

# A simulation software tool development for adiabatic CAES with thermal storage

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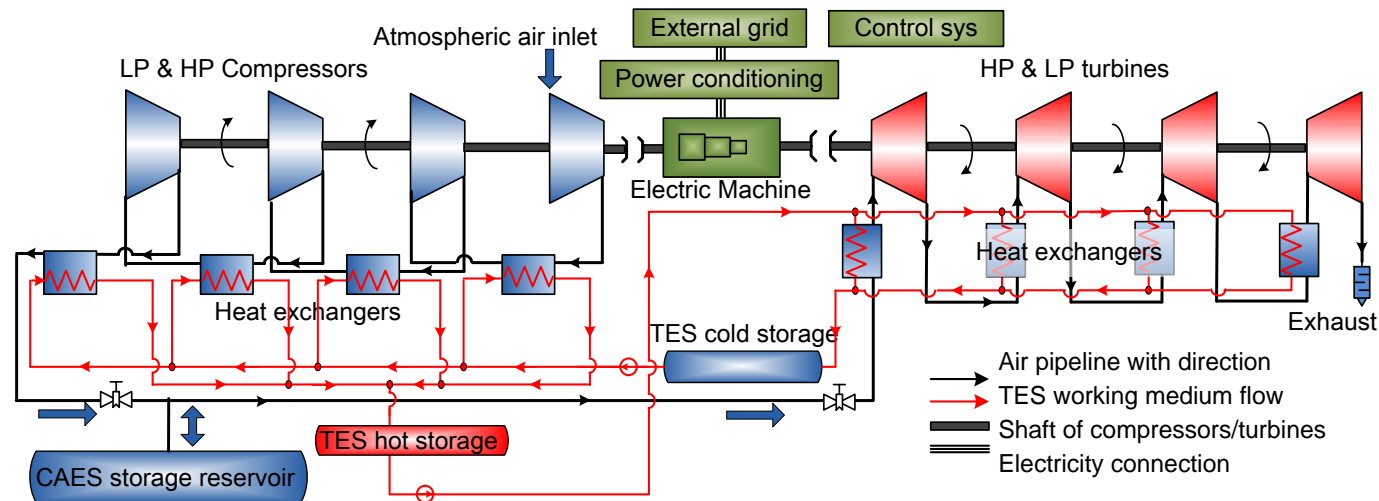
# Outline of the Presentation

1. Introduction
2. Mathematical modelling of key components
3. Application case study
4. Data driven model - machine learning

