Modeling and Simulation of a Combined Solar and Wind Systems using OpenModelica

Arash M. Dizqah[1] **Alireza Maheri**[1] **Krishna Busawon**[1] **Peter Fritzson**[2]

[1] School of Computing, Engineering and Information Sciences , Northumbria University, NE1 8ST Newcastle Upon Tyne, UK
[2] PELAB Programming Environment Lab, Dep. Of Computer and Information Science , Linköping University, SE-581 83 Linköping, Sweden

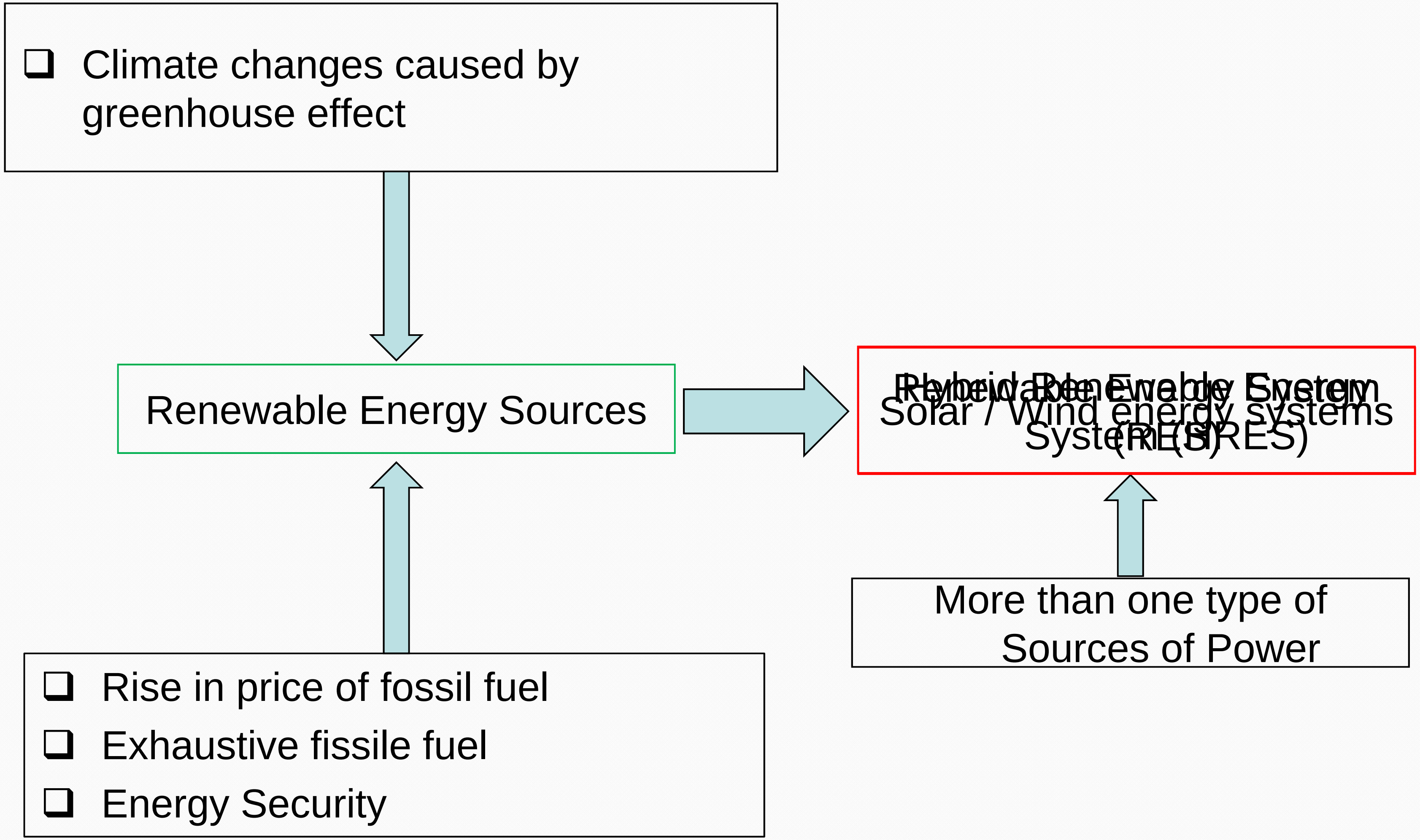
Outline

- **Combined/hybrid wind and solar energy systems (HRES)**
- **An overview on the mathematical and electrical modeling**
- **System modeling and simulation using OpenModelica**
- **Analysis and discussion**
- **Conclusion and future works**

Majority of the results presented here have been already published in:

A. M. Dizqah, K. Busawon, P. Fritzson, “Acausal Modeling and Simulation of the Standalone Solar Power Systems as Hybrid DAEs”, The 53rd Intl. Conf. Of the Scandinavian Simulation Society (SIMS), 2012.

