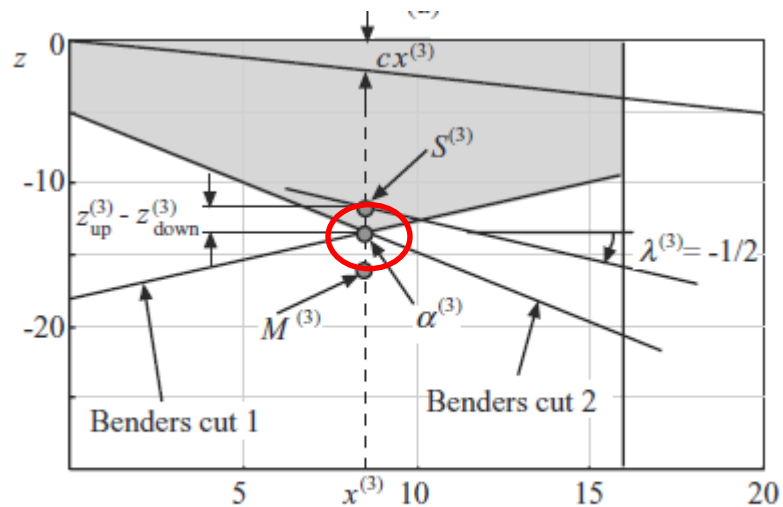
$$z^{\text{down}} = -\frac{185}{12}$$



(a)

$$z^{(\nu)}_{\text{up}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \sum_{j=1}^{m} d_j\, y_j^{(\nu)}$$

$$z^{(\nu)}_{\text{down}} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \alpha^{(\nu)}\,.$$



(b)

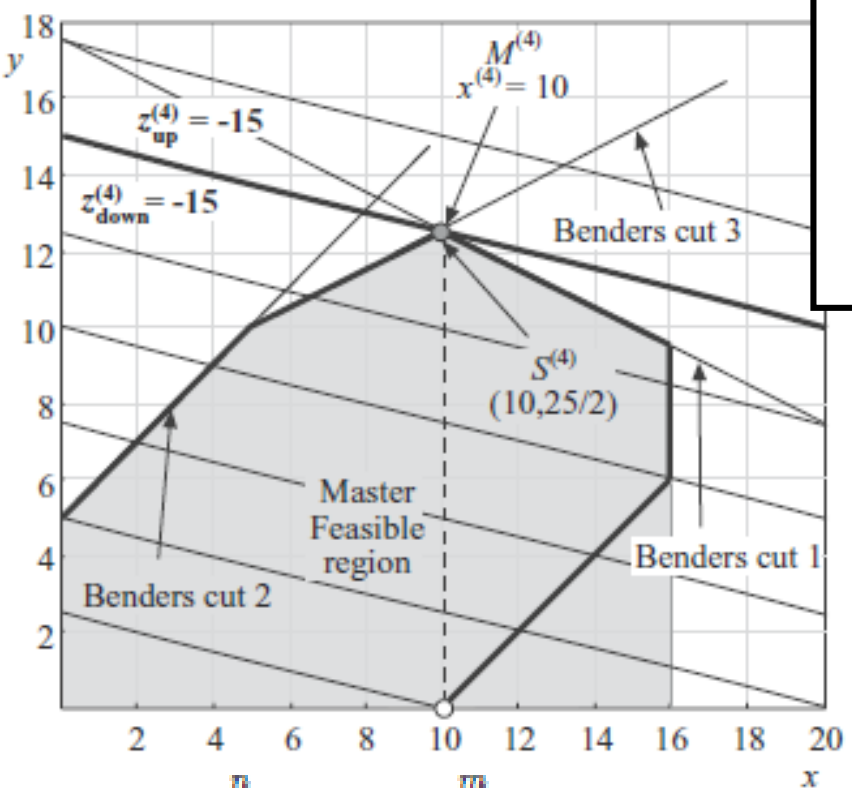
Benders dekompozicija

- 4. iteracija

GLAVNI

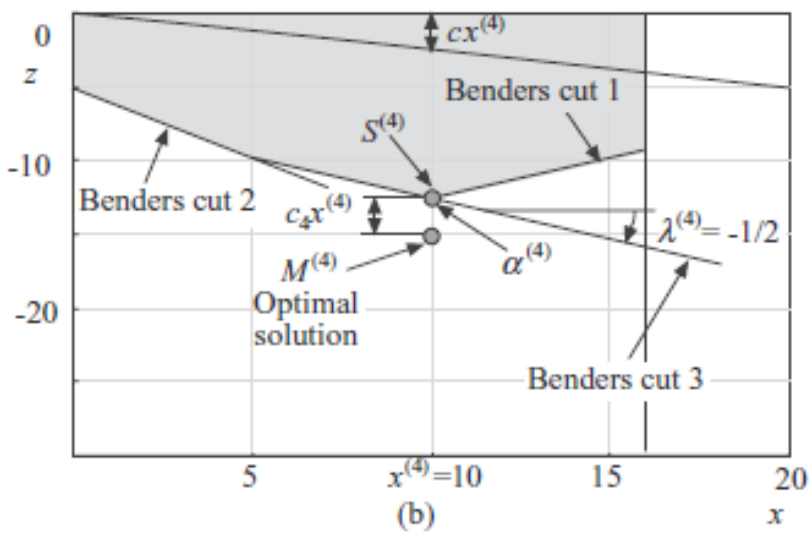
$$\begin{array}{lll} \underset{x,\alpha}{\text{minimize}} & -\frac{1}{4}x + \alpha & \\ & -\frac{19}{2} + \frac{1}{2}(x-16) & \leq \alpha \\ & -5 - (x-0) & \leq \alpha \\ & -\frac{35}{3} - \frac{1}{2}(x - \frac{25}{3}) & \leq \alpha \\ & 0 & \leq x \leq 16 \\ & -25 & \leq \alpha\,, \end{array}$$

$$x^{(4)} = 10$$
$$y^{(4)} = \frac{25}{2}$$
$$z^{\text{up}} = -15$$
$$z^{\text{down}} = -15$$



$$z_{\text{up}}^{(\nu)} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \sum_{j=1}^{m} d_j\, y_j^{(\nu)}$$

$$z_{\text{down}}^{(\nu)} = \sum_{i=1}^{n} c_i\, x_i^{(\nu)} + \alpha^{(\nu)}\,.$$



