Stability-constrained Optimal Power Flows and Applications to Electricity Markets

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Outline

- Motivation.
- OPF problems in electricity markets:
  - Security-constrained optimal power flows (SC-OPF).
  - SC-OPF energy market clearing and dispatch models:
    - AC SC-OPF model.
    - DC SC-OPF multi-period model
- Stability-Constrained OPFs:
  - Multi-objective voltage-stability-constrained (VSC) OPF.
  - Minimum singular value (MSV) VSC-OPF.
  - NN Security Boundary Constrained OPF.
- Conclusions.
- List of relevant publications.

Motivation

- Optimal Power Flow (OPF) problem:
  - Obtain daily/hourly/minute generation schedules to minimize costs and losses subject to network constraints and limits (e.g. power flows, reactive power and voltage limits).
  - Linear (LP) and Nonlinear programming (NLP) problem, depending on the modeling of the constraints and limits.

Motivation

- OPF applications to electricity markets :
  - Dispatch generation and loads to maximize "social benefit" or "social welfare"), i.e. minimize the difference between demand and supply bids.
  - In most markets, nodal-prices of electricity are also obtained from the optimization process.
- OPF problems have been successfully solved using a variety of well-known optimization techniques for large systems (e.g. Interior Point methods).

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Motivations

- Deregulation/privatization of electricity markets has increased the need for minimizing prices while meeting system security constraints.
- New SC-OPF problems are needed to address electricity market issues:
  - Objective is to produce secure and “cheaper” generation/load schedules.
  - Some “security” constraints should be replaced by constraints that better reflect system security.

SC-OPF

- "Classical" NLP SC-OPF problem:

$$
\begin{aligned}
\text{Min.} \quad & \sum_{i=1}^{N_G} a_i P_{G_i}^2 + b_i P_{G_i} + c_i \\
\text{s.t.} \quad & F_{PF}(\delta, V, Q_G, P_G) = 0 \\
& P_{G_{\text{min}}} \le P_G \le P_{G_{\text{max}}} \\
& P_T(\delta, V) \le P_{T_{\text{max}}} \\
& I_T(\delta, V) \le I_{T_{\text{max}}} \\
& Q_{G_{\text{min}}} \le Q_G \le Q_{G_{\text{max}}} \\
& V_{\text{min}} \le V \le V_{\text{max}}
\end{aligned}
$$

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SC-OPF

where the nonlinear power flow equations $F_{PF}(\delta, V, Q_G, P_G)$ have the general form (2 equations per bus $i = 1, \ldots, N$):

$$
\begin{aligned}
P_i - \sum_{k=1}^{N} V_i V_k [G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)] &= 0 \\
Q_i - \sum_{k=1}^{N} V_i V_k [G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k)] &= 0
\end{aligned}
$$

$$
P_i = \begin{cases} P_{G_i} & \forall i \in \text{generators} \\ -P_{L_i} & \forall i \in \text{loads} \end{cases}
$$

$$
Q_i = \begin{cases} Q_{G_i} & \forall i \in \text{generators} \\ -Q_{L_i} & \forall i \in \text{loads} \end{cases}
$$

$$
G_{ik}, B_{ik}, P_{L_i}, Q_{L_i} \rightarrow \text{constants}
$$

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SC-OPF

- The objective is to minimize generation costs.
- Grid “security” is represented in this model by:
  - Line power flows P_T , typically computed off-line using an N-1 contingency security criterion.
  - Current thermal limits I_T.
  - Bus voltage limits V.
- These types of problems have been solved successfully for large networks (thousands of constraints) using Interior Point methods.

SC-OPF

- In electricity markets, the “typical” NLP SC-OPF model of a double auction market is:

$$
\begin{aligned}
\text{Max.} \quad & S_b = C_d^T P_d - C_s^T P_s \\
\text{s.t.} \quad & F_{PF}(\delta, V, Q_G, P_s, P_d) = 0 \\
& 0 \le P_s \le P_{s_{\max}} \\
& 0 \le P_d \le P_{d_{\max}} \\
& P_T(\delta, V) \le P_{T_{\max}} \\
& I_T(\delta, V) \le I_{T_{\max}} \\
& Q_{G_{\min}} \le Q_G \le Q_{G_{\max}} \\
& V_{\min} \le V \le V_{\max}
\end{aligned}
$$

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SC-OPF

where $F_{PF}(\delta, V, Q_G, P_s, P_d)$ have the general form:

$$
\begin{aligned}
P_i - \sum_{k=1}^{N} V_i V_k [G_{ik}\cos(\delta_i - \delta_k) + B_{ik}\sin(\delta_i - \delta_k)] &= 0 \\
Q_i - \sum_{k=1}^{N} V_i V_k [G_{ik}\sin(\delta_i - \delta_k) - B_{ik}\cos(\delta_i - \delta_k)] &= 0 \\
P_i &= \begin{cases} P_{Go_i} + P_{s_i} & \forall i \in \text{generators} \\ -P_{Lo_i} - P_{d_i} & \forall i \in \text{loads} \end{cases} \\
Q_i &= \begin{cases} Q_{G_i} & \forall i \in \text{generators} \\ -Q_{L_i} & \forall i \in \text{loads} \end{cases}
\end{aligned}
$$

$$G_{ik}, B_{ik}, P_{Go_i}, P_{Lo_i}, Q_{L_i} \rightarrow \text{constants}$$

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SC-OPF

- This market model is basically an NLP SC-OPF that maximizes social benefit S_b, i.e. the difference between demand and supply bids.
- Nodal energy prices or LMPs are a byproduct of this optimization problem (the Lagrange multipliers of the active power components of F_{PF}).
- It is no widely used by utilities yet, but some utilities (e.g PJM) are using them for settlement purposes (e.g. determine Locational Marginal Prices or LMPs).
- In practice, market models based on LP models are more commonly used by system operators.

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SC-OPF

- For example, the following multi-period LP model may be used to clear these market (e.g. Ontario):

$$
\begin{aligned}
\text{Max.}\quad & S_b = \sum_{t=1}^{N} C_{d_t}^T P_{d_t} - C_{s_t}^T P_{s_t} \\
\text{s.t.}\quad & P_{d_{i_t}} - P_{s_{i_t}} - \sum_{j=1, j \neq i}^{n} P_{loss_{ij_t}} - \sum_{j=1, j \neq i}^{n} P_{ij_t} = 0 \quad \forall i, t \\
& P_{ij_t} - b_{ij}(\delta_{i_t} - \delta_{j_t}) = 0 \quad \forall i, j, i \neq j, t \\
& P_{T_t} = [P_{ij_t}] \leq P_{T_t \max} \quad \forall t \\
& 0 \leq P_{s_t} \leq P_{s_t \max} \quad \forall t \\
& 0 \leq P_{d_t} \leq P_{d_t \max} \quad \forall t \\
& P_{s_t} - P_{s_{t+1}} \leq Rd_{s_t} \quad \forall t \\
& P_{s_{t+1}} - P_{s_t} \leq Ru_{s_t} \quad \forall t
\end{aligned}
$$

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SC-OPF

where Rd and Ru represent the ramp-down and ramp-up constraints of the generators, respectively.

- Other temporal constraints are typically included in these types of models (e.g. operating reserves in Ontario).
- Power transfer limits are obtained off-line by means of ATC computations, considering thermal, voltage and stability limits.

SC-OPF

- Ontario market example:
  - Multi-period optimization with N = 5.
  - Solved every 5 min., for 3000+ buses and about 300 market participants.
  - Reserve bids are also considered: 10 spinning, 10 min. non-spinning, and 30 min.
  - Unconstrained solution defines uniform MCPs.

SC-OPF

- Power-flow-based contingency analyses are used to check if unconstrained solution violate limits and to “dispatch” reactive power (set generator bus voltages).
- If security violations are encountered, “sensitivities” are used to add constraints to the OPF model and procedure is repeated until no violations are encountered.
- Final constrained solution defines “uplift” prices to be added to the MCP, and are used to determine the Congestion Management Settlement Credit (CMSC) payments.

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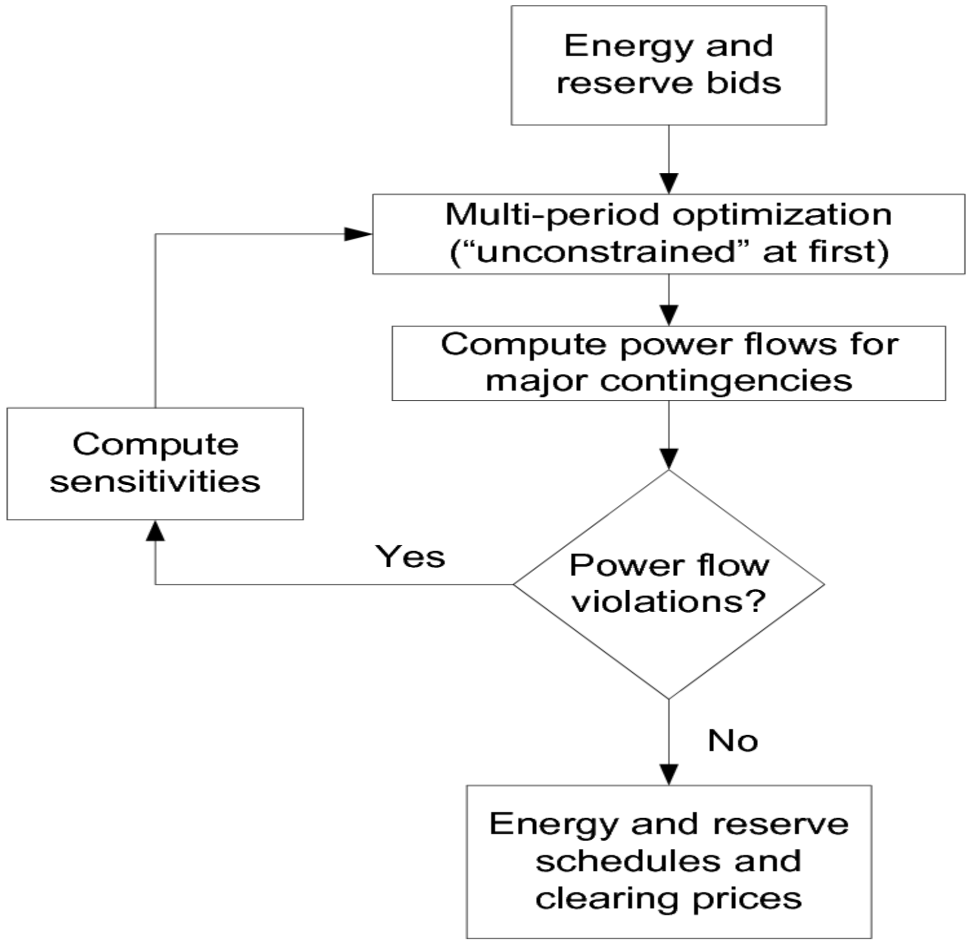
SC-OPF