Combined/hybrid wind and solar energy systems



- ☐ Climate changes caused by greenhouse effect

Renewable Energy Sources

Hybrid Renewable Energy System (HRES)

Renewable Energy System (RES)

Solar / Wind energy systems

More than one type of Sources of Power

- ☐ Rise in price of fossil fuel
- ☐ Exhaustive fissile fuel
- ☐ Energy Security

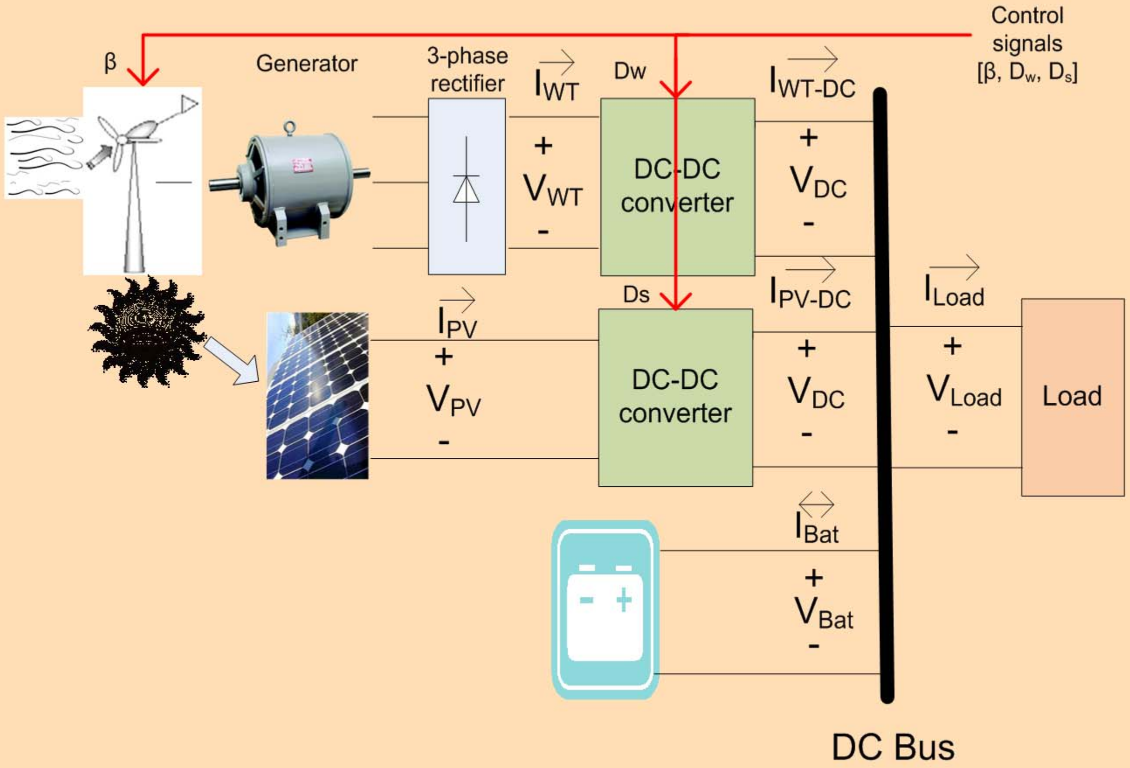
HRES Motivations

Combined/hybrid wind and solar energy systems

System overview

- The PV, wind turbine, and the battery modules are **nonlinear**.
- The PV, wind turbine, load, and the battery modules introduce **algebraic constraints**.
- The battery module is **hybrid** and has at least **two modes** of operation, i.e., charging and discharging modes.
- The converter is also a hybrid system including a high frequency state transition, However, in this study an **average model** has been used for simplicity's sake.