Glavni problem

- MASTER PROBLEM:

$$\underset{\aleph^{MP}}{\text{Minimize}}\ E_{down}^{(\upsilon)} = \sum_{l\in\Omega^{L,NEW}} C_l^{line}\cdot v_l^{(\upsilon)} + \sum_s \left(C_s^{BES\,pow}\cdot ch_s^{max(\upsilon)} + C_s^{BES\,en}\cdot soc_s^{max(\upsilon)} \right)$$

$$\sum_{l\in\Omega^{L,FACTS}} C^{FACTS}\cdot \sigma_l^{FACTS(\upsilon)} X_l + \alpha^{(\upsilon)}$$

Komplicirajuće varijable

subject to:

$$\alpha^{(\upsilon)} \geq \sum_d E_d^{SP(k)} + \sum_d \sum_{l\in\Omega^{L,NEW}} \xi_{d,l}^{LINE(k)} \cdot \left(v_l^{(\upsilon)} - v_l^{(k)} \right)$$

$$+\sum_d \sum_{l\in\Omega^{L,FACTS}} \xi_{d,l}^{FACTS(k)} \cdot \left(\sigma_l^{FACTS(\upsilon)} - \sigma_l^{FACTS(k)} \right)$$

$$+\sum_d \sum_s \left(\xi_{d,s}^{BESpow(k)} \cdot \left(ch_s^{max(\upsilon)} - ch_s^{max(k)} \right) + \xi_{d,s}^{BES\,soc(k)} \cdot \left(soc_s^{max(\upsilon)} - soc_s^{max(k)} \right) \right) \quad \forall k = 1,\ldots,\upsilon-1$$

$$0 \leq \sigma_l^{FACTS(\upsilon)} \leq \sigma_l^{FACTS,max}$$

$$\alpha^{(\upsilon)} \geq \alpha^{down}$$

$$\aleph^{MP} = \left\{ \sigma_l^{FACTS(\upsilon)}, \alpha^{(\upsilon)}, v_l^{(\upsilon)}, E_{down}^{(\upsilon)}, ch_s^{max(\upsilon)}, soc_s^{max(\upsilon)} \right\}$$

BENDERS' REZOVI

Podproblem - investicije

$$\underset{N^{SP}}{\text{Minimize}}\ E_d^{SP(\upsilon)} = \chi_d \cdot S_{base} \cdot \sum_t \left(\sum_i pg_{d,t,i}^{(\upsilon)} \cdot O_i^{gen} + \sum_w \left(pw_{d,t,w}^{(\upsilon)} \cdot O_i^w + ws_{d,t,w}^{(\upsilon)} \cdot P^w \right) \right)$$

- Novi vodovi:

$$\left(v_l^{(\upsilon)} - 1\right) \cdot M \le p_{d,t,l}^{(\upsilon)} - \Delta p_{d,t,l}^{(\upsilon)} \left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) \le \left(1 - v_l^{(\upsilon)}\right) \cdot M$$

$$\forall \{n,m\} \in l \in \Omega^{L^{NEW}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$\left(v_l^{(\upsilon)} - 1\right) \cdot M \le q_{d,t,l}^{(\upsilon)} - \Delta q_{d,t,l}^{(\upsilon)} \left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) \le \left(1 - v_l^{(\upsilon)}\right) \cdot M \ \forall \{n,m\} \in l \in \Omega^{L^{NEW}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$v_l^{(\upsilon)} = v_l^{fixed(\upsilon)} \qquad : \xi_{d,l}^{LINES(\upsilon)} \qquad \forall l \in \Omega^{L^{NEW}}, \forall d \in \Omega^D$$

- Spremnici energije:

$$0 \le p_{d,t,s}^{ch(\upsilon)} \le ch_s^{max(\upsilon)} \qquad \forall s \in \Omega^S, t \in \Omega^T, \forall d \in \Omega^D$$

$$0 \le p_{d,t,s}^{dis(\upsilon)} \le ch_s^{max(\upsilon)} \qquad \forall s \in \Omega^S, t \in \Omega^T, \forall d \in \Omega^D$$

$$0 \le soc_{d,t,s}^{(\upsilon)} \le soc_s^{max(\upsilon)} \qquad \forall s \in \Omega^S, t \in \Omega^T, \forall d \in \Omega^D$$

$$soc_{d,t,s}^{(\upsilon)} = soc_{d,t-1,s}^{(\upsilon)} + p_{d,t,s}^{ch(\upsilon)} - p_{d,t,s}^{dis(\upsilon)} \qquad \forall s \in \Omega^S, t \in \Omega^T, \forall d \in \Omega^D$$

$$soc_s^{max(\upsilon)} = soc_s^{max,fixed(\upsilon)} \qquad : \xi_{d,s}^{soc(\upsilon)} \qquad \forall s \in \Omega^S, \forall d \in \Omega^D$$

$$ch_s^{max(\upsilon)} = ch_s^{max,fixed(\upsilon)} \qquad : \xi_{d,s}^{BESpow(\upsilon)} \qquad \forall s \in \Omega^S, \forall d \in \Omega^D$$