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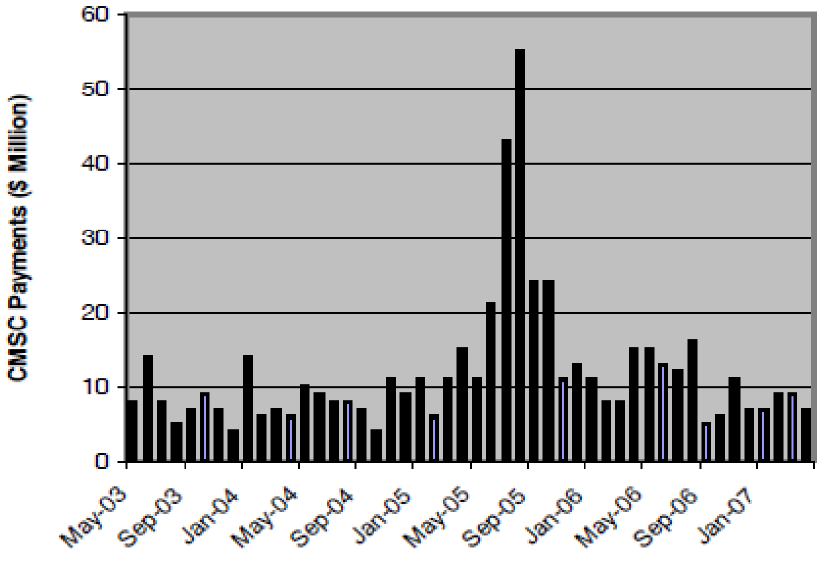
SC-OPF

- In Ontario, total CMSC payments made by the IESO over the period May 2003-April 2007 averaged $11.77 million/ month (H. Ghasemi and A. Maria, “Benefits of Employing an On-line Security Limit Derivation Tool in Electricity Markets,” in *Proc. IEEE-PES General Meeting, July 2008)*:



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SC-OPF

- The line power flow limits vary with the solution of the auction; thus, fixed limits are not representative of system conditions, negatively affecting prices and system security.
- This has led to the development of stability constrained OPF models.

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Multi-objective VSC-OPF

- The objective is to maximize both social benefit and system “loadability”, i.e. voltage stability margins (VSM):

$$
\begin{array}{ll}
\text{Max.} & (1-w)\underbrace{(C_d^T P_d - C_s^T P_s)}_{S_b} + w\lambda_c \\
\text{s.t.} & F_{PF}(\delta, V, Q_G, P_s, P_d) = 0 \\
& F_{PF_c}(\delta_c, V_c, Q_{Gc}, P_s, P_d, \lambda_c) = 0 \\
& 0 \le P_s \le P_{s\text{max}} \\
& 0 \le P_d \le P_{d\text{max}} \\
& \lambda_{c\text{min}} \le \lambda_c \le \lambda_{c\text{max}} \\
& I_T(\delta, V) \le I_{T\text{max}} \\
& Q_{G\text{min}} \le Q_G \le Q_{G\text{max}} \\
& V_{\text{min}} \le V \le V_{\text{max}} \\
& I_{T_c}(\delta_c, V_c) \le I_{T_c\text{max}} \\
& Q_{Gc\text{min}} \le Q_{Gc} \le Q_{Gc\text{max}} \\
& V_{c\text{min}} \le V_c \le V_{c\text{max}}
\end{array}
$$

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Multi-objective VSC-OPF

where λ_c represents the VSM, and all *c* constraints correspond to the system at its "critical" point (max. VSM).

- By varying the weight *w* ($0 < w < 1$), more or less stress can be put on security.
- In practice, *w* should be very small to avoid "undesirable" effects on the market power levels and prices.
- Problems with this technique:
  - Number of constraints are doubled.
  - LPMs are not directly a by-product of this model, given the objective function definition which mixes system costs with security.
  - No consideration for system dynamics.

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MSV VSC-OPF

- The objective again is to maximize social benefit while guaranteeing a min. VSM:

$$
\begin{aligned}
\text{Max.} \quad & S_b = C_d^T P_d - C_s^T P_s \\
\text{s.t.} \quad & F_{PF}(\underbrace{\delta, V, Q_G, P_s, P_d}_{z,p}) = 0 \\
& \sigma_{min}(\underbrace{D_z F_{PF}|_o}_{J_{PF}}) \geq \ \sigma_c \\
& 0 \leq P_s \leq P_{s_{\max}} \\
& 0 \leq P_d \leq P_{d_{\max}} \\
& I_T(\delta, V) \leq I_{T_{\max}} \\
& Q_{G_{\min}} \leq Q_G \leq Q_{G_{\max}} \\
& V_{\min} \leq V \leq V_{\max}
\end{aligned}
$$

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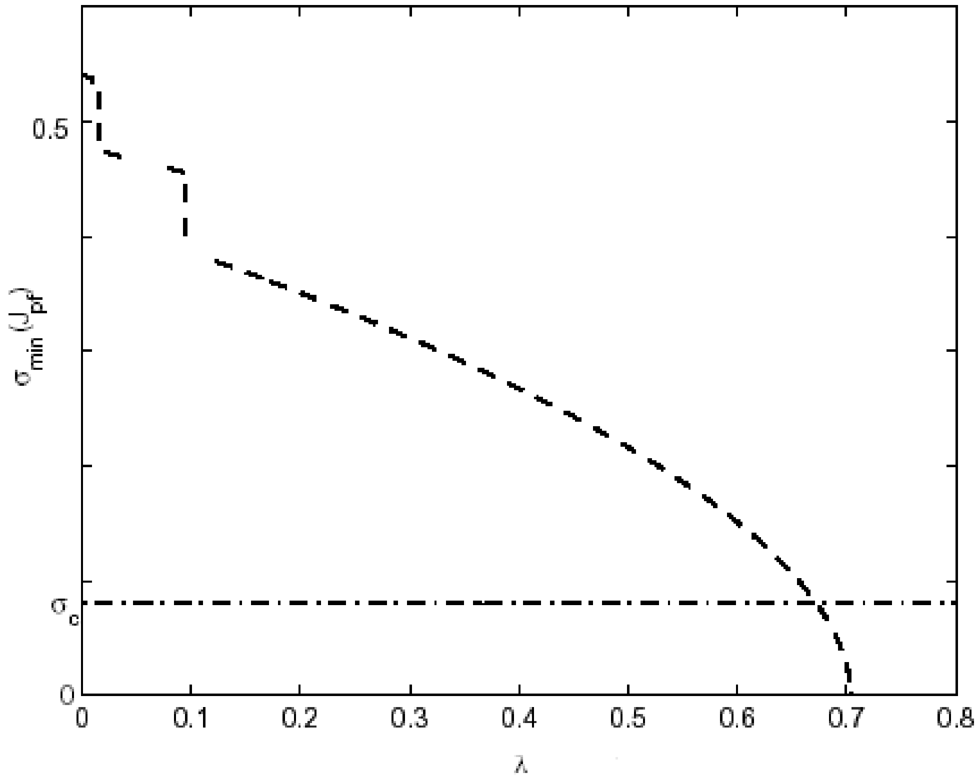
MSV VSC-OPF

- where $\sigma_{min}(J_{PF})$ is a VS index that becomes zero at a singularity point of the power flow Jacobian:



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MSV VSC-OPF

- This is an NLP problem with an implicit constraint solved as follows:

$$
\begin{aligned}
\text{Min.} \quad & S(\chi) \\
\text{s.t.} \quad & F(\chi) = 0 \\
& \underline{H} \le H(\chi) \le \overline{H} \\
& \underline{\chi} \le \chi \le \overline{\chi}
\end{aligned}
$$

  - Interior point solution approach:

$$
\begin{aligned}
\text{Min.} \quad & S(\chi) - \mu_s \sum_i (\ln s_i + \ln q_i) \\
\text{s.t.} \quad & F(\chi) = 0 \\
& -s - q + \overline{H} - \underline{H} = 0 \\
& -H(\chi) - q + \overline{H} = 0 \\
& s \ge 0, \quad q \ge 0
\end{aligned}
$$

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MSV VSC-OPF

– Lagrange-Newton method:

$$
\begin{aligned}
L_\mu(u) &= S(\chi) - \mu_s \sum_i (\ln s_i + \ln q_i) - \rho^T F(\chi) \\
&\quad -\varsigma^T(-s - q + \overline{H} - \underline{H}) - \tau^T(-H(\chi) - q + \overline{H})
\end{aligned}
$$

$$
\Rightarrow \qquad \nabla_u L_\mu(u) = 0
$$

– The solution procedure requires finding the Hessian:

$$
\nabla^2_\chi L_\mu(u) = \nabla^2_\chi S(\chi) - \rho^T \nabla^2_\chi F(\chi) + \tau^T \nabla^2_\chi H(\chi)
$$