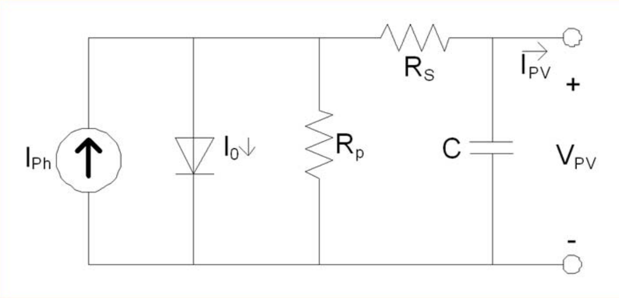
The topology and components

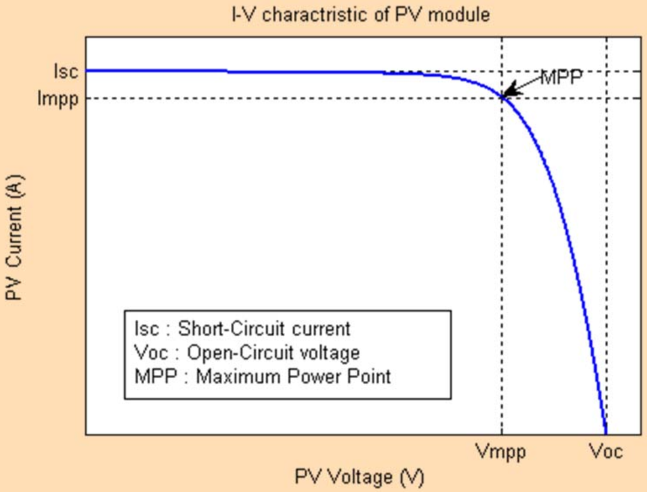


An overview on the mathematical/electrical modeling

The PV module equivalent electrical circuit and the I-V curve

$$I_{pv} = I_{ph} - I_0 \left\{ exp(\frac{V_{pv} + R_s I_{pv}}{n_d N_s} \frac{q}{KT_c}) - 1 \right\} - \frac{V_{pv} + R_s I_{pv}}{R_{sh}}.$$



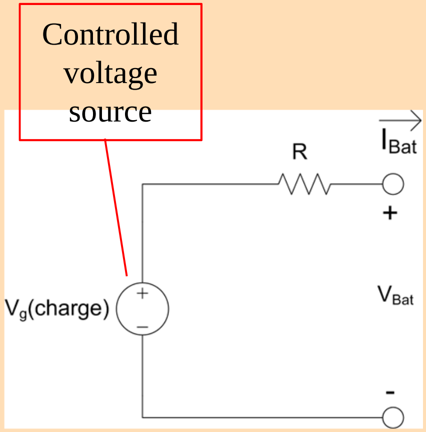


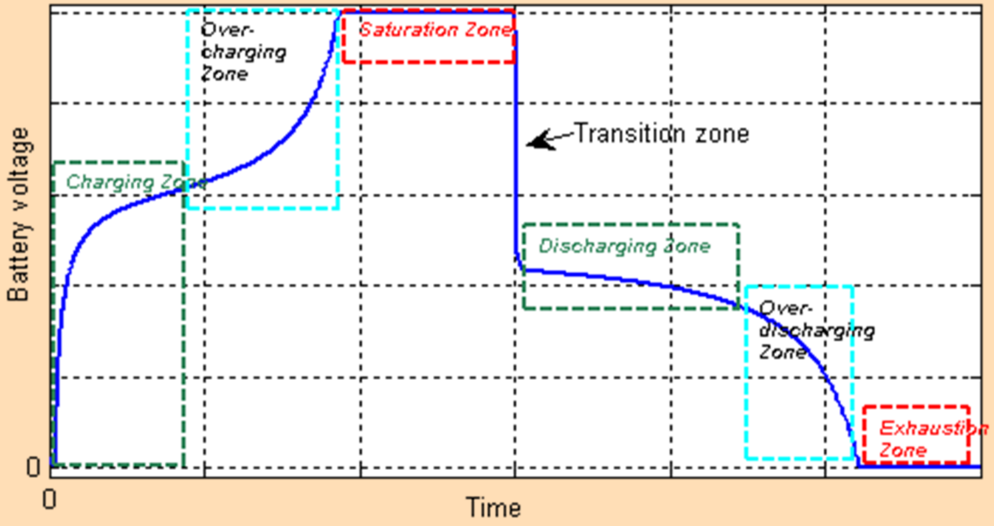
An overview on the mathematical/electrical modeling

