Control Strategy For An Off-Grid Hybrid Stirling Engine/Supercapacitor Power Generation System

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Overview

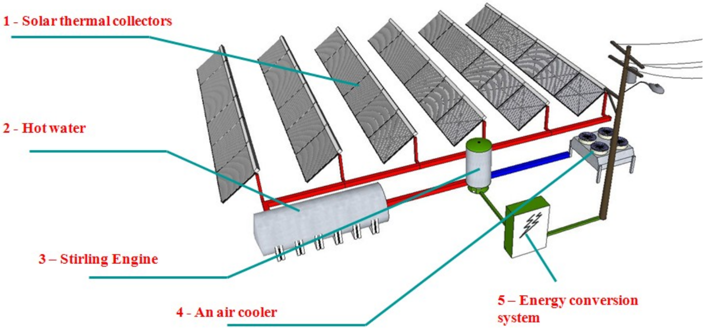
- Off-Grid Micro Solar Power Plants
- The Micro Solar Thermodynamic Plant
- Modeling and Control Energy conversion system
- Simulation Results
- Validation on Experimental Testbed
- Conclusion and Future Work

Off-Grid Micro Solar Power Plants

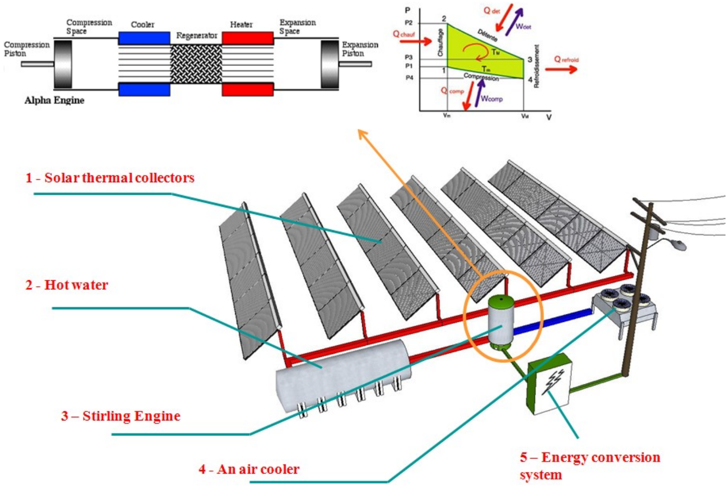
- Today, 1.4 billion people, or 300 million households, have no access to electricity. They earn less than 2 dollars per day and spend more than 15 dollars per month per family on energy. (India, Indonesia, Bangladesh, Nigeria, Sub-Saharian Africa)

- Schneider Electric launched the Microsol project that aims at developing micro solar thermodynamic plants producing a minimum of 150kWhe/day functioning 24h/24 thanks to an appropriate thermal energy storage.

Micro Solar Thermodynamic Plant



Micro Solar Thermodynamic Plant



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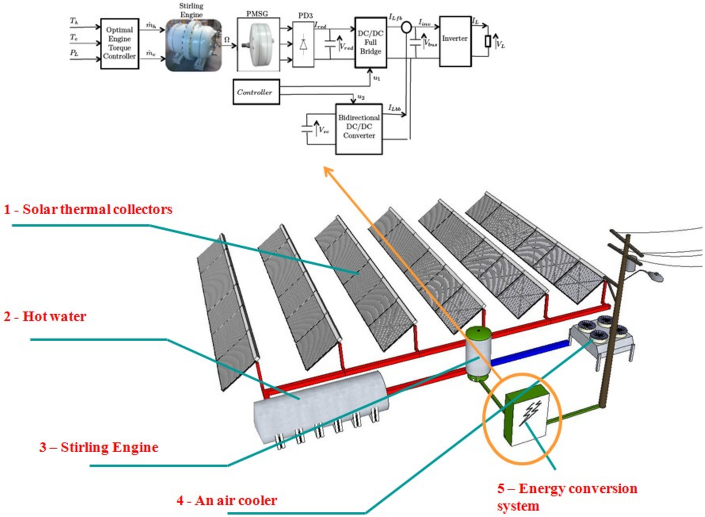
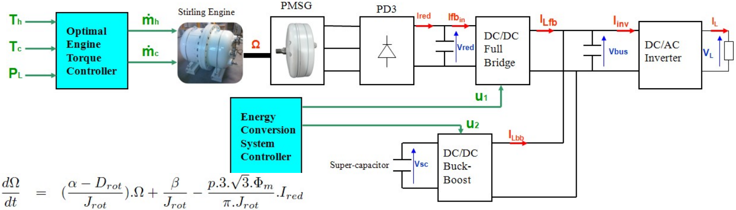
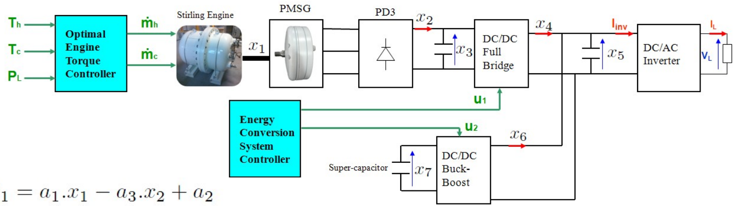