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MSV VSC-OPF

– Since $H(\chi)$ has an implicit constraint, to obtain $\nabla^2_\chi H(\chi)$:

$$\left.\frac{\partial^2\sigma_{min}(J_{PF})}{\partial\chi_i\chi_j}\right|_{\chi_*+\Delta\chi} \approx \frac{\left.\frac{\partial\sigma_{min}(J_{PF})}{\partial\chi_i}\right|_{\chi_*} - \left.\frac{\partial\sigma_{min}(J_{PF})}{\partial\chi_i}\right|_{\chi_*+\Delta\chi}}{\Delta\chi_j}$$

based on approximations that are obtained from the properties of the singular value:

$$\Delta\sigma_{min}(J_{PF}) \ \approx \ U_1^T \, D_z^2 F_{PF}|_* \, \Delta z \, V_1$$

$$\Delta\sigma_{min}(J_{PF}) \ \approx \ -U_1^T \, D_z^2 F_{PF}|_* \, D_z F_{PF}|_*^{-1} \, D_p F_{PF}|_* \, \Delta p \, V_1$$

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MSV VSC-OPF

- Some system dynamics (oscillatory stability) can be represented in the VSC-OPF problem by replacing the MSV $\sigma_{min}(J_{PF})$ constraint with the singular value of a dynamic Jacobian.
- Problems with this model:
  - Proposed handling of implicit constraint yields approximate solutions.
  - High computational costs.

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MSV VSC-OPF

- Replacing the implicit MSV constraint with an explicit representation based on singular value decomposition (SVD):

$$
\begin{aligned}
\text{Max.} \quad & S_b = C_d^T P_d - C_s^T P_s \\
\text{s.t.} \quad & F_{PF}(\delta, V, Q_G, P_s, P_d) = 0 \\
& u_n^T \, J_{PF}(\delta, V) \, w_n \geq \ \sigma_c \\
& 0 \leq P_s \leq P_{s_{\text{max}}} \\
& 0 \leq P_d \leq P_{d_{\text{max}}} \\
& I_T(\delta, V) \leq I_{T_{\text{max}}} \\
& Q_{G_{\text{min}}} \leq Q_G \leq Q_{G_{\text{max}}} \\
& V_{\text{min}} \leq V \leq V_{\text{max}}
\end{aligned}
$$

MSV VSC-OPF

- J_{PF} is an “invariant” sub-Jacobian of $D_z F_{PF}$.
- Solution is iterative:

Algorithm: Solution of the VSC-OPF using a SVD

begin
  $\sigma_c \leftarrow$ Off-line VS study
  $k \leftarrow 1$
  $(\delta^*, V_L^*, V_G^*) \leftarrow$ VSC-OPF (“relaxed”)
  $(u_n, \sigma_n, w_n) \leftarrow \text{SVD}(J_{PF}|_*)$
  if $\sigma_n \geq \sigma_c$ **then**
    end
  else
    repeat
      $k \leftarrow k + 1$
      $(\delta^*, V_L^*, V_G^*) \leftarrow$ VSC-OPF
      $(u_n, \sigma_n, w_n)^{(k)} \leftarrow \text{SVD}(J_{PF}|_*)$
    until $\sigma_n^{(k)} \geq \sigma_c$
  end
  $(\delta^*, V_L^*, Q_G^*, V_G^*, P_S^*, P_D^*) \rightarrow$ Optimum
end

MSV VSC-OPF

- Observations:
  - Relatively easy to implement.
  - Faster to solve and more robust.
  - MSV constraint is properly enforced as opposed to previous solution method.
  - It requires an iterative solution process, where appropriate (u_n, w_n) are calculated at each iteration k ($k \leq 3$ for all the test cases studied).
- In principle, oscillatory stability limits could be accounted for in the MSV security constraint using a dynamic Jacobian, but not other dynamic phenomena.

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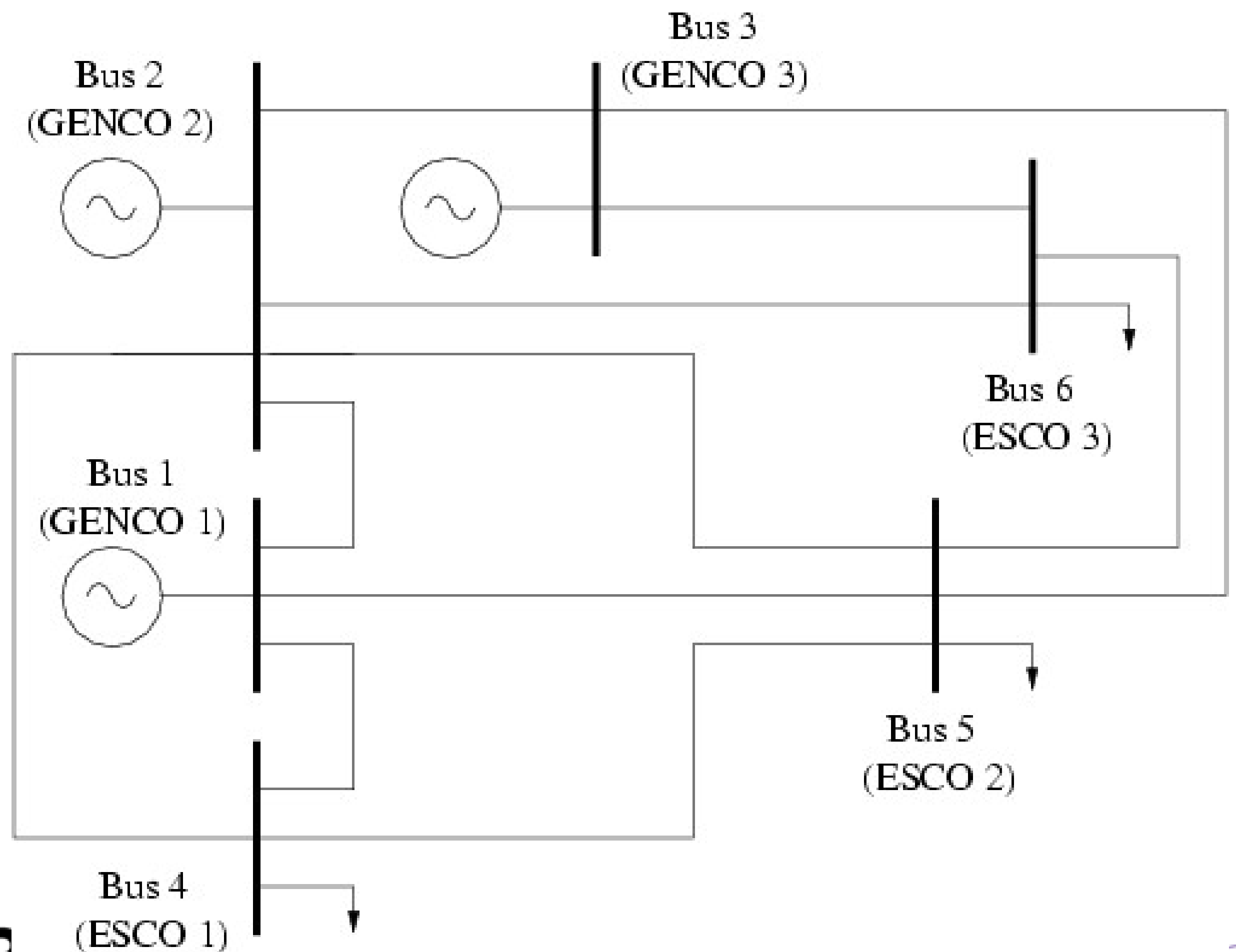
VSC-OPF Example