The battery equivalent electrical circuit and operating modes

$$\frac{\mathrm{d}charge}{\mathrm{d}t}(t) = \frac{1}{3600} I_{bat}(t).$$

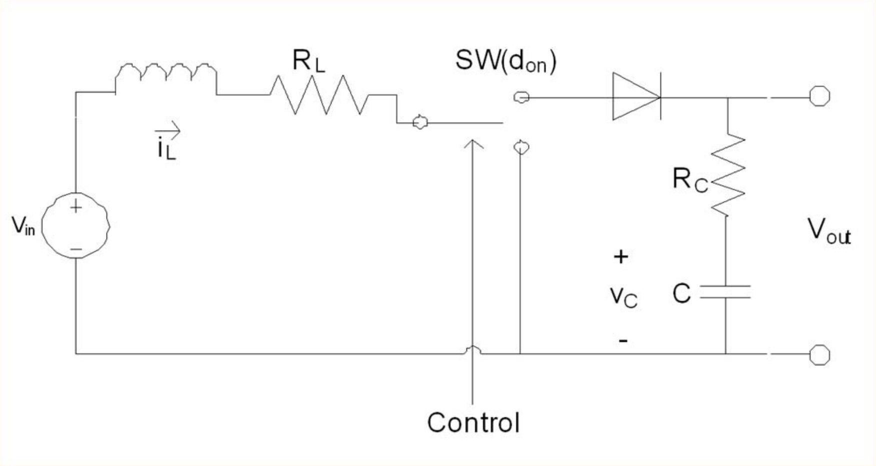
$$V_{bat} = \begin{cases} V_0 - RI_{bat} + V_{exp} - \dfrac{P_1 C_{max}}{C_{max} - charge} charge - \dfrac{P_1 C_{max}}{charge + 0.1 C_{max}} I_{bat} & \text{mode=charging,} \\ \\ V_0 - RI_{bat} + V_{exp} + \dfrac{P_1 C_{max}}{charge - C_{max}} charge + \dfrac{P_1 C_{max}}{charge - C_{max}} I_{bat} & \text{mode=discharging.} \end{cases}$$


Controlled voltage source



An overview on the mathematical/electrical modeling

The boost-type converter electrical circuit and the average model



$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{v}_C(t) \end{bmatrix} = \begin{bmatrix} -\frac{R_L}{L} - \frac{R_C(1-D)}{L(1+\frac{R_C}{R})} & -\frac{1-D}{L(1+\frac{R_C}{R})} \\ \frac{1-D}{C(1+\frac{R_C}{R})} & -\frac{1}{RC(1+\frac{R_C}{R})} \end{bmatrix} \times \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}(t).$$

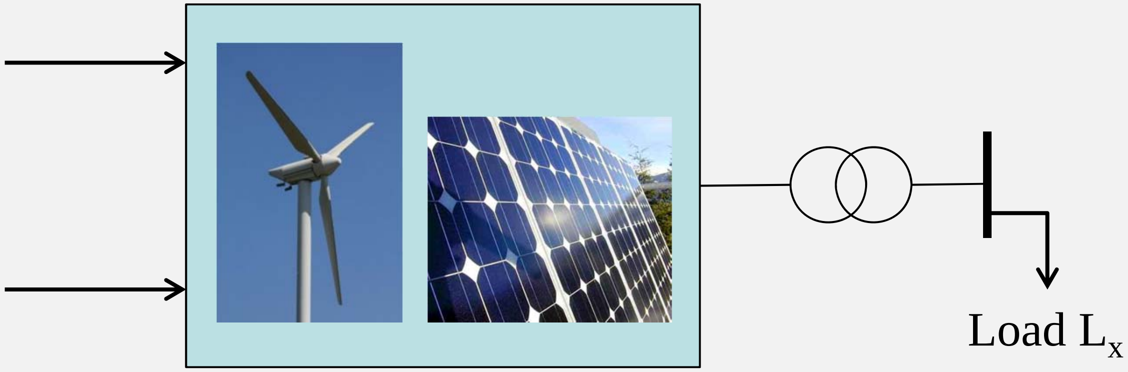
$$V_{out}(t) = \begin{bmatrix} \frac{R_C(1-D)}{1+\frac{R_C}{R}} & \frac{1}{1+\frac{R_C}{R}} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_C(t) \end{bmatrix}.$$

An overview on the mathematical/electrical modeling

The combined/hybrid power generation plant

Non-manipulated variables (perturbations): [Sx, Tx, Ux, Lx]

Manipulated variables: [β, D_w, D_s]