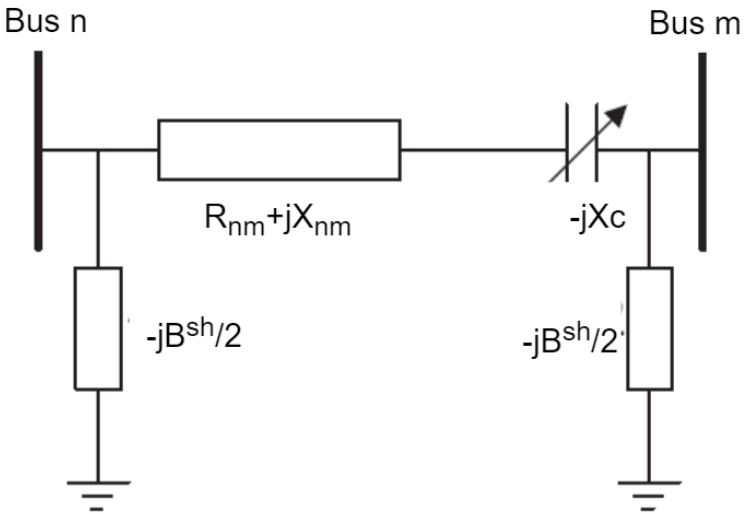
Fiksiranje komplicirajućih varijabli i određivanje dualnih varijabli

Podproblem - investicije

- FACTS – TCSC :

$$G_l^{\mathrm{FACTS}(\upsilon)} = \frac{R_l}{(R_l)^2 + \left(X_l \cdot \left(1 - \sigma_l^{\mathrm{FACTS}(\upsilon)}\right)\right)^2}$$

$$B_l^{\mathrm{FACTS}(\upsilon)} = \frac{X_l \cdot \left(1 - \sigma_l^{\mathrm{FACTS}(\upsilon)}\right)}{(R_l)^2 + \left(X_l \cdot \left(1 - \sigma_l^{\mathrm{FACTS}(\upsilon)}\right)\right)^2}$$



- Dinamički pristup:

If $\theta_{d,t,l}^{(\upsilon)} \geq 0$ then $\ell_{d,t,l} = 1$, otherwise, $\ell_{d,t,l} = 0$.

$$\ell_{d,t,l} \cdot \Delta p_{d,t,l}^{\mathrm{FACTS,min}(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) - (1 - \ell_{d,t,l}) \cdot M \leq p_{d,t,l}^{(\upsilon)} \quad \forall l \in \Omega^{L^{\mathrm{EX,FACTS}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$(1 - \ell_{d,t,l}) \cdot \Delta p_{d,t,l}^{\mathrm{FACTS,max}(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) - \ell_{d,t,l} \cdot M \leq p_{d,t,l}^{(\upsilon)} \quad \forall l \in \Omega^{L^{\mathrm{EX,FACTS}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$\ell_{d,t,l} \cdot \Delta p_{d,t,l}^{\mathrm{FACTS,max}(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) + (1 - \ell_{d,t,l}) \cdot M \geq p_{d,t,l}^{(\upsilon)} \quad \forall l \in \Omega^{L^{\mathrm{EX,FACTS}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

$$(1 - \ell_{d,t,l}) \cdot \Delta p_{d,t,l}^{\mathrm{FACTS,min}(\upsilon)}\left(\Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{(\upsilon)}\right) + \ell_{d,t,l} \cdot M \geq p_{d,t,l}^{(\upsilon)} \quad \forall l \in \Omega^{L^{\mathrm{EX,FACTS}}}, \forall t \in \Omega^T, \forall d \in \Omega^D$$

Podproblem – druga ograničenja

- Jednakost snaga u čvorištima:

$$\sum_{w\in M^n} pw_{d,t,w}^{(\upsilon)} + \sum_{i\in M^n} pg_{d,t,i}^{(\upsilon)} - \sum_{o(l)\in M^n} p_{d,t,l}^{(\upsilon)} + \sum_{d(l)\in M^n} p_{d,t,l}^{(\upsilon)} - 0.5\sum_{l\in M^n} pls_{d,t,l}^{(\upsilon)} + \sum_{s\in M^n} p_{d,t,s}^{\mathrm{dis}(\upsilon)}$$

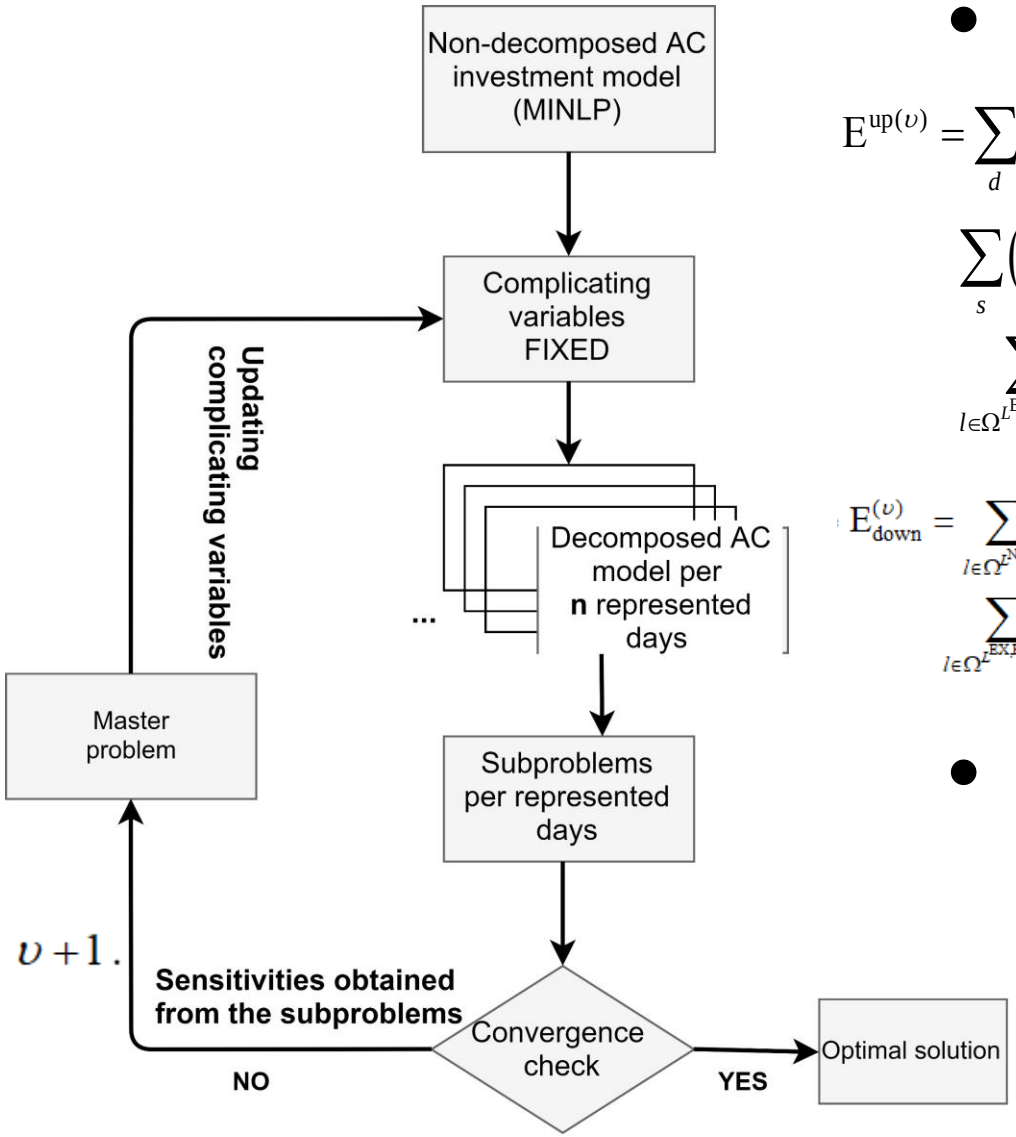
$$= PD_{d,t,n} + \sum_{s\in M^n} p_{d,t,s}^{\mathrm{ch}(\upsilon)} \quad \forall n\in\Omega^N, \forall t\in\Omega^T, \forall d\in\Omega^D$$