# 1. Introduction

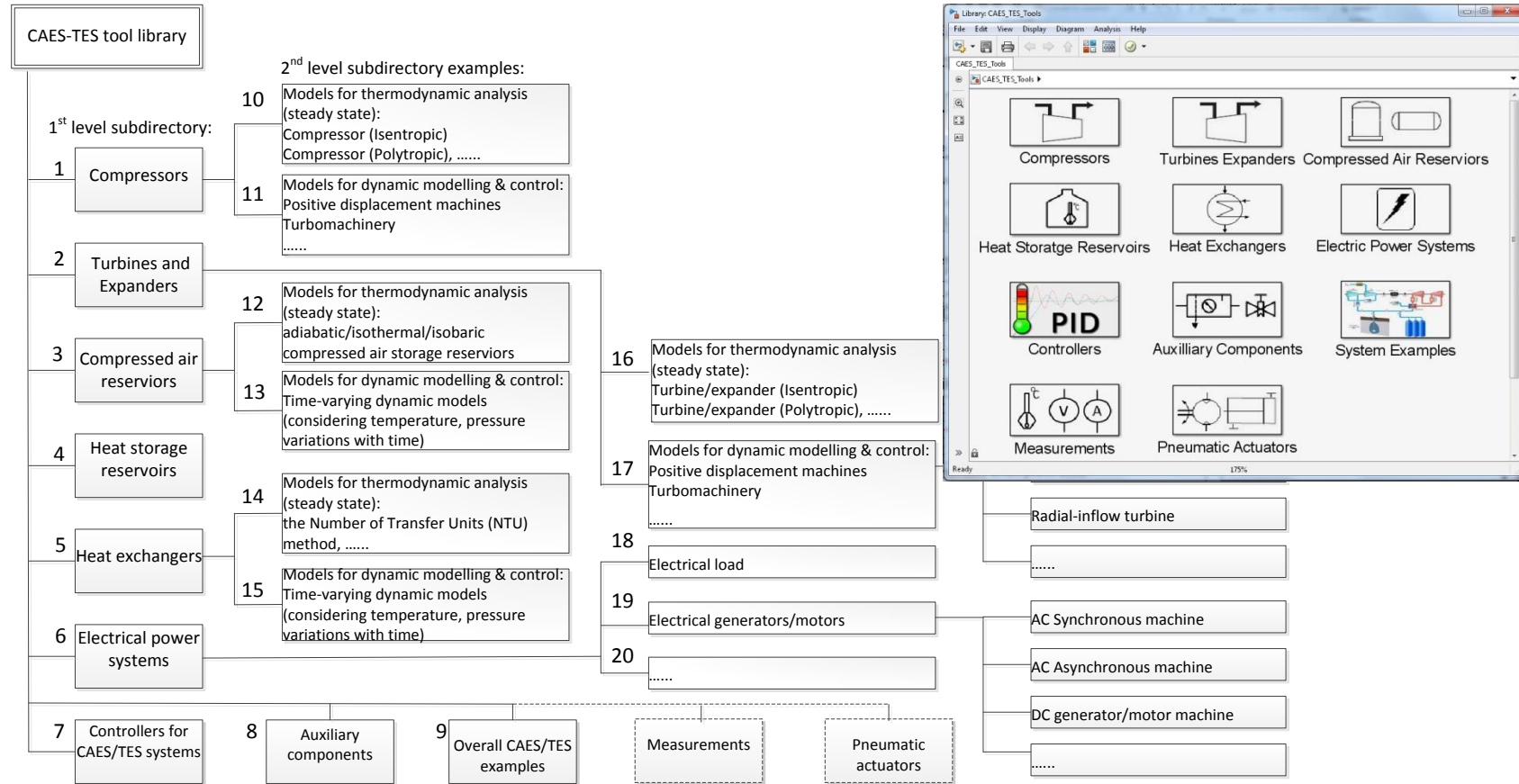
- Adiabatic Compressed Air Energy Storage (CAES) with Thermal Energy Storage (TES) is a complex system with subsystem coupling, components interactions and parameter sensitive.
- Cycle efficiency depends on whole system dynamic behaviours.
- Dynamic modelling of complete systems is essential to provide support for feasibility studies of EES applications, system optimisation and control strategy development, and management of grid integration.

***Demand for a whole system dynamic modelling and simulation tool development***



# 1. Introduction

- A Simulink based tool for **1D dynamic modelling & control CAES-TES** is developed.
- **Areas:** mathematics, thermodynamics, heat transfer, mechanical & electrical engineering.
- **Features:** model based design, signal I/O connection, case studies, compiled and protected, design & test documentation, initial server test for public release.



# 1. Introduction

Design documentation:

Version no. and developer(s)

Introduction

mathematical modelling

module simulation model  
(inputs, outputs,  
parameters)

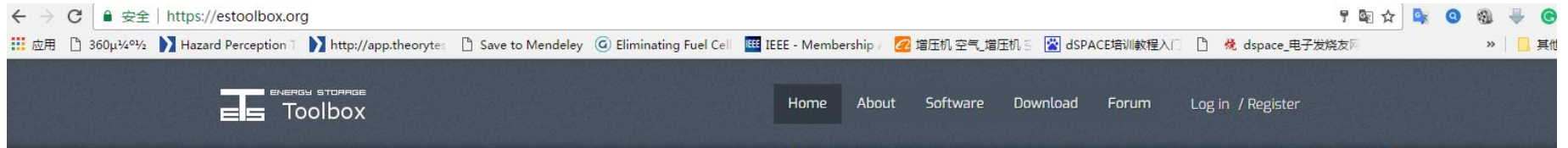
Code explanation  
corresponding to  
modelling equations