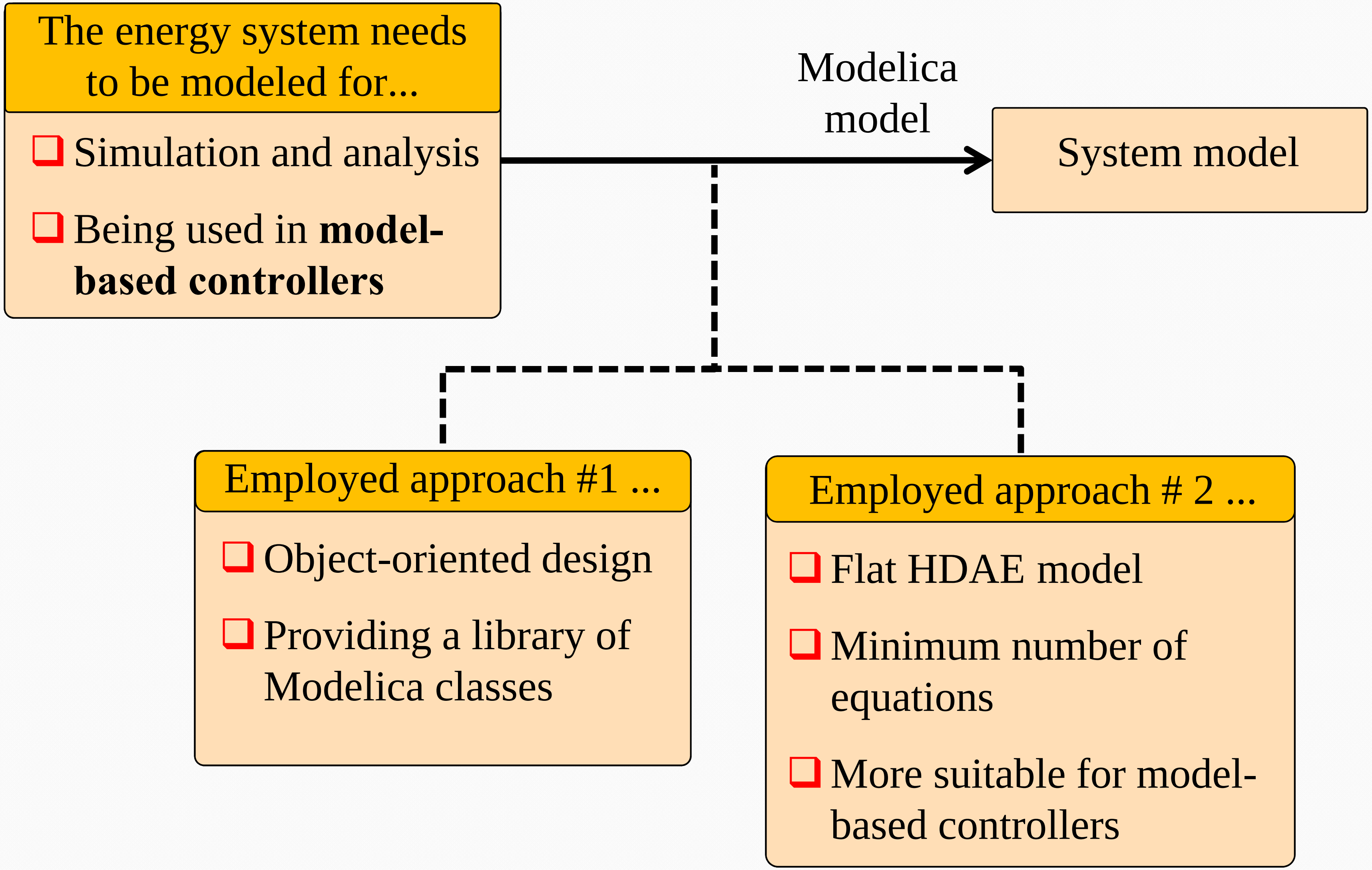


Load L_x

It is ...

- A system describing with nonlinear HDAEs of Index-1
- A MIMO system

System modeling and simulation using OpenModelica



The energy system needs to be modeled for...

- Simulation and analysis
- Being used in **model-based controllers**

Modelica model

System model

Employed approach #1 ...

- Object-oriented design
- Providing a library of Modelica classes

Employed approach # 2 ...

- Flat HDAE model
- Minimum number of equations
- More suitable for model-based controllers