Energy Conversion System



$$
\begin{aligned}
\frac{d\Omega}{dt} &= \left(\frac{\alpha - D_{rot}}{J_{rot}}\right).\Omega + \frac{\beta}{J_{rot}} - \frac{p.3.\sqrt{3}.\Phi_m}{\pi.J_{rot}}.I_{red} \\
\frac{dI_{red}}{dt} &= -\frac{Rs}{Ls}.I_{red} - \frac{3.p}{2.\pi}.\Omega(t).I_{red} + \frac{3.\sqrt{3}}{2.\pi.L_s}.E_m(t) \\
&\quad -\frac{1}{2.Ls}.V_{red} \\
\frac{dV_{red}}{dt} &= \frac{1}{Cf}.[I_{red} - Ifb_{in}] \\
Ifb_{in} &= k.i_{Lfb}.u_1 \\
\frac{di_{Lfb}}{dt} &= \frac{k}{Lfb}.V_{red}.u_1 - \frac{1}{Lfb}.V_{bus} \\
\frac{dV_{bus}}{dt} &= \frac{1}{C_{tot}}.[i_{Lfb} + i_{Lbb} - I_{inv}] \\
I_{inv} &= \frac{P_L}{\eta_{inv}.V_{bus}} \\
\frac{di_{Lbb}}{dt} &= \frac{1}{Lbb}.V_{sc}.u_2 - \frac{1}{Lbb}.V_{bus} \\
\frac{dV_{sc}}{dt} &= \frac{-1}{C_{sc}}.i_{Lbb}.u_2
\end{aligned}
$$

Energy Conversion System



$$\dot{x}_1 = a_1.x_1 - a_3.x_2 + a_2$$
$$\dot{x}_2 = -a_4.x_2 - a_5.x_1.x_2 + a_6.x_1 - a_7.x_3$$
$$\dot{x}_3 = a_8.x_2 - a_8.k.x_4.u_1$$
$$\dot{x}_4 = -a_9.x_5 + k.a_9.x_3.u_1$$
$$\dot{x}_5 = a_{10}.(x_4 + x_6) - \frac{a_{10}}{\eta_{inv}}.\frac{P_L}{x_5}$$
$$\dot{x}_6 = -a_{11}.x_5 + a_{11}.x_7.u_2$$
$$\dot{x}_7 = -a_{12}.x_6.u_2$$

control variables :

- $u_1 \in [0,1]$: duty ratio of the Full Bridge.
- $u_2 \in [0,1]$: duty ratio of the Buck Boost.

Constraints :

- $x_i \geq 0$ except x_6.
- strong control saturation.