operation example

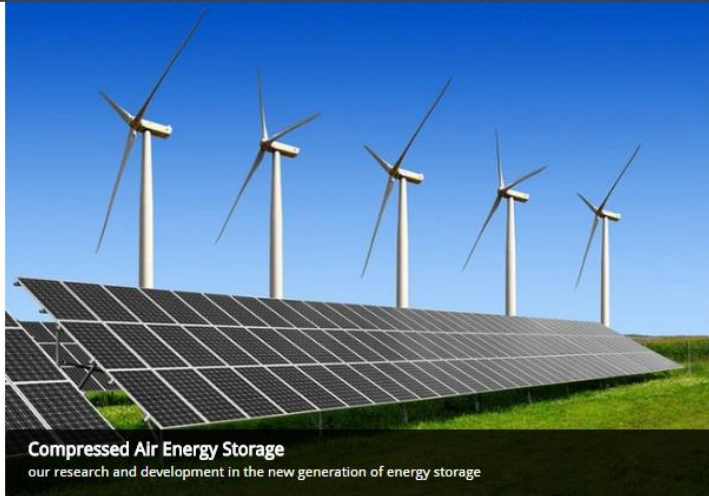
**Name**

- Final Version
- 130304\_PMDc\_Generator\_Design\_Doc.docx
- 160105\_DC\_Motor\_Module\_Example\_Older\_Version.docx
- 160108\_Module\_template\_draft.docx
- 160210\_Simplified\_scroll air expander software documentation\_V1.1\_final.docx
- 160226\_Water-Water\_Shell\_Tube\_HEX\_Module.docx
- 160304\_PMDc\_Motor\_Design\_doc.docx
- 160309\_HeatExchanger\_SteadyState\_software\_documentation\_V1.docx
- 160315\_Reciprocating\_piston\_type\_air\_compressor\_software\_documentation\_V1.1.docx
- 160323\_Scroll air expander software documentation\_V1.0.docx
- 160324\_Asynchronous motor\_v1.1.docx
- 160331\_Vane\_type\_air\_compressor\_software\_documentation\_V1\_draft\_ready.docx
- 160404\_SEDC\_Motor\_Design\_doc.docx
- 160404\_ShCDC\_Motor\_Design\_doc.docx
- 160405\_SEDC\_Generator\_Design\_doc.docx
- 160405\_ShCDC\_Generator\_Design\_doc.docx
- 160406\_SEDC\_Generator\_Design\_doc.docx
- 160406\_SEDC\_Motor\_Design\_doc.docx
- 160408\_Asynchronous motor\_v1.1\_final\_version.docx
- 160511\_ELoad.docx
- 270315\_Adiabatic\_air\_tank\_software\_documentation\_V1.1.docx
- 310315\_Salt\_dome\_cavern\_documentation\_V1.1.docx

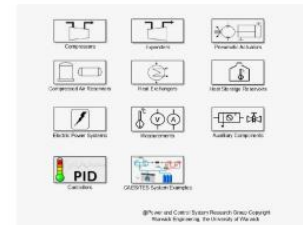
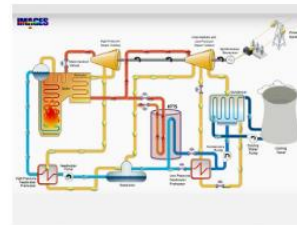
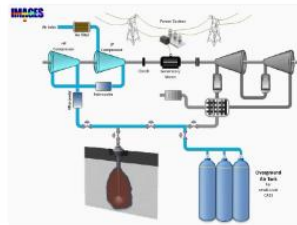
# 1. Introduction



The screenshot shows a web browser window with the URL <https://estoolbox.org>. The browser's address bar and tabs are visible, showing various open pages related to energy storage and control systems. The website header features the 'ENERGY STORAGE Toolbox' logo on the left and navigation links for 'Home', 'About', 'Software', 'Download', 'Forum', and 'Log in / Register' on the right.