$$\sum_{i\in M^n} qg_{d,t,i}^{(\upsilon)} - \sum_{o(l)\in M^n} q_{d,t,l}^{(\upsilon)} + \sum_{d(l)\in M^n} q_{d,t,l}^{(\upsilon)} - 0.5\sum_{l\in M^n} qls_{d,t,l}^{(\upsilon)} = QD_{d,t,n} \quad \forall n\in\Omega^N, \forall t\in\Omega^T, \forall d\in\Omega^D$$

- Generatori:
  - Ograničenja radne/jalove snage
  - Ograničenja rampa podizanja/spuštanja snage
- Ograničenja napona
- Ograničenja proizvodnje vjetroelektrana
- Set varijabli podproblema:

$$\aleph^{\mathrm{SP}} = \left\{ \begin{array}{l} pg_{d,t,i}^{(\upsilon)}, p_{d,t,l}^{(\upsilon)}, qg_{d,t,i}^{(\upsilon)}, q_{d,t,l}^{(\upsilon)}, \kappa_{d,t,i}^{Q\min(\upsilon)}, \kappa_{d,t,i}^{Q\max(\upsilon)}, \Delta v_{d,t,n}^{(\upsilon)}, \theta_{d,t,n}^{(\upsilon)}, \theta_{d,t,l}^{+(\upsilon)}, \theta_{d,t,l}^{-(\upsilon)}, pls_{d,t,l}^{(\upsilon)}, qls_{d,t,l}^{(\upsilon)}, \\ \Delta\theta_{d,t,l,g}^{(\upsilon)}, pw_{d,t,w}^{(\upsilon)}, ws_{d,t,w}^{(\upsilon)}, soc_{d,t,s}^{(\upsilon)}, p_{d,t,s,}^{\mathrm{ch}(\upsilon)}, p_{d,t,s,}^{\mathrm{dis}(\upsilon)}, v_l^{(\upsilon)}, \sigma_l^{\mathrm{FACTS}(\upsilon)}, ch_s^{\max(\upsilon)}, soc_s^{\max(\upsilon)} \end{array} \right\}$$

Flowchart -Bender's algoritam



- Granice:

$$\mathrm{E}^{\mathrm{up}(\upsilon)} = \sum_{d} \mathrm{E}_{d}^{\mathrm{SP}(\upsilon)} + \sum_{l \in \Omega^{L^{\mathrm{NEW}}}} v_l^{\mathrm{fixed}} \cdot C^{\mathrm{line}} + \sum_{s} \left(C^{\mathrm{BESpow}} \cdot ch_s^{\mathrm{max,fixed}} + C^{\mathrm{BESen}} \cdot soc_s^{\mathrm{max,fixed}} \right) + \sum_{l \in \Omega^{L^{\mathrm{EX,FACTS}}}} C^{\mathrm{FACTS}} \cdot \sigma_l^{\mathrm{FACTS,fixed}} \cdot X_l$$

$$\mathrm{E}_{\mathrm{down}}^{(\upsilon)} = \sum_{l \in \Omega^{L^{\mathrm{NEW}}}} C_l^{\mathrm{line}} \cdot v_l^{(\upsilon)} + \sum_{s} \left(C_s^{\mathrm{BESpow}} \cdot ch_s^{\max(\upsilon)} + C_s^{\mathrm{BESen}} \cdot soc_s^{\max(\upsilon)} \right) \sum_{l \in \Omega^{L^{\mathrm{EX,FACTS}}}} C^{\mathrm{FACTS}} \cdot \sigma_l^{\mathrm{FACTS}(\upsilon)} \cdot X_l + \alpha^{(\upsilon)}$$

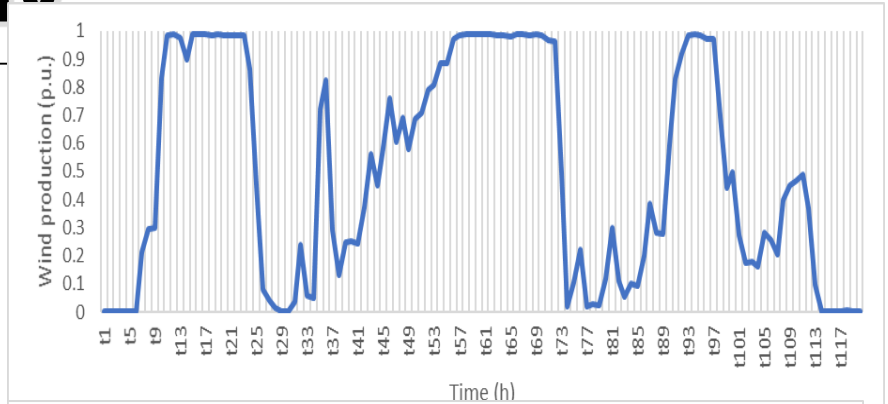
- Provjera konvergencije:

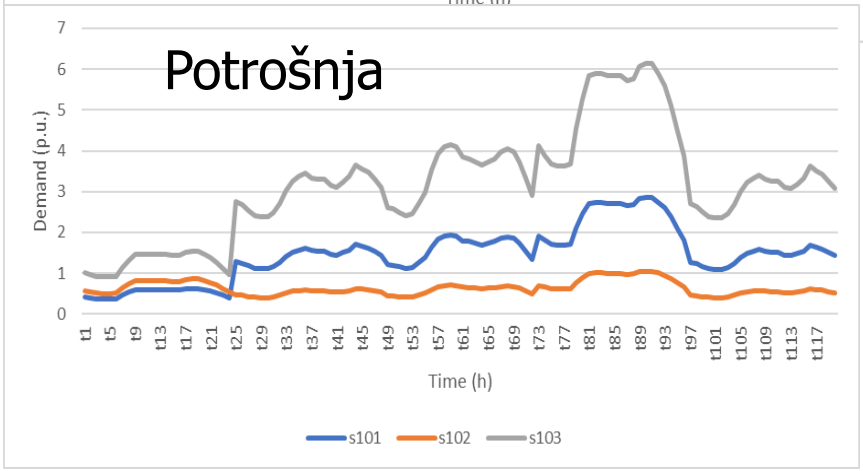
$$\left| \mathrm{E}^{\mathrm{up}(\upsilon)} - \mathrm{E}^{\mathrm{down}(\upsilon)} \right| \leq \varepsilon$$

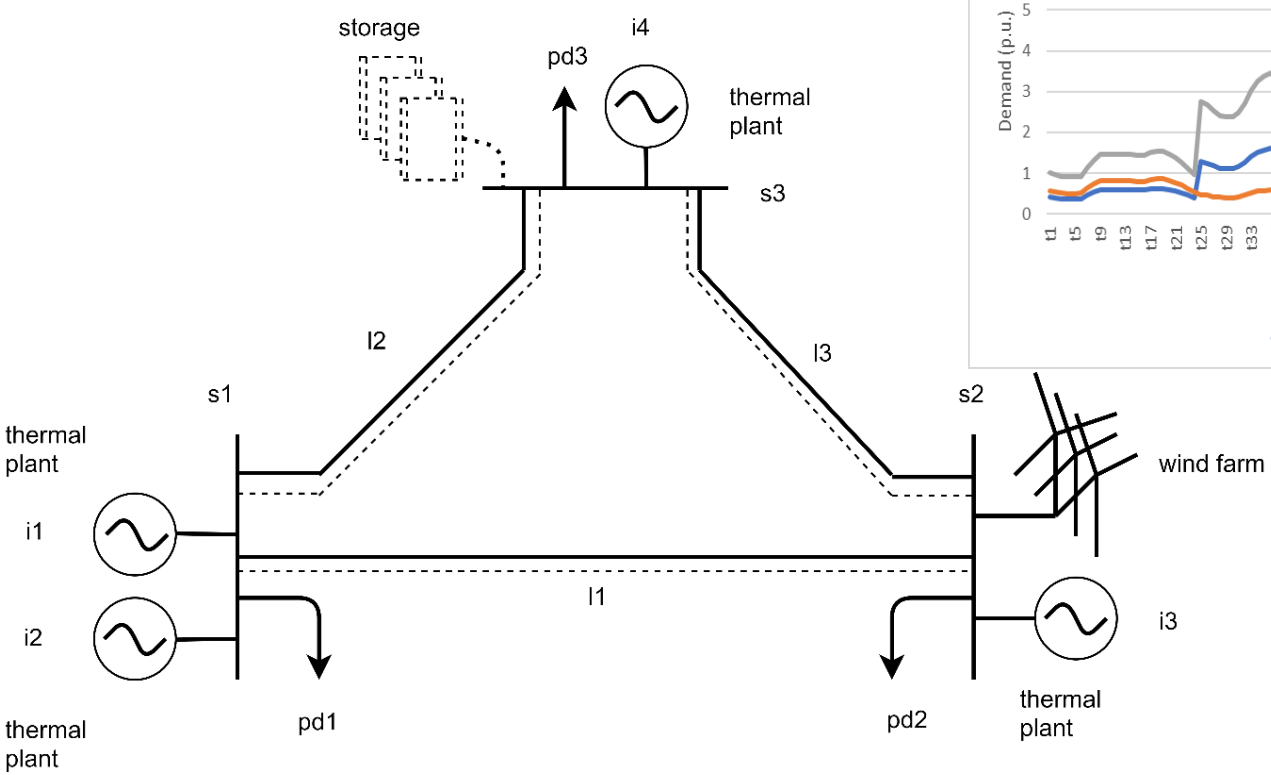
Case study – mali sustav

- 3 čvorišta
- 4 konvencionalne elektrane
- 1 vjetropark
- 5 reprezentativnih dana

Proizvodnja vjetroparka







d1= 215.591

d2= 21.058

d3= 34.093

d4= 17.047

d5= 77.212

Case Study – investicijski troškovi

$$lf_{\text{LINES}} = 40$$
$$lf_{\text{BES}} = 20$$
$$lf_{\text{TCSC}} = 20$$
$$r = 5\%$$

- Vodovi:

$$C_l^{\text{line,yearly}} = C_l^{\text{line,in}} \cdot \frac{r \cdot (1+r)^{lf}}{(1+r)^{lf} - 1}$$