Modeling the system as Modelica classes

The Modelica model of the whole solar power system

```
model HRES SolarSystem
  Modelica.Blocks.Sources.Constant Sx(k = 300.0);
  Modelica.Blocks.Sources.Constant Tx(k = 298.15);
  Modelica.Electrical.Analog.Basic.Ground ground;
  HRES.PVArray pvarray(Npvp = 10);
  Modelica.Blocks.Sources.TimeTable DutyCycle(table = [...]);
  Modelica.Blocks.Sources.Step ramp(startTime = 5, offset = 10, height = -6);
  Modelica.Electrical.Analog.Basic.VariableResistor load;
  HRES.BoostConverter converter(Rl = 0.001, Rc = 0.3, L = 0.0005,C = 0.005);
  HRES.LeadAcidBattery battery1;
  HRES.LeadAcidBattery battery2;
  HRES.LeadAcidBattery battery3;
  HRES.LeadAcidBattery battery4;
equation
  connect(Tx.y,pvarray.Tx);
  connect(Sx.y,pvarray.Sx);
  connect(pvarray.n,ground.p);
  connect(pvarray.p,converter.p1);
  connect(converter.n1,ground.p);
  connect(converter.n2,ground.p);
  connect(DutyCycle.y,converter.D);
  connect(converter.p2,load.p);
  connect(ramp.y,load.R);
  connect(load.n,ground.p);
  connect(converter.p2,battery1.p);
  connect(battery1.n,battery2.p);
  connect(battery2.n,battery3.p);
  connect(battery3.n,battery4.p);
  connect(battery4.n,ground.p);
end HRES SolarSystem;
```

One Port

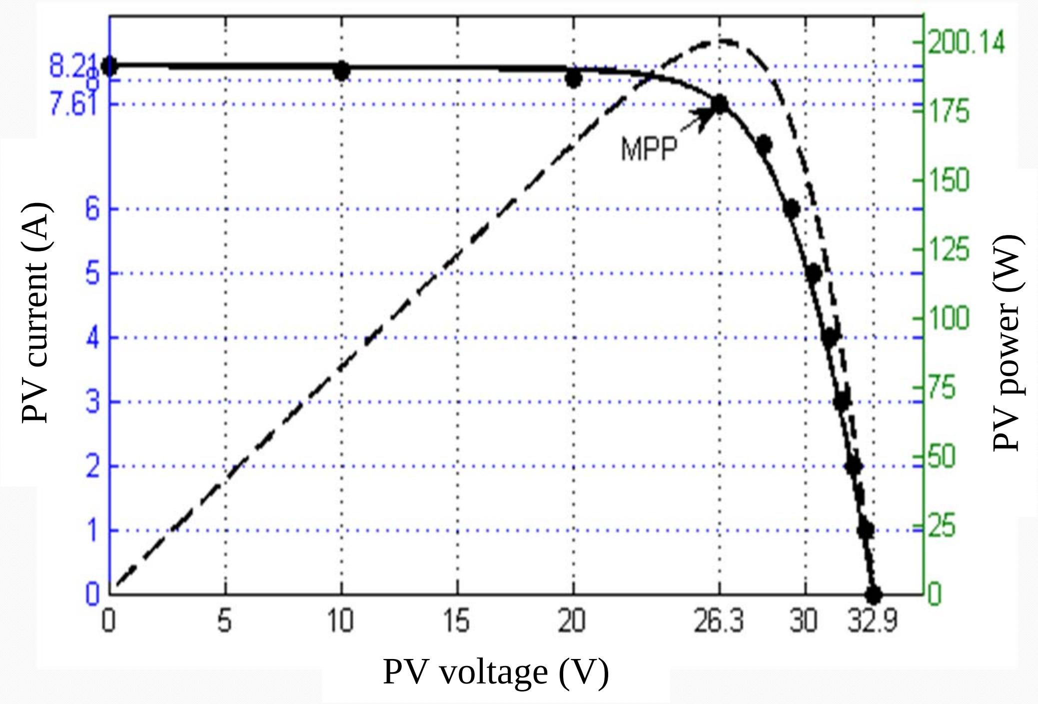
Two Port

One Port

The lead-acid battery Modelica class; the red ellipse indicates a segment that handles the mode transition events.

```
class LeadAcidBattery
    ...
    PositivePin p;
    NegativePin n;
    discrete  Boolean chargeState(start = true);
    ...
equation
    chargeState = if ibat  0 then true else false;
    der(charge) = (1/3600) * ibat;
    der(V exp) = if chargeState then
                         P2 /3600 *abs(i) *(P3 - V exp)
                     else -(P2 *abs(i))/3600 *V exp;
    when change(chargeState) and pre(chargeState) then
        tmp = if not chargeState then
                  pre(vbat) - V0 - R *pre(ibat)-
                  …
                else 0;
        reinit(Vexp, tmp);
    end when;
    soc = 1 – charge/Cmax;
    vbat = if chargeState then
              V 0-R ibat-(P1*Cmax)/(Cmax-charge) *charge-
              …
            else V 0-Ribat-(P1*Cmax)/(Cmax-charge)*charge-
                  …;
end LeadAcidBattery;
```

Modeling the system as Modelica classes



The simulated I-V (solid-line) and P-V (dashed-line) curves of the KC200GT PV module and empirical points provided by the manufacturer (the circle markers)

Validating the PV module simulation results

❑The developed PV model has been simulated separately.