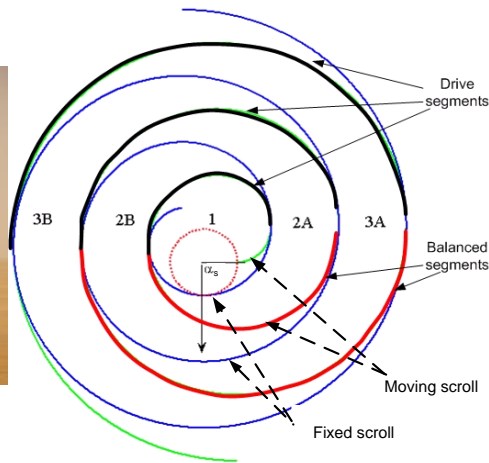
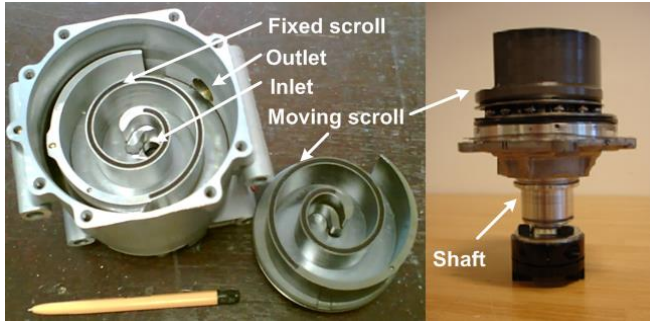
**Compressed Air Energy Storage**  
our research and development in the new generation of energy storage



<https://estoolbox.org/index.php/download>

## 2. Mathematical modelling of key components

scroll-type air motor:



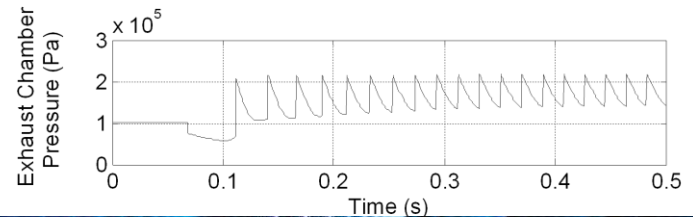
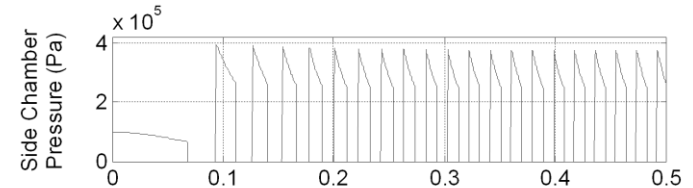
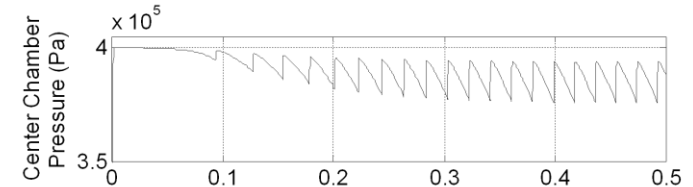
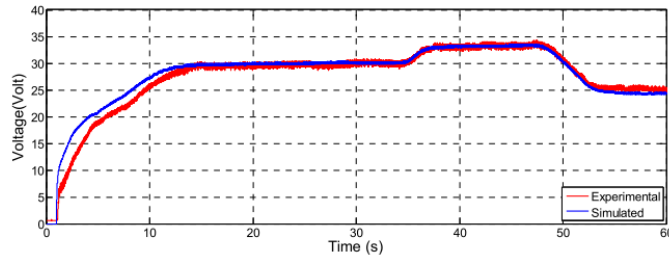
$$V_{s\_c}(\alpha_s) = z[(kr_s - k^2\pi - x_0r_s + x_0k\pi)\cos\alpha_s + (kr_s\tilde{\rho}_0\pi - r_s\tilde{\rho}_0 - y_0r_s + y_0k\pi)\sin\alpha_s + (kr_s\pi + 2k\tilde{\rho}_0\pi)\alpha + k^2\pi\alpha_s^2 - kr_s + \frac{1}{3}k^2\pi^3 - \frac{1}{2}kr_s\pi^2 + \tilde{\rho}_0r_s\pi + \frac{1}{2}r_s^2\pi + \tilde{\rho}_0^2\pi]$$

$$V_{s\_s}(\alpha_s, i) = z[\pi r_s^2 + 2\pi r_s(\tilde{\rho}_0 + k(\alpha_s + \pi + 2(i-1)\pi))]$$

$$V_{s\_e}(\alpha_s) = V_{total} - V_{s\_c}(\alpha_s) - \sum_{i=1}^{n_p} 2V_{s\_s}(\alpha_s, i)$$

$$\dot{\omega}_s = \frac{1}{J_s}[-K_{S-C3}S_3(\omega_s, P_{s\_c}, P_{s\_s}, P_{s\_e}) - K_{V3}\omega_s + \tau_{s\_total}(P_{s\_c}, P_{s\_s}, P_{s\_e})]$$