→ Kapitalni povratni faktor (CRF)

- Spremnici energije:

$$C_s^{\text{BESpow}}\left(C_s^{\text{BESen}}\right) = C_s^{\text{BESpow,in}}\left(C_s^{\text{BESen,in}}\right) \cdot \frac{r \cdot (1+r)^{lf}}{(1+r)^{lf} - 1}$$

- FACTS uređaji – TCSC (engl. „Thyristor Controlled Series Capacitors"):

$$S^{\text{op,TCSC}} = X_C \frac{\left(S_l^{\max}\right)^2}{S_{\text{base}}}$$

$$X_C = sx_l^{\text{FACTS}} \cdot X_l$$

$$f^{\text{TCSC}} = 0.0015 \cdot \left(S^{\text{op,TCSC}}\right)^2 - 0.713 \cdot S^{\text{op,TCSC}} + 153.75 \quad (\$/kvar)$$

$$C^{\text{TCSC,in}} = f^{\text{TCSC}} \cdot S^{\text{op,TCSC}} \cdot 1000$$

$$C^{\text{TCSC}} = C^{\text{TCSC,in}} \cdot \frac{r \cdot (1+r)^{lf}}{(1+r)^{lf} - 1}$$

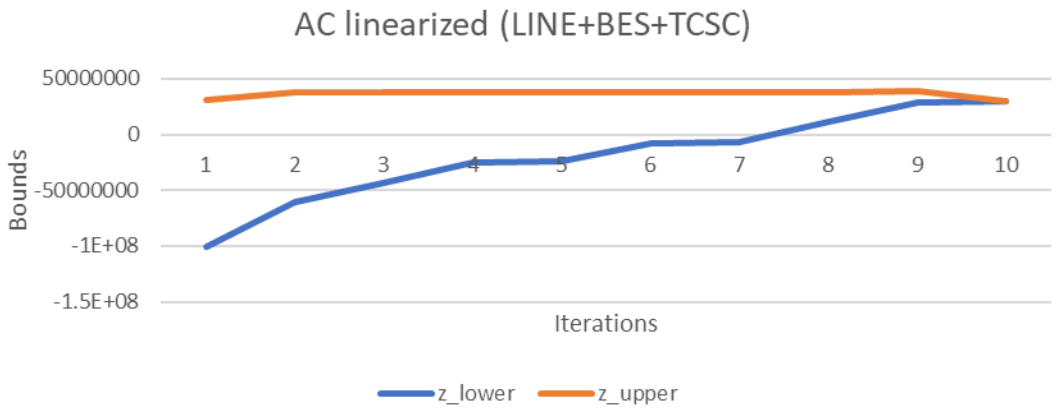
$$C_l^{\text{line}} = \$188{,}710/\text{year}$$
$$C_s^{\text{BESpow}} = \$80{,}240/\text{year}$$
$$C_s^{\text{BESen}} = \$3{,}209/\text{year}$$
$$C^{\text{TCSC}} = \$7{,}813{,}771/\text{year}$$

Rezultati

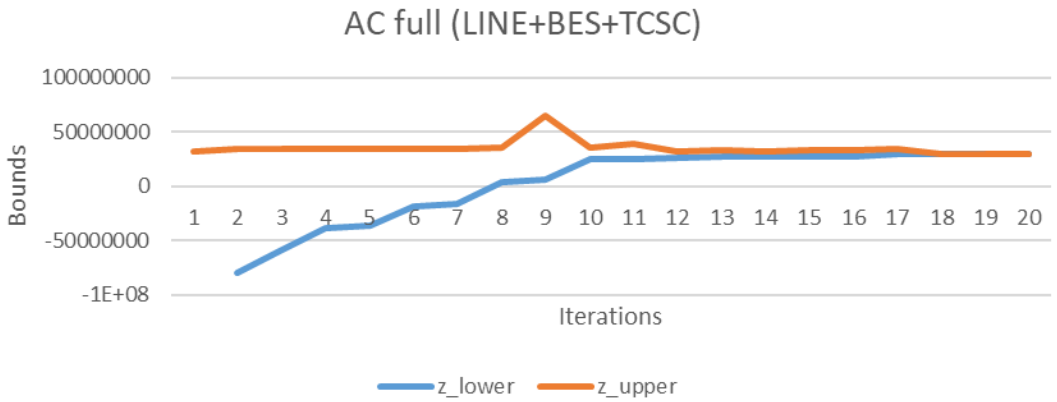
Bez investicije	TEP DC OPF	TEP AC OPF linearizirani	TEP AC OPF cjeloviti
OC konvencionalni generatori ($)	**18.047.800**	**19.686.643**	**20.750.630**
Odbačena energija vjetra (p.u.)	3.876	5.512	5.706
Radni gubici (p.u.)	0	1.137,80	1.580,60
Investment decisions **LINE+BES+TCSC**	**l5; σ=0,13**	**l4, l5, l6; σ=0,012**	**l4, l5, l6**
OC konvencionalni generatori ($)	**15.791.942** -12,4%	**17.655.448** -10,3%	**17.821.297** -14,1%
Odbačena energija vjetra (p.u.)	3.575	5.507	5.671
Radni gubici (p.u.)	0	1.000,70 -12.1%	918,40 -41.9%
Vrijeme (sec)	17,02	81,75	421,53