Control objectives :

- Regulate $x_5 = V_{bus}$ around $x_5^{st} = V_{bus}^{ref} = 50V$
- Hold $x_7 = V_{sc}$ around $x_7^{st} = V_{sc}^{ref} = 125V$

Model Analysis

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Model Analysis

$$\dot{z} = A(u_1)z + B \cdot \begin{pmatrix} a_2 \\ x_5 \end{pmatrix}$$

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- a_2 depend on the SM
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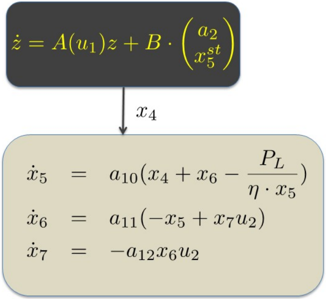
Control Architecture



Control Architecture

$$\dot{z} = A(u_1)z + B \cdot \begin{pmatrix} a_2 \\ x_5^{st} \end{pmatrix}$$

x_4

$$\begin{aligned} \dot{x}_5 &= a_{10}(x_4 + x_6 - \frac{P_L}{\eta \cdot x_5}) \\ \dot{x}_6 &= a_{11}(-x_5 + x_7 u_2) \\ \dot{x}_7 &= -a_{12} x_6 u_2 \end{aligned}$$

$x_6^{ref}(x_4, x_5, P_L)$

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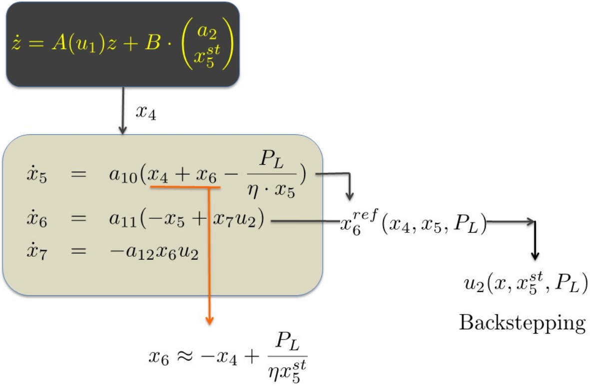
$x_6^{ref}(x_4, x_5, P_L)$

$u_2(x, x_5^{st}, P_L)$

Backstepping

Control Architecture



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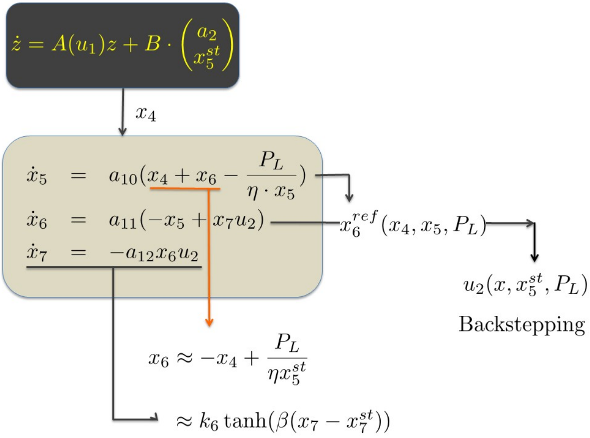

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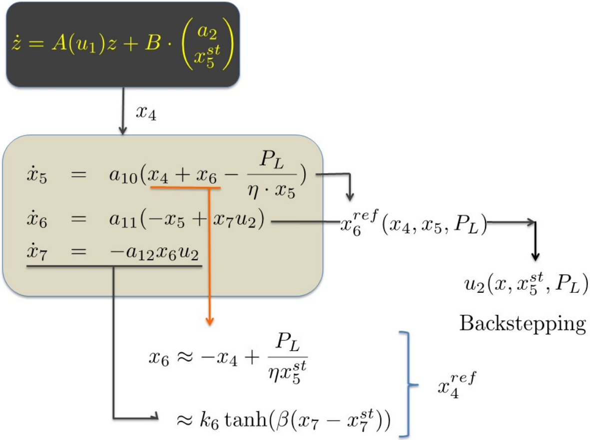

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u_1^{st} $\quad x_4$

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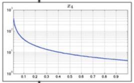
$x_6^{ref}(x_4, x_5, P_L)$