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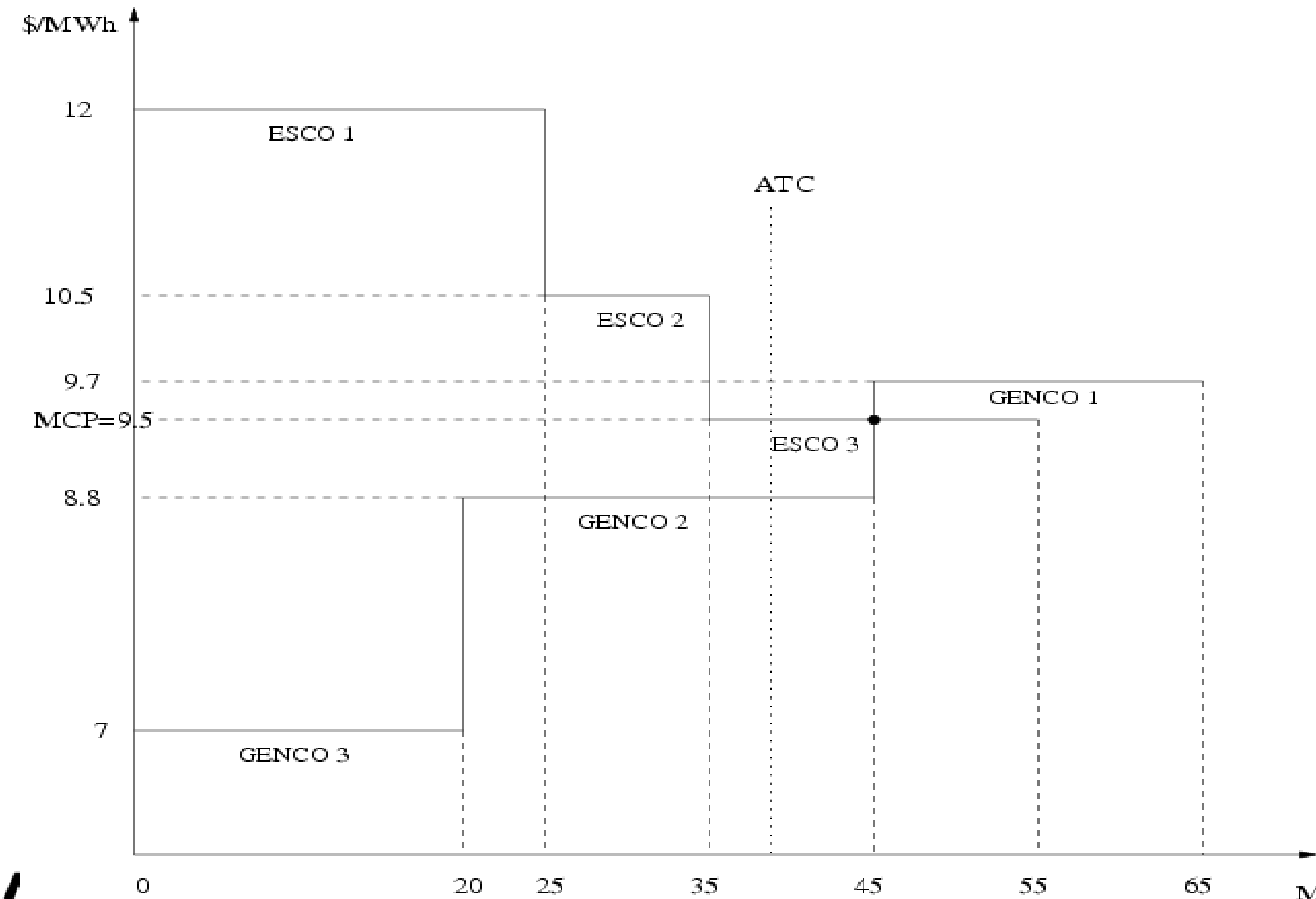
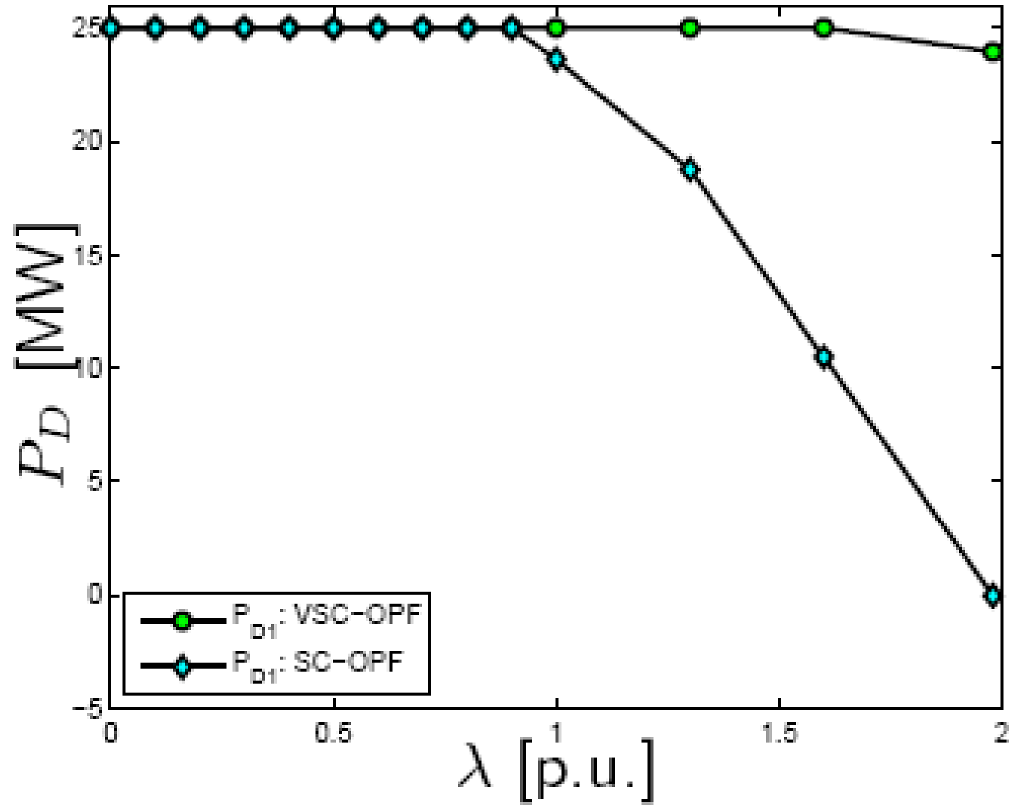
VSC-OPF Example



VSC-OPF Example

- ESCO 1 power as loading (represented by the loading factor λ) increases:



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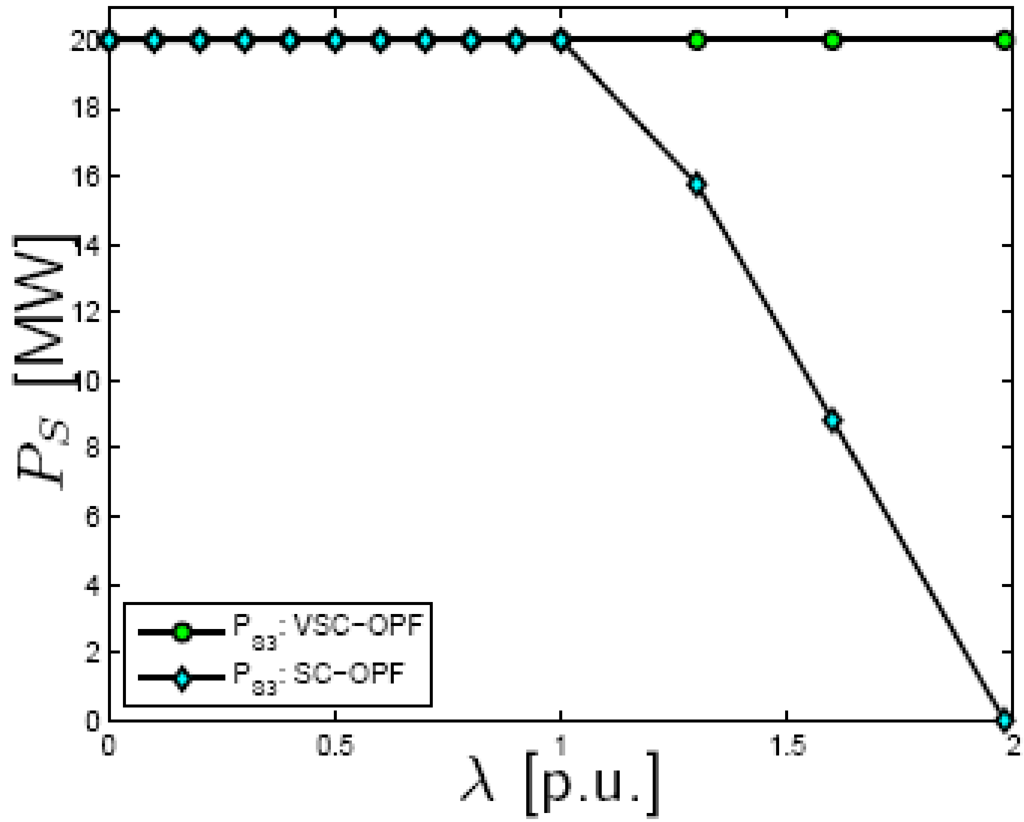
VSC-OPF Example

- GENCO 3 power as loading increases:



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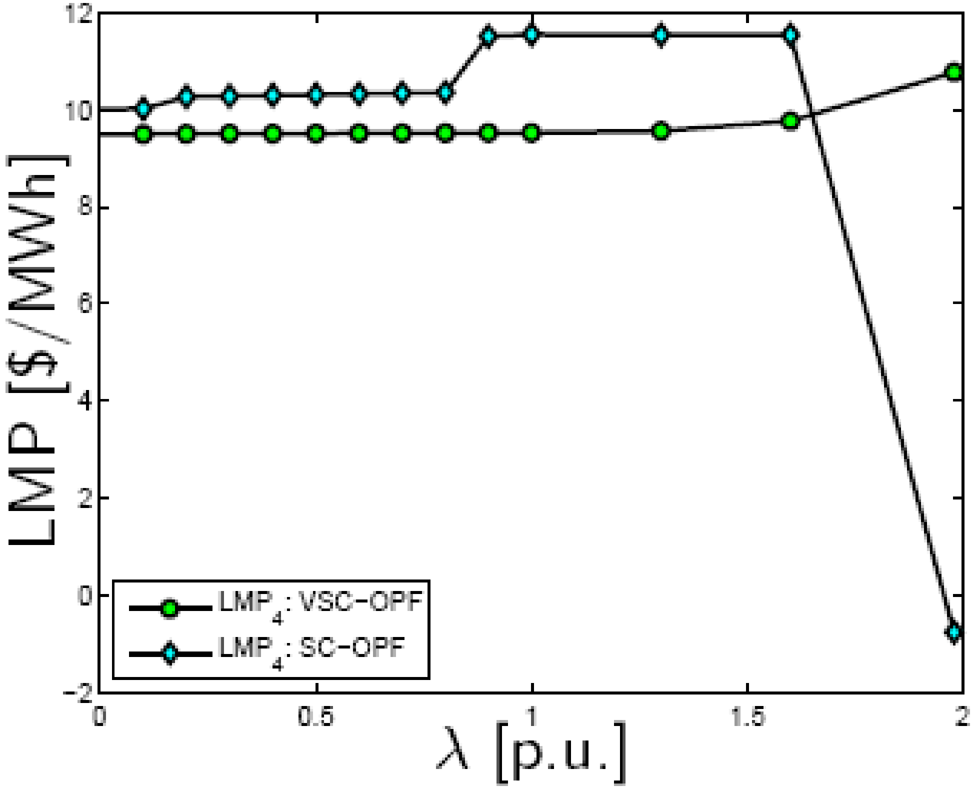
VSC-OPF Example