$$K_{S-C3}S_3(\omega_s, P_{s\_c}, P_{s\_s}, P_{s\_e}) = \begin{cases} F_{s\_total}(P_{s\_c}, P_{s\_s}, P_{s\_e}) & \omega_s = 0 \text{ and } F_{s\_total}(P_{s\_c}, P_{s\_s}, P_{s\_e}) \leq F_{S3} \\ \text{sign}(\omega_s) \times \partial_s \times F_{S3} & \omega_s \neq 0 \text{ and } 0 < \partial_s < 1 \end{cases}$$



# 2. Mathematical modelling of key components

## Induction motor:

$$V_{qs} = R_s i_{qs} + \frac{d\phi_{qs}}{dt} + \omega \phi_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \omega \phi_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d\phi'_{qr}}{dt} + (\omega - \omega_r) \phi'_{dr}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d\phi'_{dr}}{dt} - (\omega - \omega_r) \phi'_{qr}$$

$$T_e = 1.5P(\phi_{ds} i'_{qr} - \phi_{qs} i'_{dr})$$

$$\phi_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\phi_{ds} = L_s i_{ds} + L_m i'_{dr}$$

$$\phi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$\phi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L'_r = L'_{lr} + L_m$$

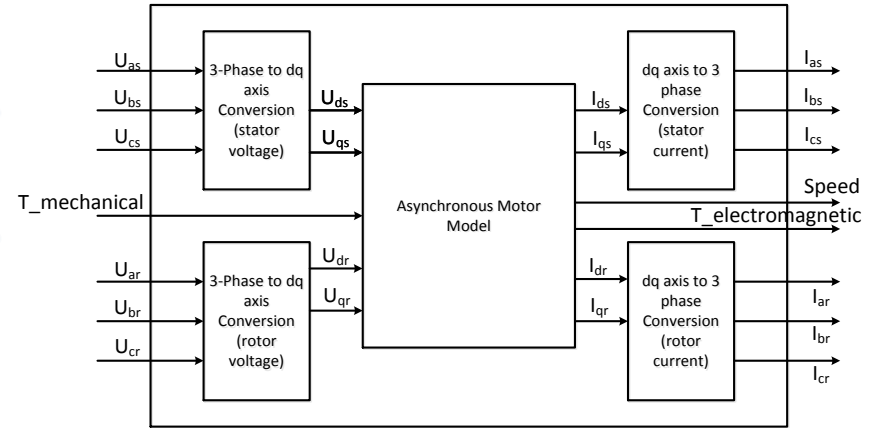
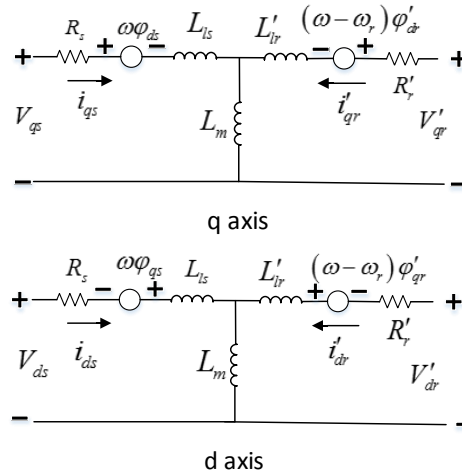
$$X_{ls} = 2\pi f L_{ls}$$