$u_2(x, x_5^{st}, P_L)$

Backstepping

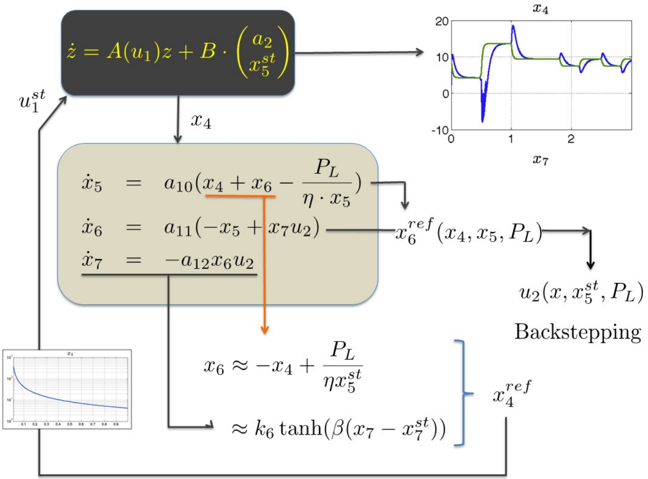


$$x_6 \approx -x_4 + \frac{P_L}{\eta x_5^{st}}$$

$$\approx k_6 \tanh(\beta(x_7 - x_7^{st}))$$

x_4^{ref}

Control Architecture



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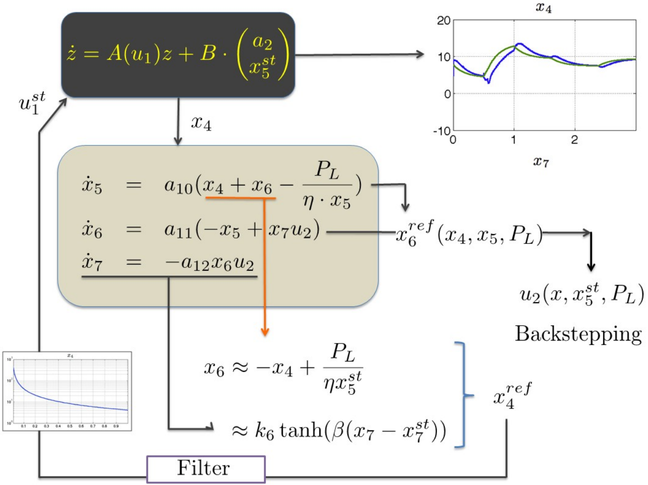
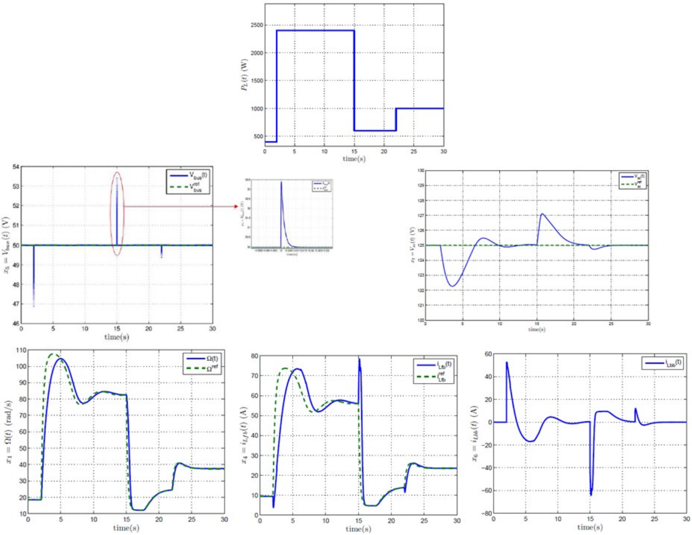
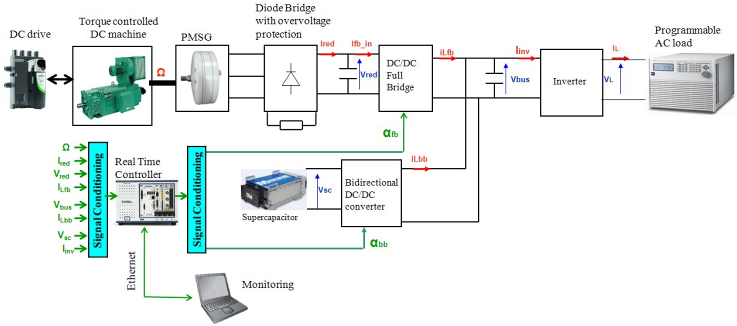