Iteracijski razvoj Benders algoritma

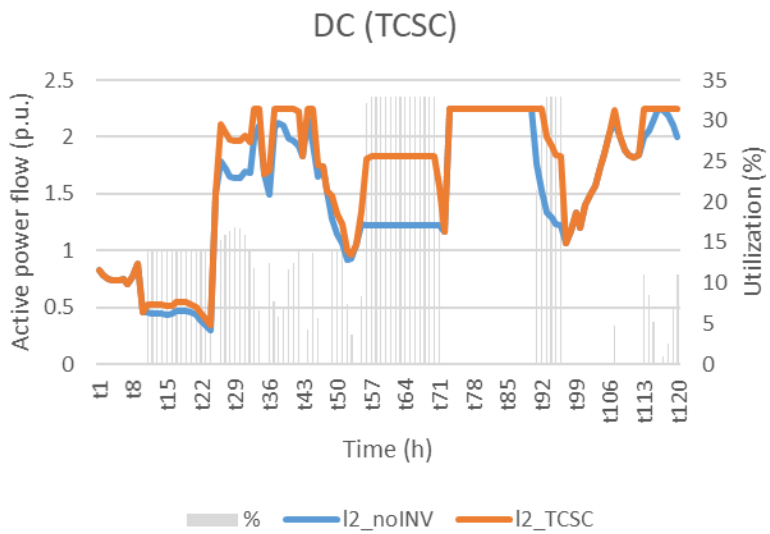
- TEP AC OPF linearizirani model: 10 iteracija; 81,75 sec



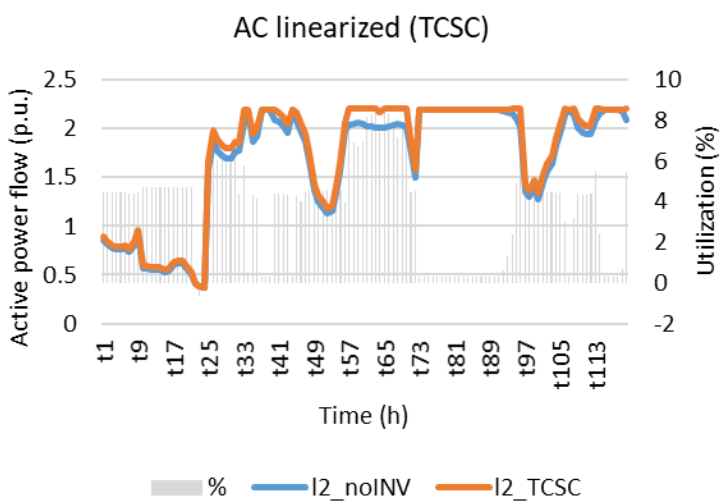
- TEP AC OPF cjeloviti model: 20 iteracija; 421,53 sec

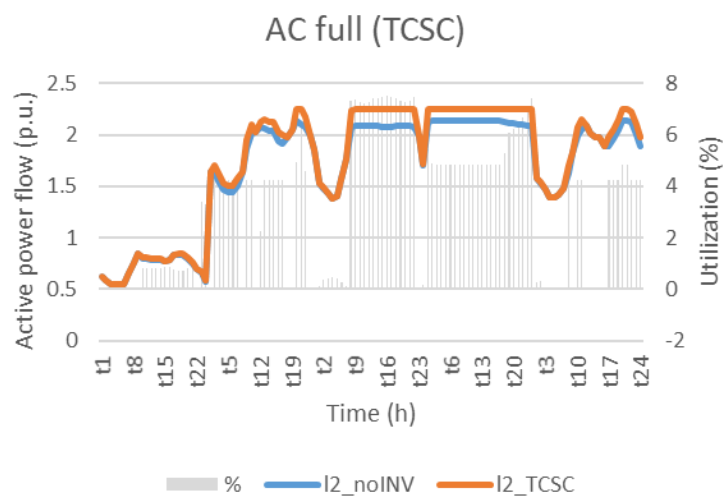


Iskorištenost vodova - TCSC



- Veća iskorištenost kod DC OPF modela, čak do 35%
- AC OPF modeli – do 9%





Zaključak

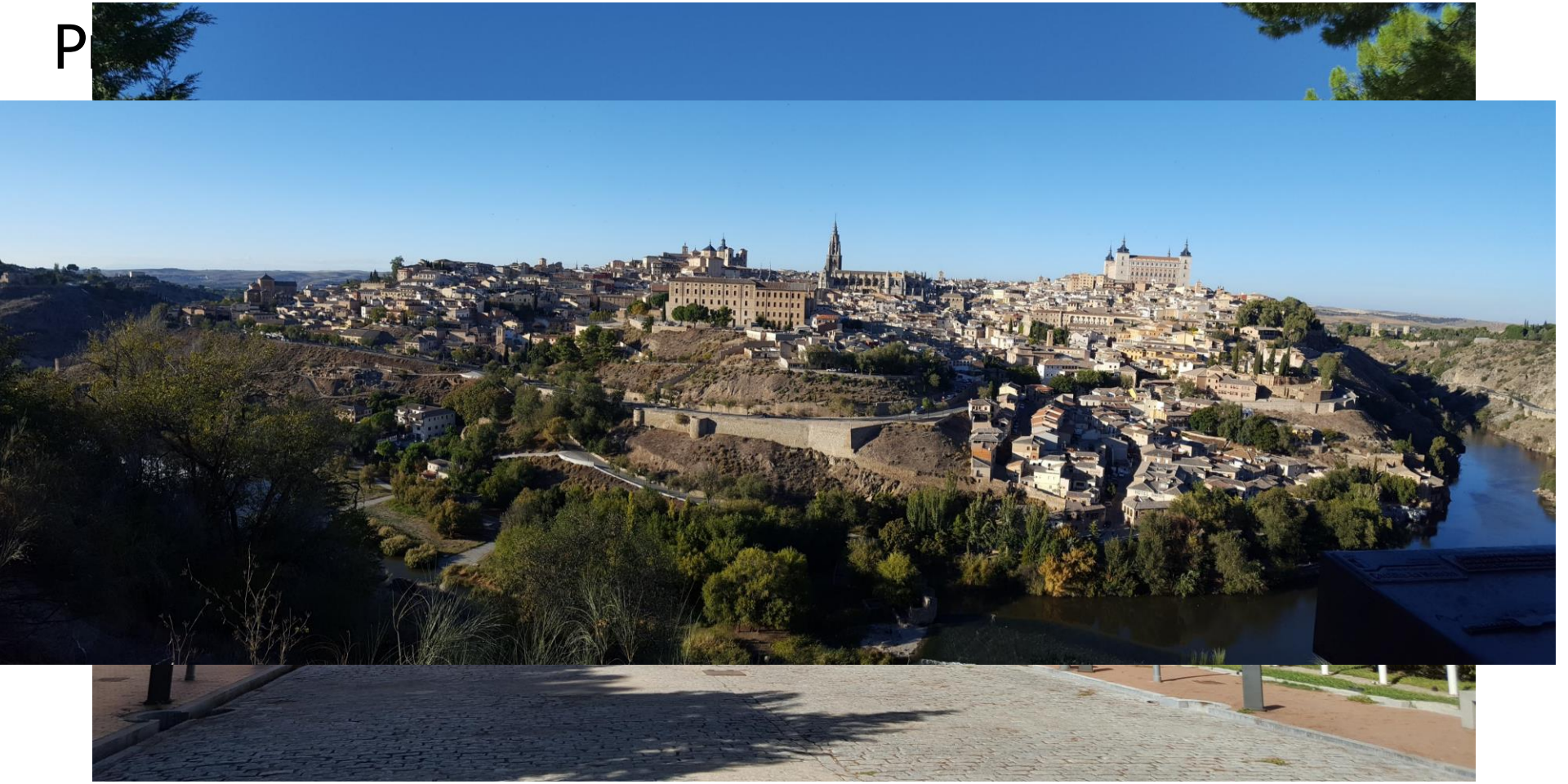
- Investicijski modeli u AC OPF zahtijevaju investicije u <u>dodatne vodove</u>
- Zbog većih troškova investicije – manje investicije u spremnike energije i TCSC
- TCSC povećava iskorištenost prijenosnog voda ovisno o stupnju kompenzacije
- Sljedeći koraci u istraživanju:
  1. Napraviti simulacije na velikom sustavu IEEE RTS 96 system koristeći TEP AC OPF linearizirani model
  2. Analiza osjetljivosti prema:
     a) Različitim faktorima investicijskih troškova BES i TCSC
     b) Različitim faktorima osjetljivosti izgradnje novih vodova