❑The simulation results validated with the available data in manufacturer datasheet.

❑ It follows accurately the empirical data available by the manufacturer.

❑ The simulated MPP is matched to the empirical data provided by the manufacturer (26.3V, 7.61A).

❑The datasheet of the PV module is available from www.kyocerasolar.com/assets/001/5195.pdf

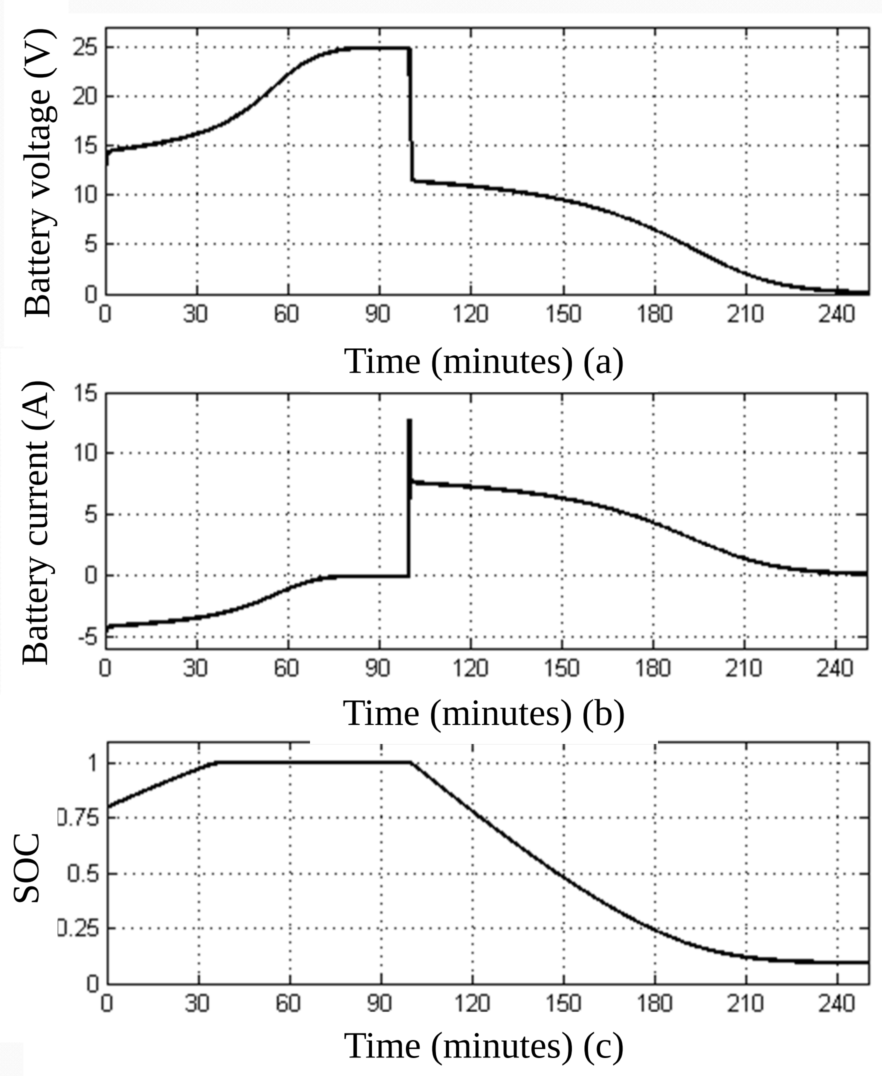
northumbria UNIVERSITY

LINKÖPINGS UNIVERSITET

Modeling the system as Modelica classes

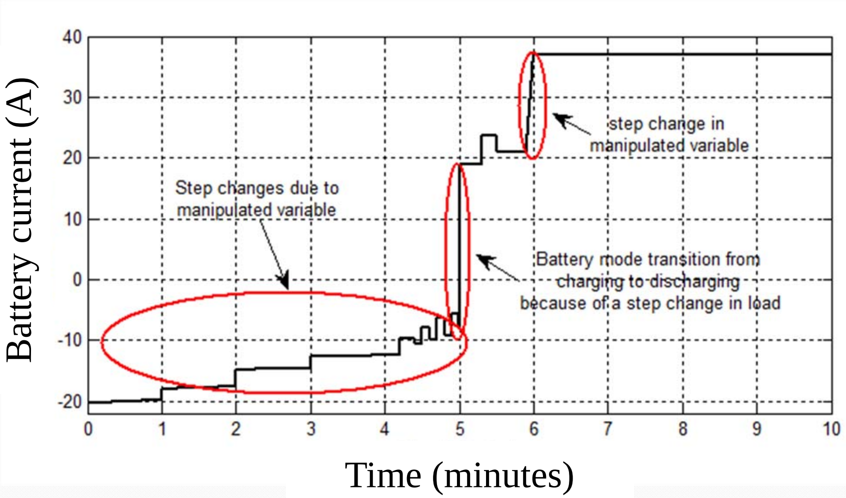
Validating the battery simulation results