Simulation Results



Validation on Experimental Testbed



- The torque controlled DC machine emulates the Stirling Engine.
- Sampling period $\tau = \mathbf{100}\ \mu s$ on the real time target.
- Online computation of the steady states knowing x_4^{st}.
- **MPC** based on 2d order approx. of $\exp(A(u_1))$.
- Use of a constant Lyapunov stability matrix $P_d(u_1^{st}) = P_d(0.5)$

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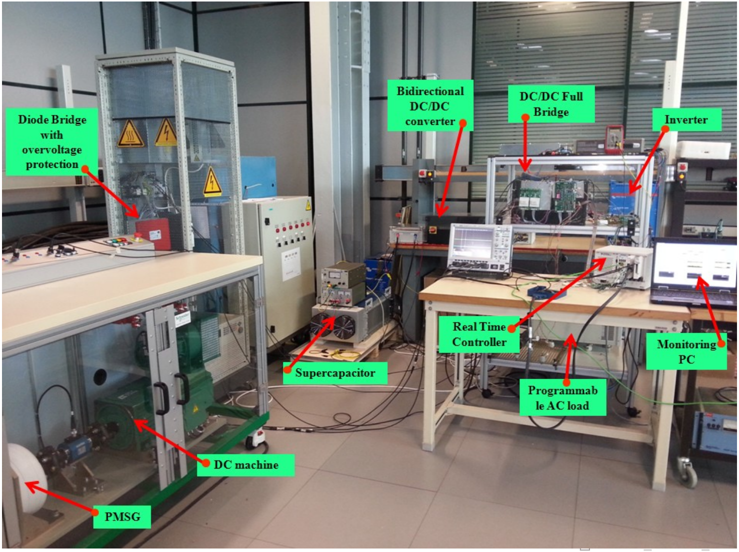

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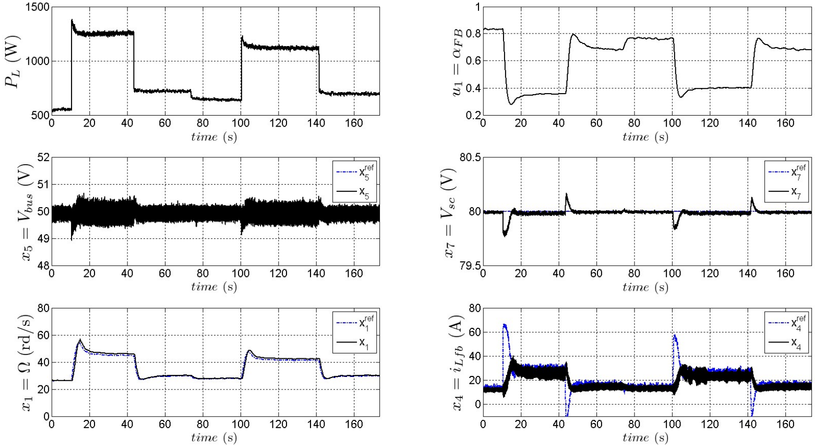

Conclusions and Perspectives

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- Setting the mean model of the energy conversion system.
- Control of the DC bus voltage (Stiff) and the voltage of the super-capacitor for step power demand variations.
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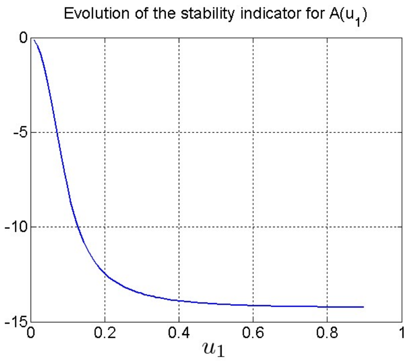
- Control of the DC bus voltage (Stiff) and the voltage of the super-capacitor for step power demand variations.
- Experimental Validation on a dedicated testbed

Future work

- Validation with the thermodynamic Stirling Engine
- Identification of the torque expression with respect to temperatures and mass flow rates using real data
- Identification of the Stirling engine model using real data