$$X'_{lr} = 2\pi f L'_{lr}$$

$$X_m = 2\pi f L_m$$

$$\frac{d\omega_m}{dt} = \frac{1}{J}(T_e - F\omega_m - T_m)$$

$$\frac{d\theta_m}{dt} = \omega_m$$

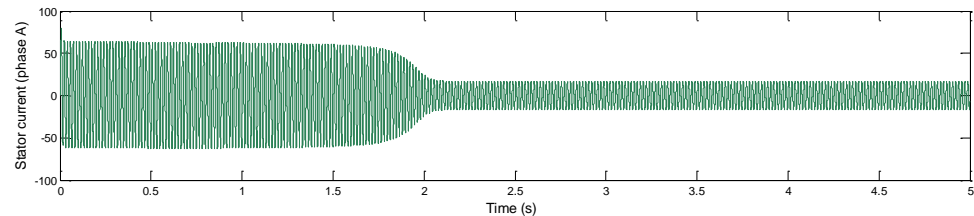
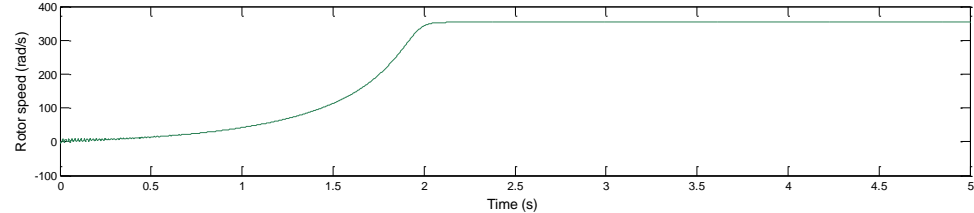