- LMP at Bus 4 as loading increases:



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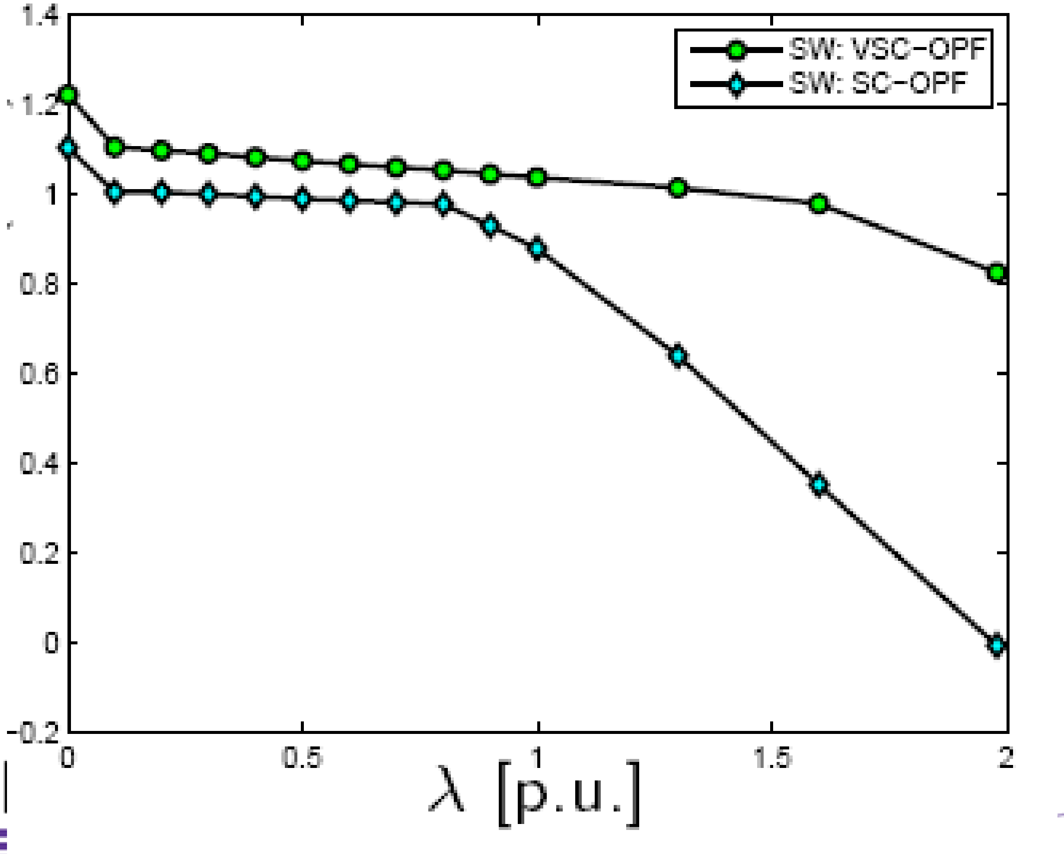
VSC-OPF Example

- Social benefit S_b as loading increases:



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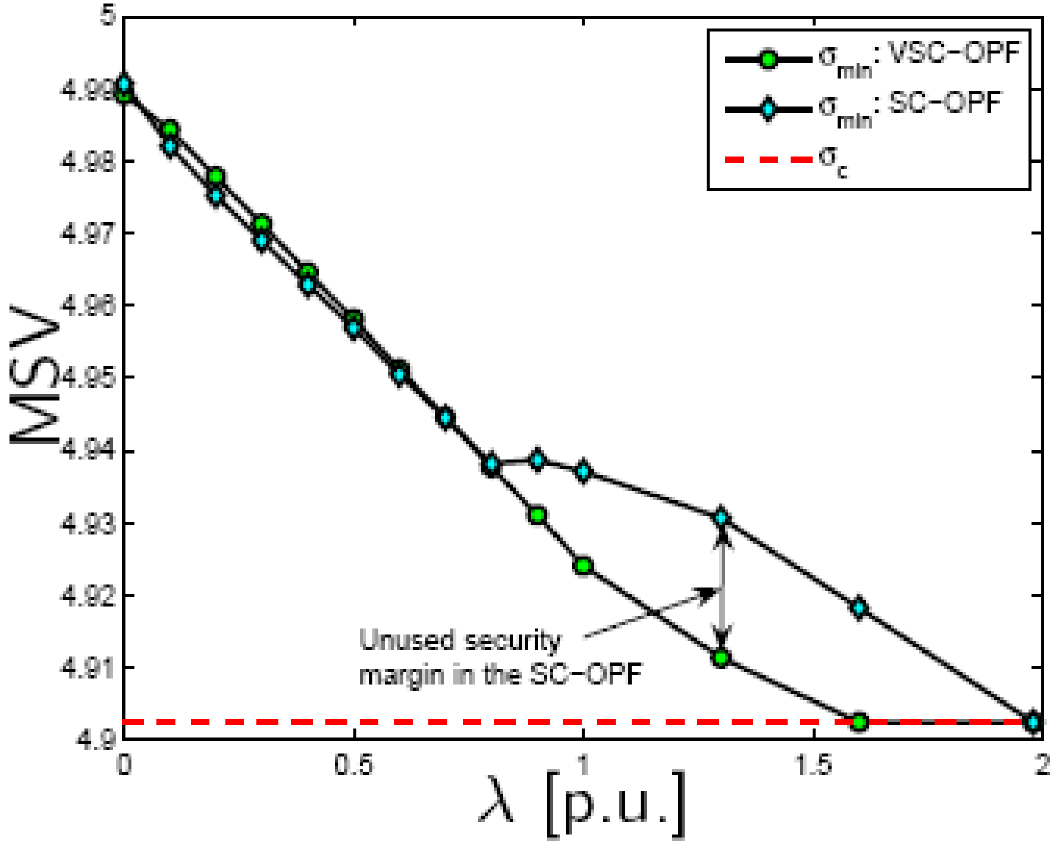
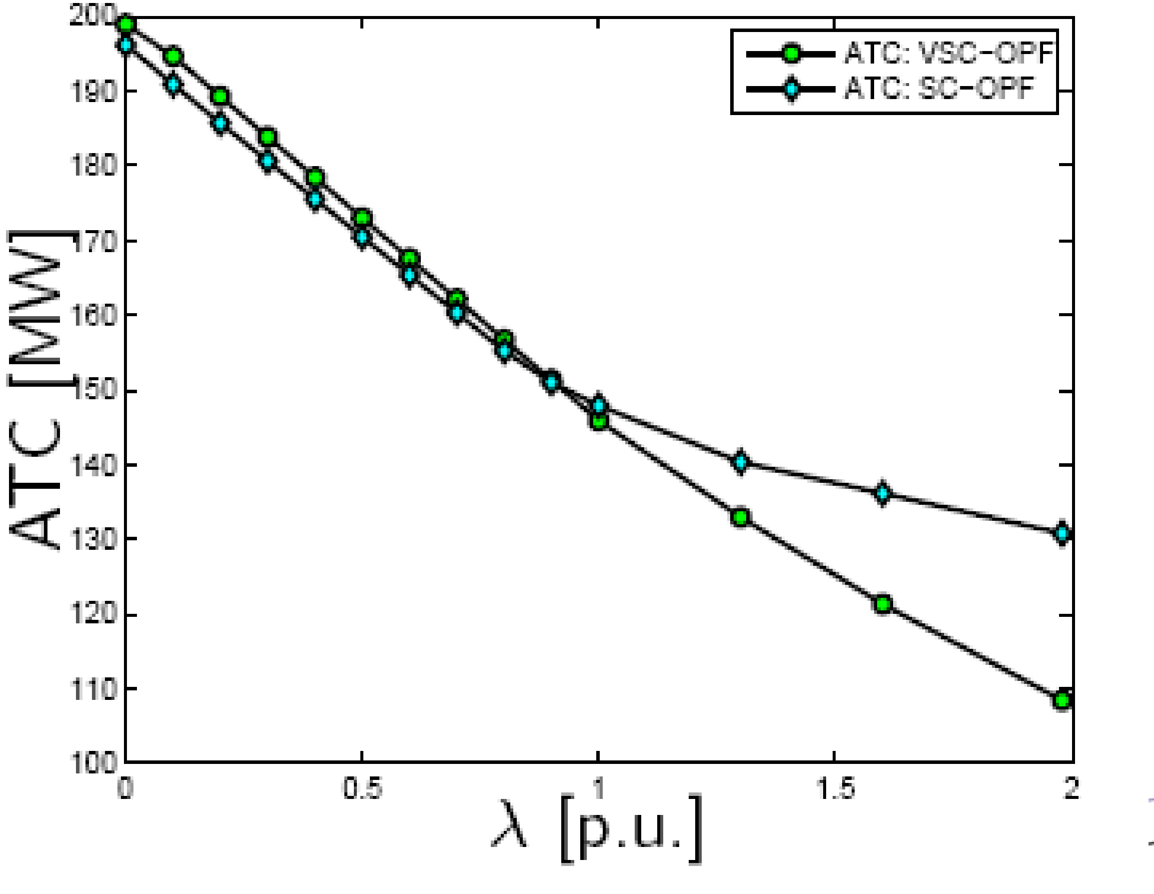
VSC-OPF Example

- MSV as loading increases:



VSC-OPF Example

- ATC as loading increases:



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VSC-OPF Example

- Better operating conditions:
  - Higher voltages.
  - Lower losses.
  - Higher VSM.
- Better market conditions:
  - Lower nodal-prices.
  - Higher transaction levels.