Zahvala

School of Industrial Engineering of Toledo,

University of Castilla-La Mancha

P



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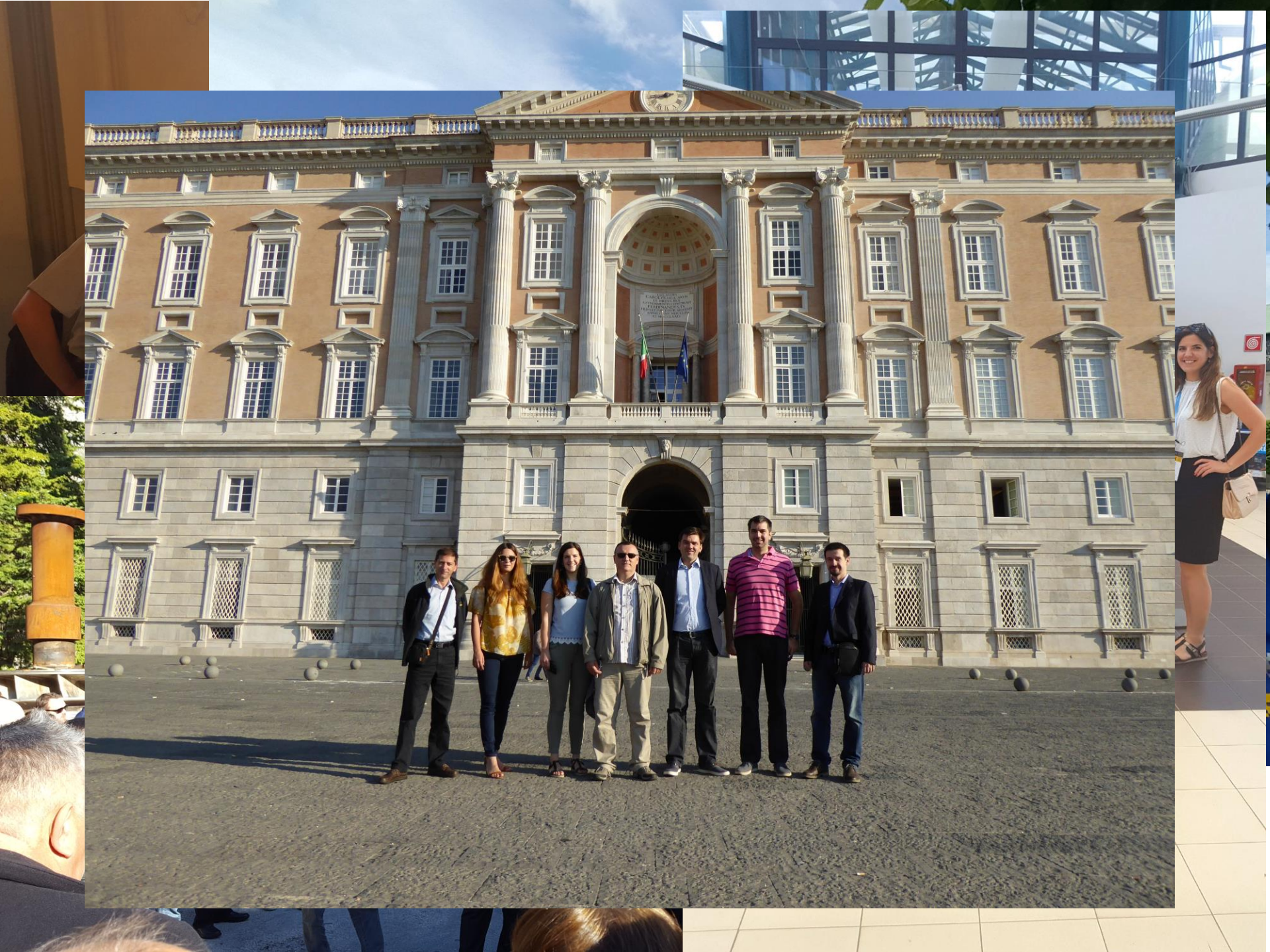

Zahvala

Hvala na pažnji!

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