$$U_{as} = 220\sqrt{2} \sin(120\pi t) V$$

$$U_{bs} = 220\sqrt{2} \sin(120\pi t - 120^\circ) V$$

$$U_{cs} = 220\sqrt{2} \sin(120\pi t - 240^\circ) V$$

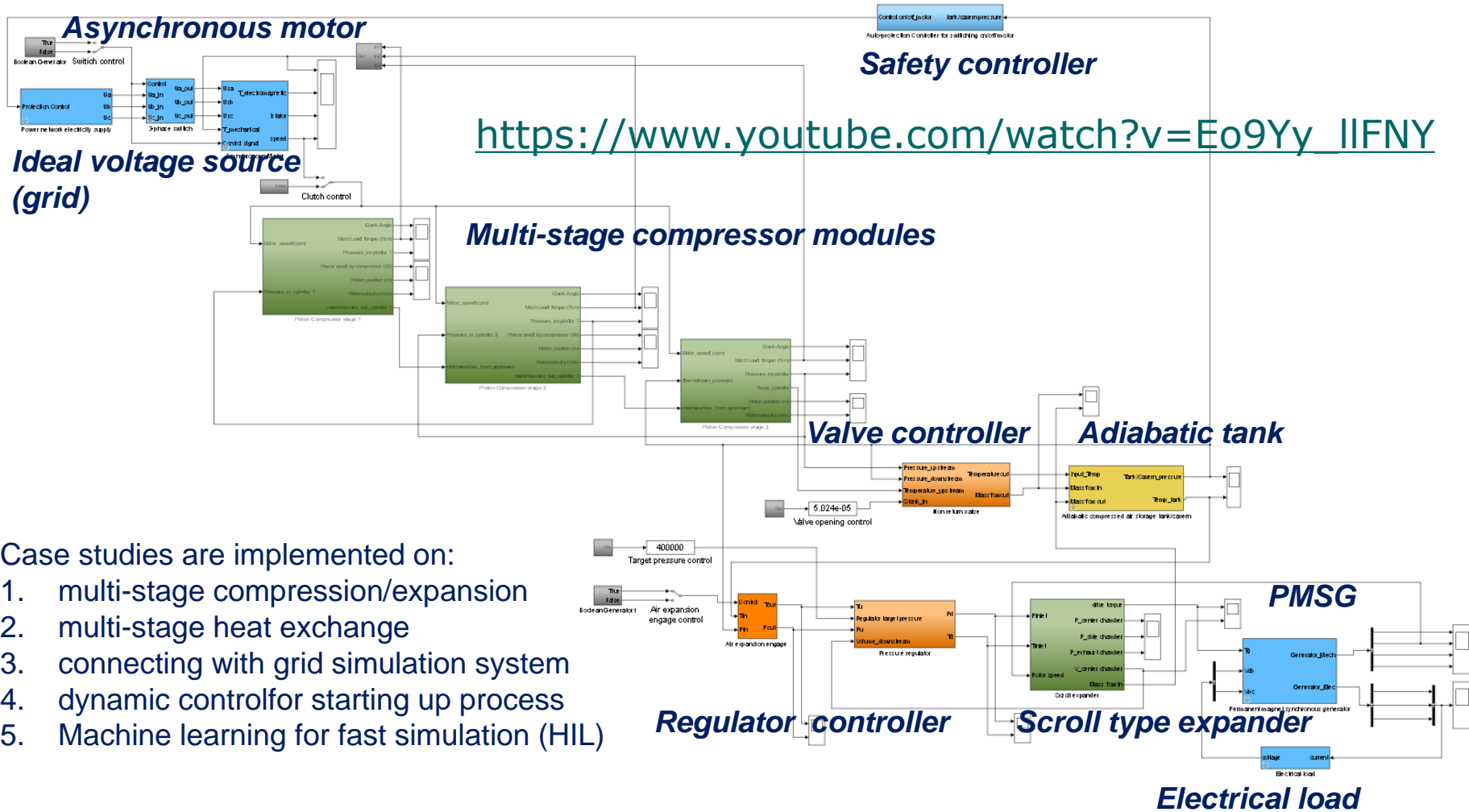
$$U_{ar} = U_{br} = U_{cr} = 0 V$$





# 3. Application case study

- a whole CAES system dynamic model:



Case studies are implemented on:

1. multi-stage compression/expansion
2. multi-stage heat exchange
3. connecting with grid simulation system
4. dynamic control for starting up process
5. Machine learning for fast simulation (HIL)

## 4. Data driven model - machine learning

### Motivation

### Illustration of complexity - CAES with TES

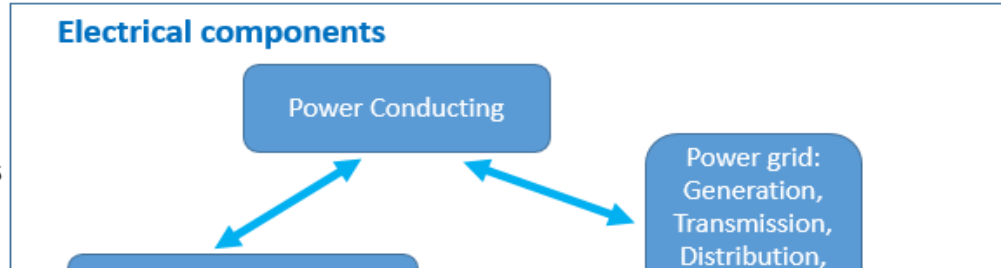
System Element Response time:

**Electrical:** less than 1s

**Electrical-Mechanical:** less than 1s

**Thermal-Mechanical:** seconds to minutes

**Thermal:** minutes to hours



### **Problem:**

If use numerical models for all components, when more components are connected to the system simulation, the simulation speed is getting slower and slower