Model Analysis

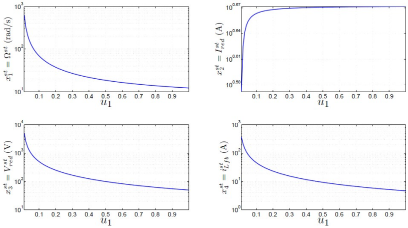
- $A(u_1)$ is Hurwitz



Model Analysis

- $A(u_1)$ is Hurwitz
- $\forall u_1 \in [0,1]$, steady-state :

$$x^{st}(u_1) := -[A(u_1)]^{-1} B \begin{pmatrix} a_2 \\ x_5^{st} \end{pmatrix}$$



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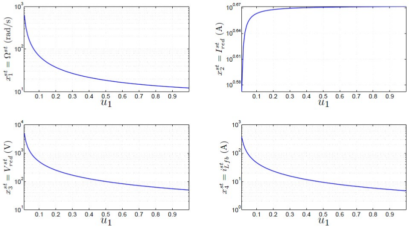

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$$\Delta \left[x^T [P_d(u_1)] x \right] < 0$$

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$$\Delta \Big[x^T [P_d(u_1)] x \Big] < 0$$

- Highly oscillatory

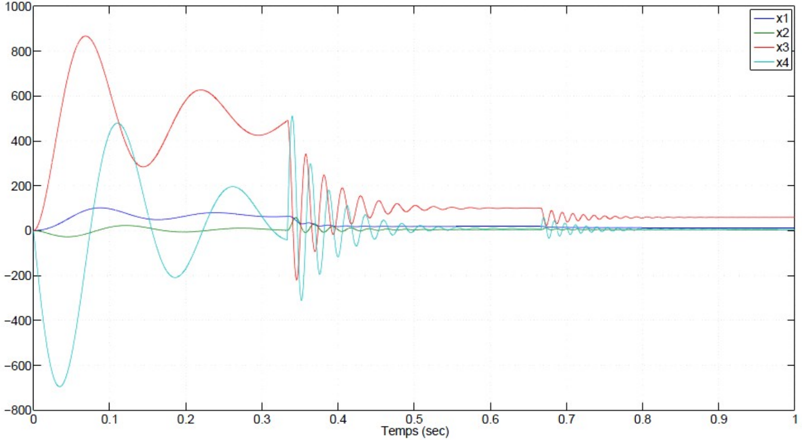
```
>> eig(A14(0.5))

ans =

  1.0e+003 *

  -9.5234
  -0.0639
  -0.0141 + 0.4193i
  -0.0141 - 0.4193i
```

Some Open Loop Simulations :



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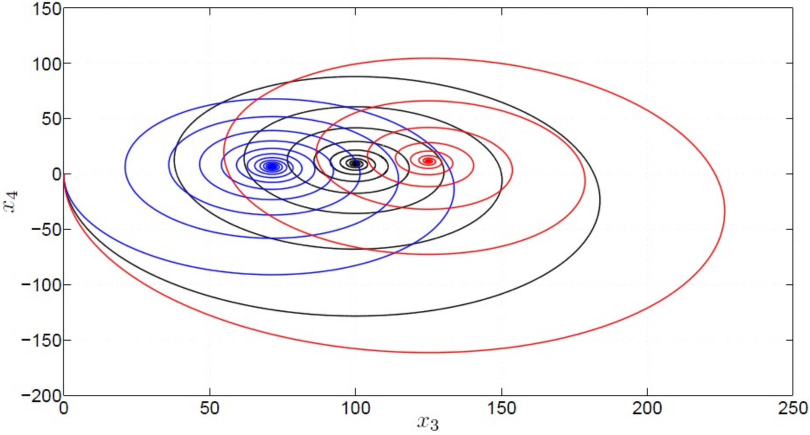

One Step MPC for Subsystem 1

$$u_1^{opt} = \arg \min_{u_1 \in [0,1]} J(u_1) := \left[\left\| z^+(u_1) - z^{st} \right\|^2_{P_d(u_1^{st})} \right]$$