NN SBC-OPF

- In this model, the security constraint is represented in this case by a NN-based security boundary:

$$
\begin{aligned}
\text{Max.} \quad & S_b = C_d^T P_d - C_s^T P_s \\
\text{s.t.} \quad & F_{PF}(\delta, V, Q_G, P_s, P_d) = 0 \\
& F_{NN}(P_s, P_d) \geq c \\
& 0 \leq P_s \leq P_{s\text{max}} \\
& 0 \leq P_d \leq P_{d\text{max}} \\
& I_T(\delta, V) \leq I_{T\text{max}} \\
& Q_{G\text{min}} \leq Q_G \leq Q_{G\text{max}} \\
& V_{\text{min}} \leq V \leq V_{\text{max}}
\end{aligned}
$$

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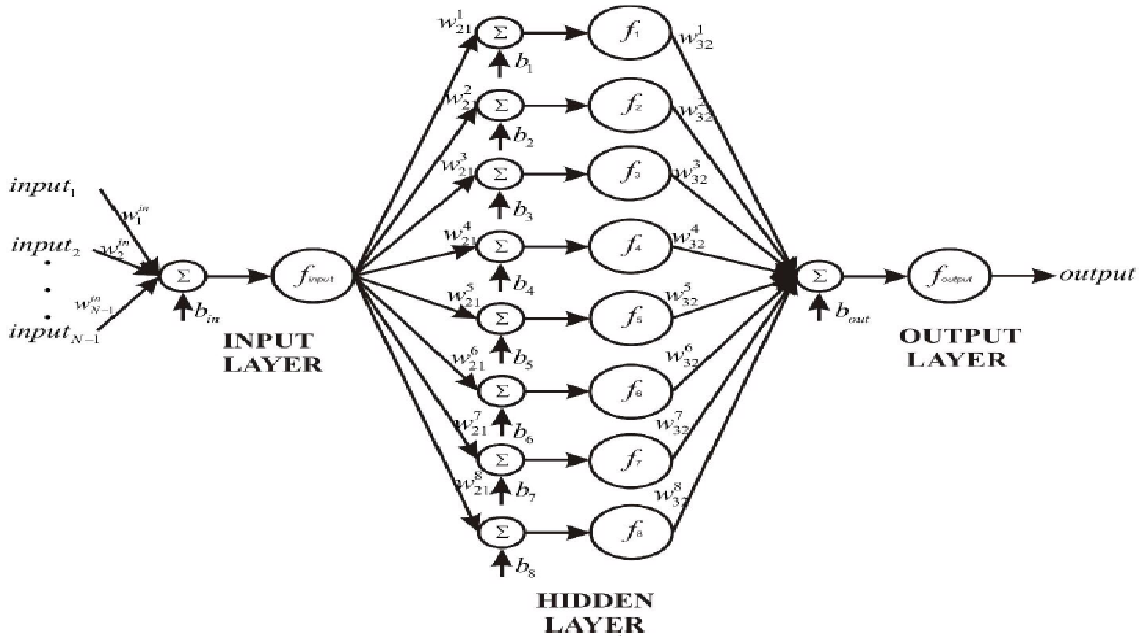
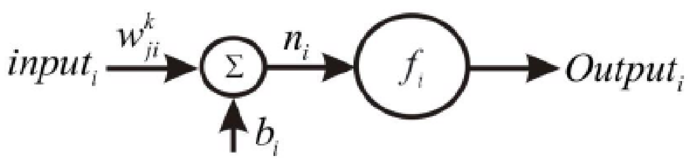
NN SBC-OPF

- The NN SB is obtained using a BPNN:



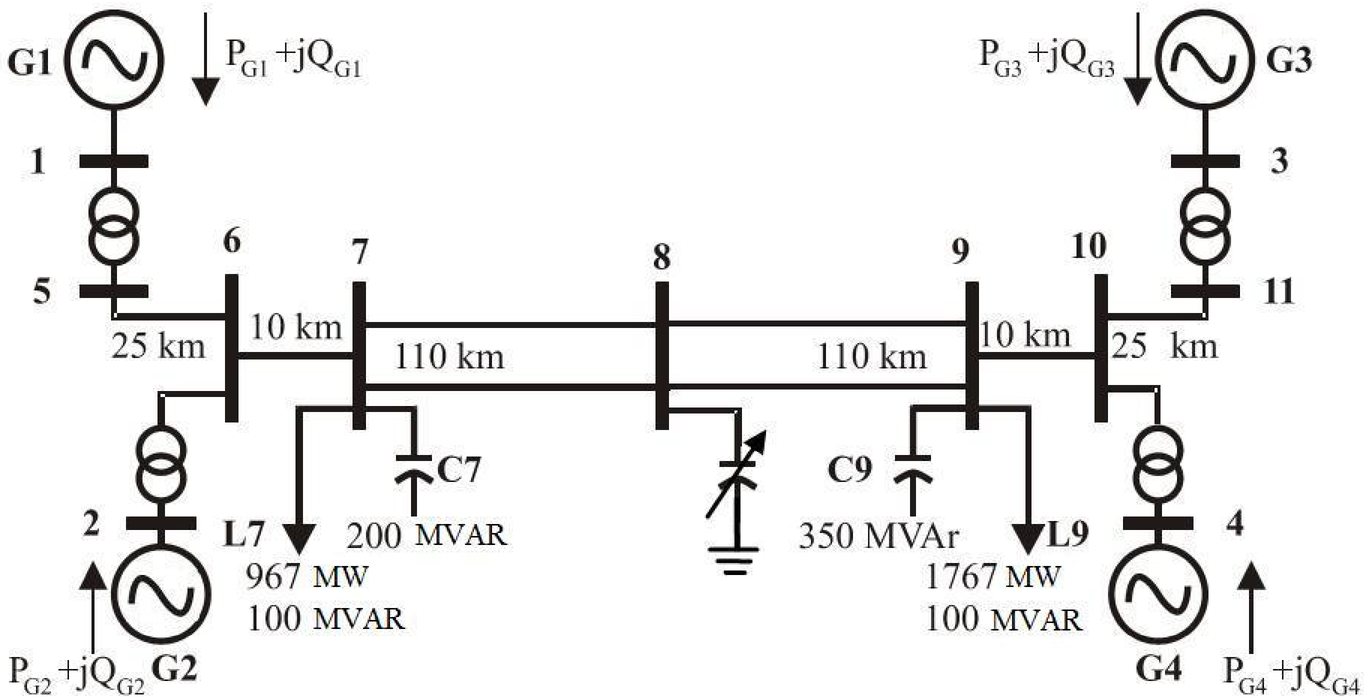


$$Output_i = f_i\left(input_i\, w_{ji}^k + b_i\right) = f_i\left(n_i\right)$$

$$f_i(n_i) = \frac{2}{1 + 2^{-2n_i}} - 1$$

NN SBC-OPF

- Example of an NN security and stability boundary for a 2 area system with respect to load increases in both areas:



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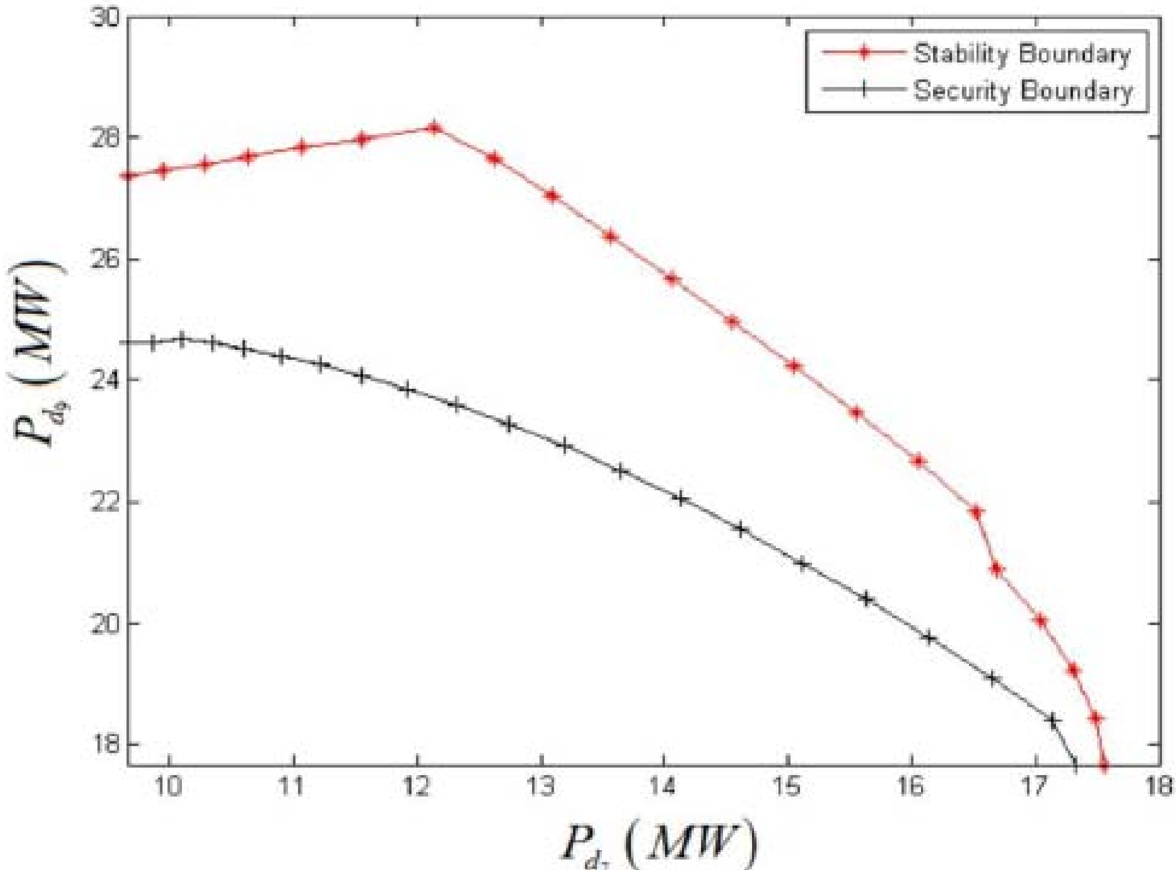
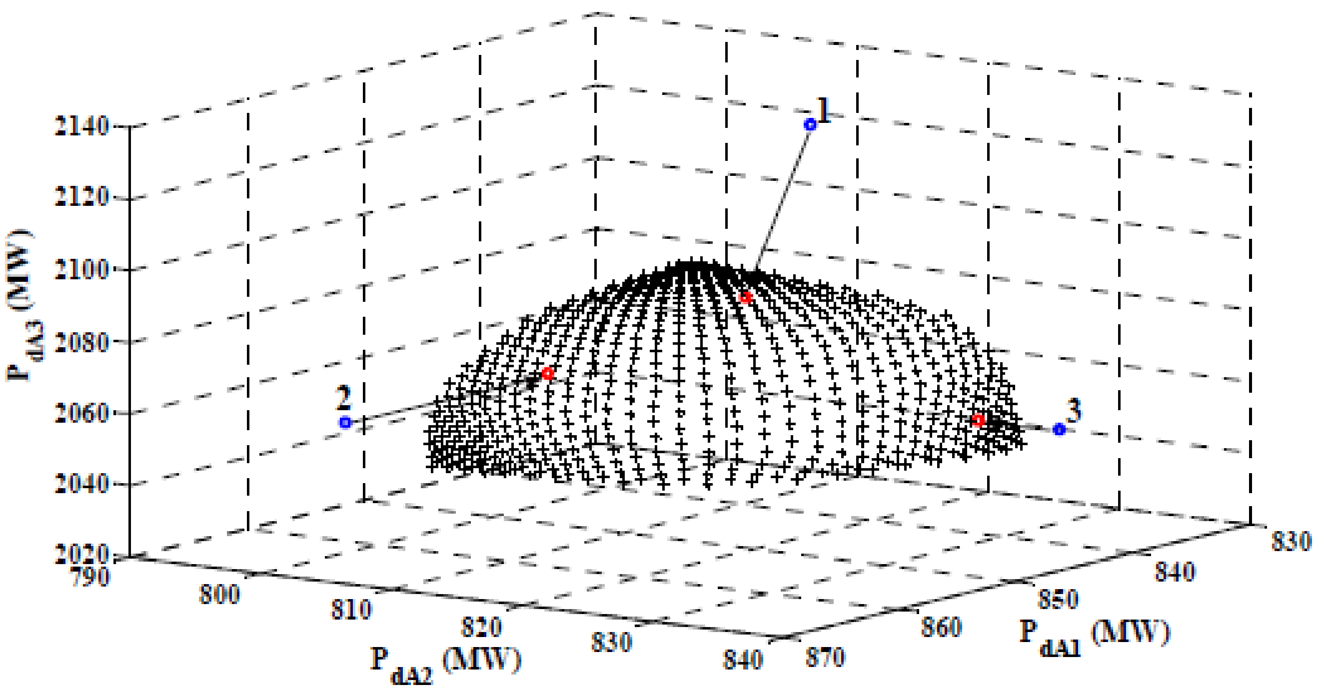


Stability Boundary
Security Boundary
$P_{d_9}\ (MW)$
$P_{d_7}\ (MW)$
30
28
26
24
22
20
18
10
11
12
13
14
15
16
17
18

NN SBC-OPF

- Example of an NN security boundary for a 3 area system (118-bus IEEE benchmark system) with respect to load increases in all areas:



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NN SBC-OPF

- Security constraint representation using an NN-based SB in a load curtailment OPF model:

$$
\begin{aligned}
\text{Min} \quad & S_b = C_s^T P_s - C_d^T \Delta P_d \\
\text{s.t.} \quad & F_{PF}\left(\delta, V, Q_g, P_s, P_d, Q_d\right) = 0 \\
& 0 \le P_s \le P_{s\max} \\
& Q_{s\min} \le Q_s \le Q_{s\max} \\
& V_{\min} \le V \le V_{\max} \\
& \lambda_\ell - \sum_{k=1}^{8} f_{k_m}\left(\left(\left(\hat{\lambda}^T\ w_m^{in} + b_{in_m}\right) w_{21_m}^k + b_{k_m}\right) w_{32_m}^k\right. \\
& \left. + b_{out_m}\right) \le 0 \qquad \forall\, m = 1, \ldots, G \\
& \Delta P_{dj} \le 0 \quad \forall j = 1, \ldots, N \\
& \Delta P_{dj} = \left(\lambda_j - \lambda_{j0}\right) P_{dj0} \quad \forall j = 1, \ldots, N \\
& \qquad = \left(\alpha d_j - \alpha_0 d_{j0}\right) P_{dj0} \\
& Q_{dj} = \tan\left(\varphi_j\right) P_{dj} \quad \forall j = 1, \ldots, N \\
& 0 \le d_j \le 1 \quad \forall j = 1, \ldots, N \\
& \sum_{j=1}^{N} d_j = 1 \\
& \alpha \ge 0
\end{aligned}
$$

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NN SBC-OPF

- Similarly, for the more realistic multi-period DC-OPF model:

$$\text{Min. J} = \sum_{t=1}^{T} \sum_{i=1}^{N_G} C_{i,t} P_{G_i,t}$$

$$\text{s.t. } P_{G_k,t} - P_{L_k,t} - \sum_{k=1,k\neq m}^{N} P_{km,t}^{\text{loss}} - \sum_{k=1,k\neq m}^{N} P_{km,t} = 0 \qquad \forall k,m \in \text{Bus}, \ \forall t$$

$$P_{km,t} - b_{km}(\delta_{k,t} - \delta_{m,t}) = 0 \qquad \forall k,m,\ k \neq m,\ \forall t$$

$$P_{G_i}^{\min} \leq P_{G_i,t} \leq P_{G_i}^{\max} \qquad \forall i \in \text{Gen.},\ \forall t$$

$$P_{G_i,t} - P_{G_i,t+1} \leq R_{DN_i} \qquad \forall i \in \text{Gen.},\ \forall t$$

$$P_{G_i,t+1} - P_{G_i,t} \leq R_{UP_i} \qquad \forall i \in \text{Gen.},\ \forall t$$

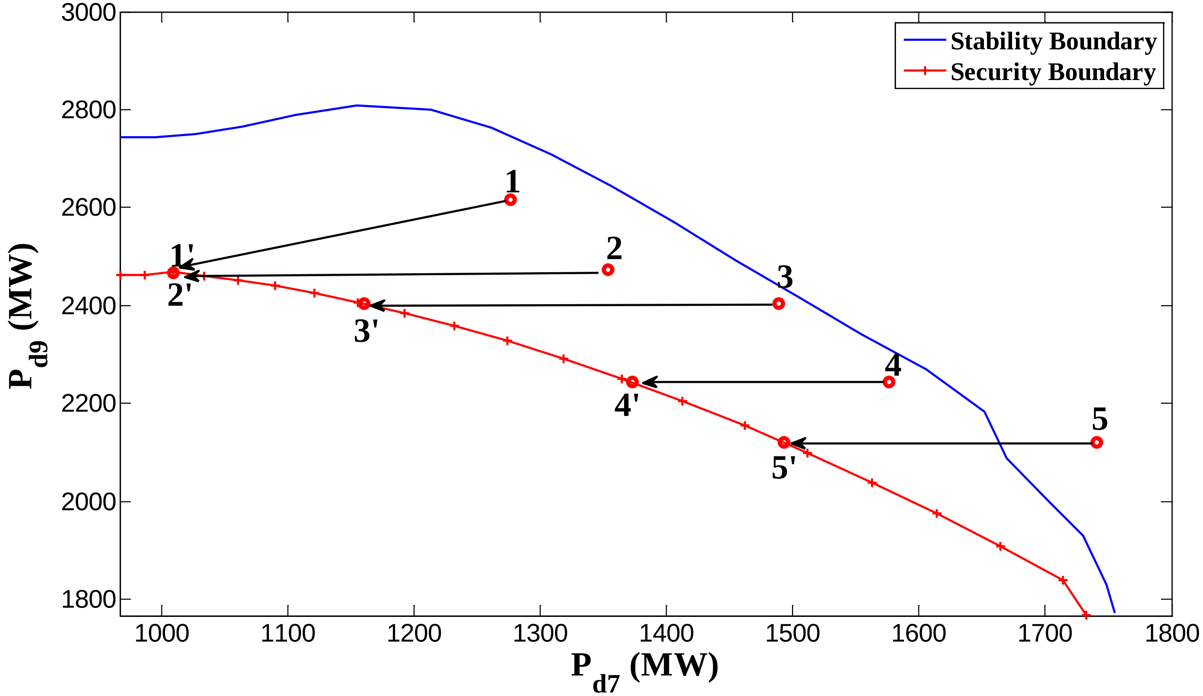
$$K_{G_\ell,t}^{c} - f_{PWL}\left(\hat{K}_{G_\ell,t}\right) \geq 0 \qquad \forall t$$

NN SBC-OPF

- Observations:
  - The NN SB constraint accounts for all system dynamics and an N-1 contingency criterion, but has limited number of input variables.
  - The NN SB function changes with system conditions.
  - The optimization problem is of similar complexity than an SC-OPF, since the SB is represented using a relatively simple and well-defined nonlinear function.