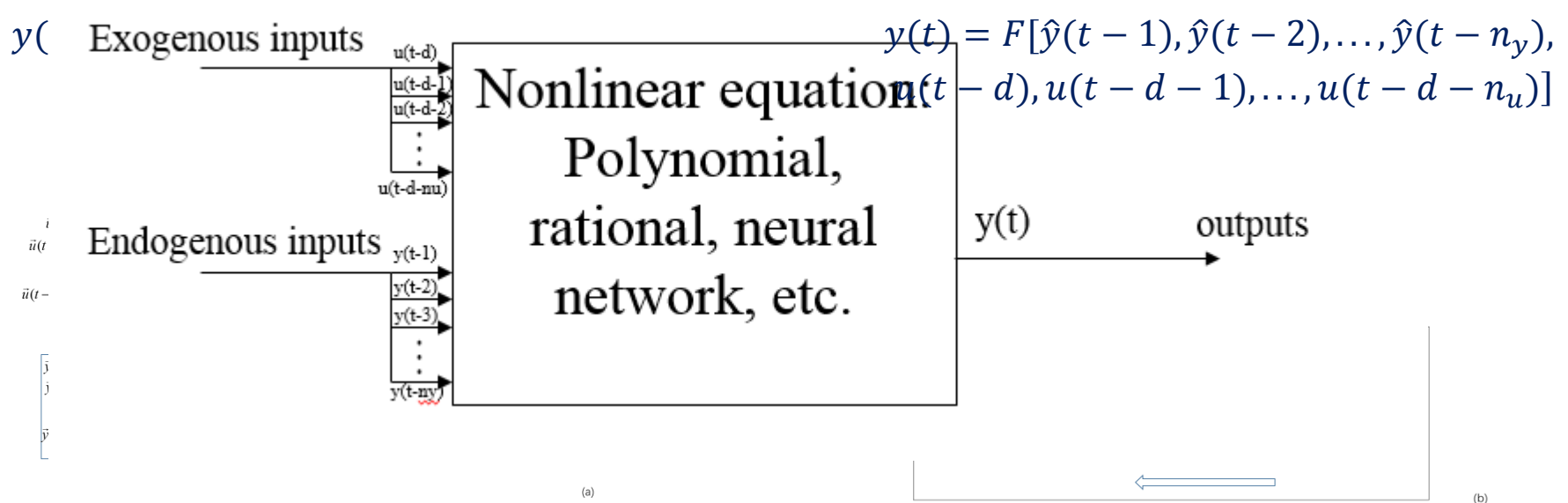
**Mechanical components**

## 4. Data driven model - machine learning

Nonlinear autoregressive with exogenous inputs (NARX) neural network (NN) model

**NARX model open-loop equation:**

**NARX model close-loop equation:**

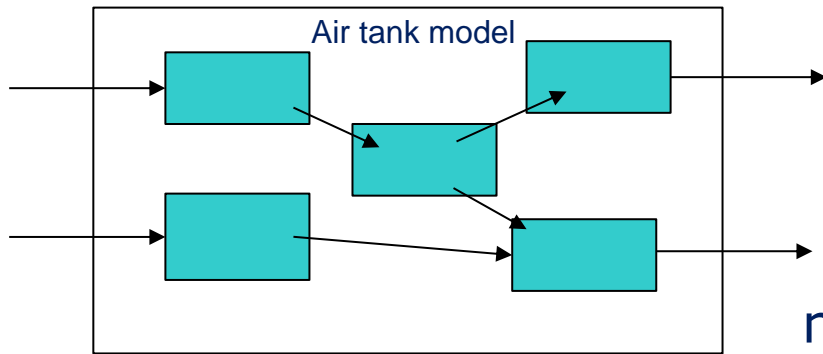


**Open-loop NN  
(for training use)**

**Close-loop NN  
(for further training and  
approximation approach)**

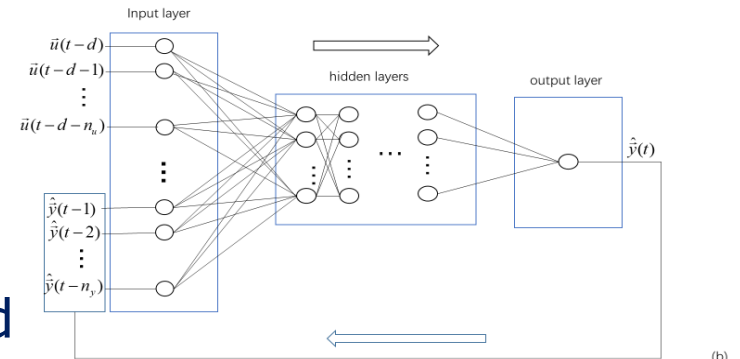
# 4. Data driven model - machine learning

**Numerical model: accurate but slow**

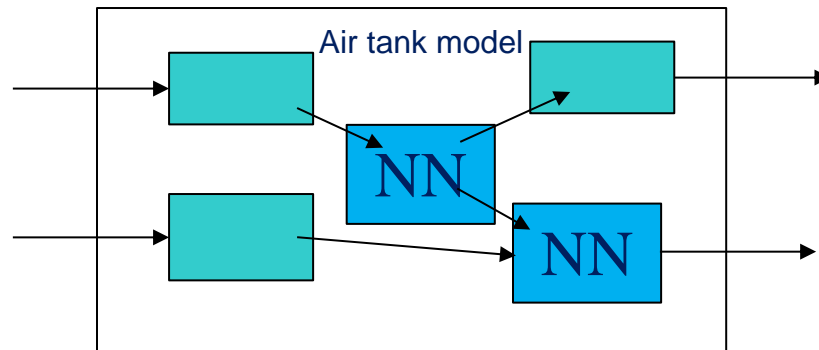
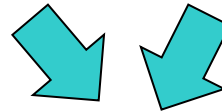


 : subsystems for a numerical model

**NARX NN model: fast but less accurate**



**mixed**



**NARX NN-numerical  
mixed model: fast model  
with accuracy**

**Thank you!**