NN SBC-OPF

- For the 2-area system, the load-curtailment OPF model yields:



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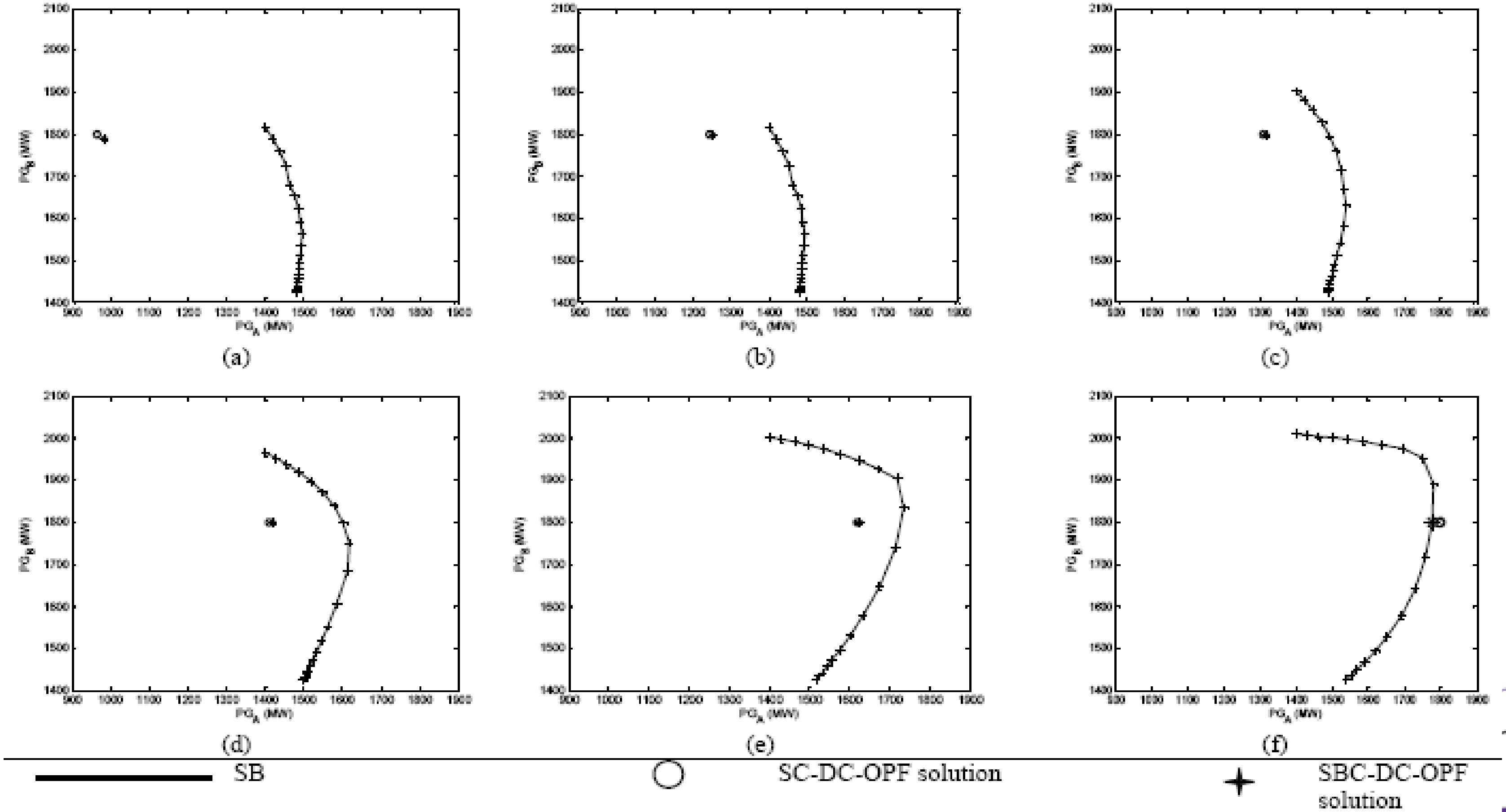
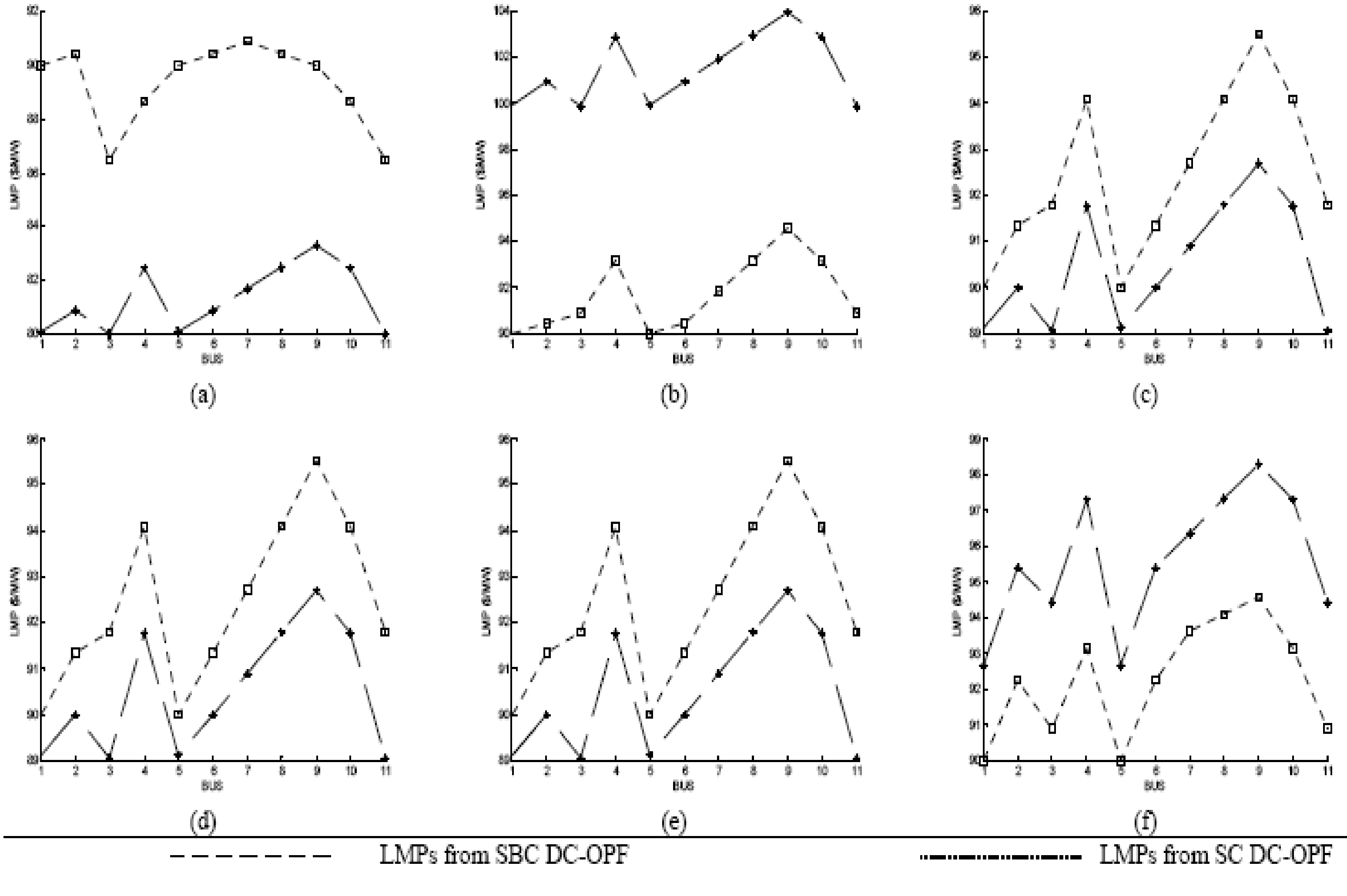
NN SBC-OPF

- For the 2-area system, the multi-period SBC-DC-OPF model yields:



NN SBC-OPF



Conclusions

- Proper representation of system security in market clearing and dispatch mechanisms leads to better market and system conditions.
- Proposed methods so far are somewhat impractical:
  - Large NLP problems (several thousand constraints and variables), and solutions should be obtained in 1-2 min.
  - Convergence issues in some of these methods need further study, considering that global optimum values are not a great concern.

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Conclusions

- Current work:
  - Linearizing the SB constraint in the NN SBC-DC-OPF.
  - Developing a new VS index with “better” behavior than the MSV index, to replace the MSV constraint in the VSC-OPF model.

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Relevant Publications

- F. Milano, C. A. Cañizares, and M. Ivernizzi, “Multi-objective Optimization for Pricing System Security in Electricity Markets,” *IEEE Transactions on Power Systems*, Vol. 18, No. 2, May 2003, pp. 596-604.
- S. K. M. Kodsi and C. A. Cañizares, “Application of a Stability-constrained Optimal Power Flow to Tuning of Oscillation Controls in Competitive Electricity Markets,” *IEEE Transactions on Power Systems*, vol. 22, no. 4, November 2007, pp. 1944-1954.
- R. J. Avalos, C. A. Cañizares, and M. Anjos, “Practical Voltage-Stability-Constrained Optimal Power Flow,” *Proc. IEEE-PES General Meeting*, invited paper, Pittsburgh, PA, July 2008
- V. J. Gutierrez-Martinez, C. A. Cañizares, C. R. Fuerte-Esquivel, A. Pizano-Martinez, and X. Gu, “Neural-Network Security-Boundary Constrained Optimal Power Flow,” accepted to appear in *IEEE Transactions on Power Systems*, March 2010.
- C. Battistelli, C. A. Cañizares, M. Chehreghani, V. J. Gutierrez-Martinez, and C. R. Fuerte-Esquivel, “Practical Security-Boundary-Constrained Dispatch Models for Electricity Markets,” *Proc. Power Systems Computation Conference*, submitted November 2010.

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