- The developed Modelica model for Panasonic LC-R127R2PG battery has been simulated separately for all zones.
- The battery Modelica model validated with the available data in manufacturer datasheet.
- According to the simulation scenario, battery is charging for 100 minutes and then it is discharged.
- Discharging with the average current of 7.2A, it takes around 35 min to reach the cut-off voltage (10.2V). It matches perfectly with datasheet.
- The datasheet of the battery is available from www.farnell.com/datasheets/1624915.pdf



The simulated (a) battery voltage, (b) battery current, and (c) the SOC of the battery.

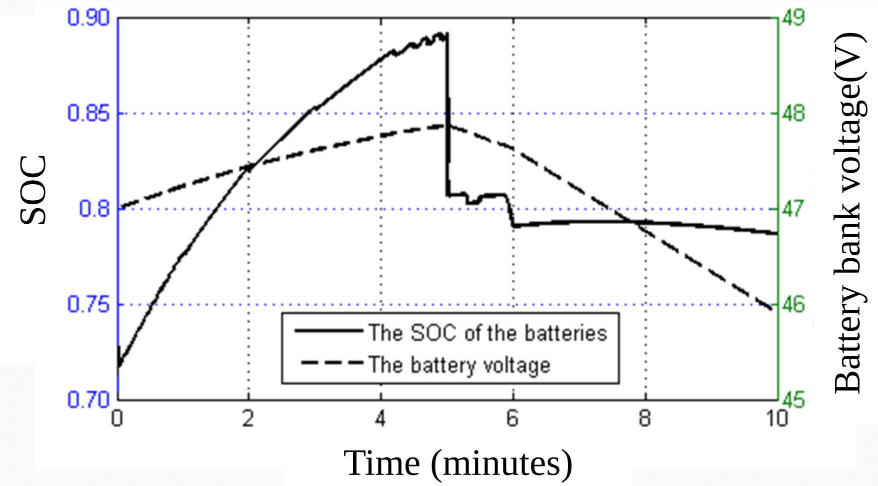
Modeling the system as Modelica classes



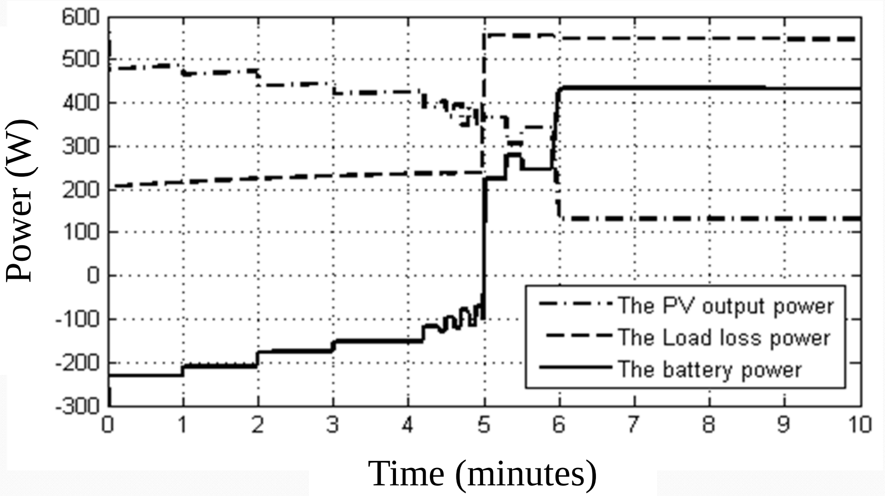
The simulated battery current.

Simulation scenario

- Before t=5min, the generated power by the PV module experiences a stepwise decrease due to manipulating the control signal, D.
- The load demand suddenly exceeds the generated power at t=5 min.
- The generated power by the PV array declines at t = 6min by manipulating the control signal, D.



The simulated voltage and the SOC (State of Charge) of the batteries.



The simulated generated and consumed powers.

Modeling as a flat HDAE using OpenModelica

The Modelica model of the whole system

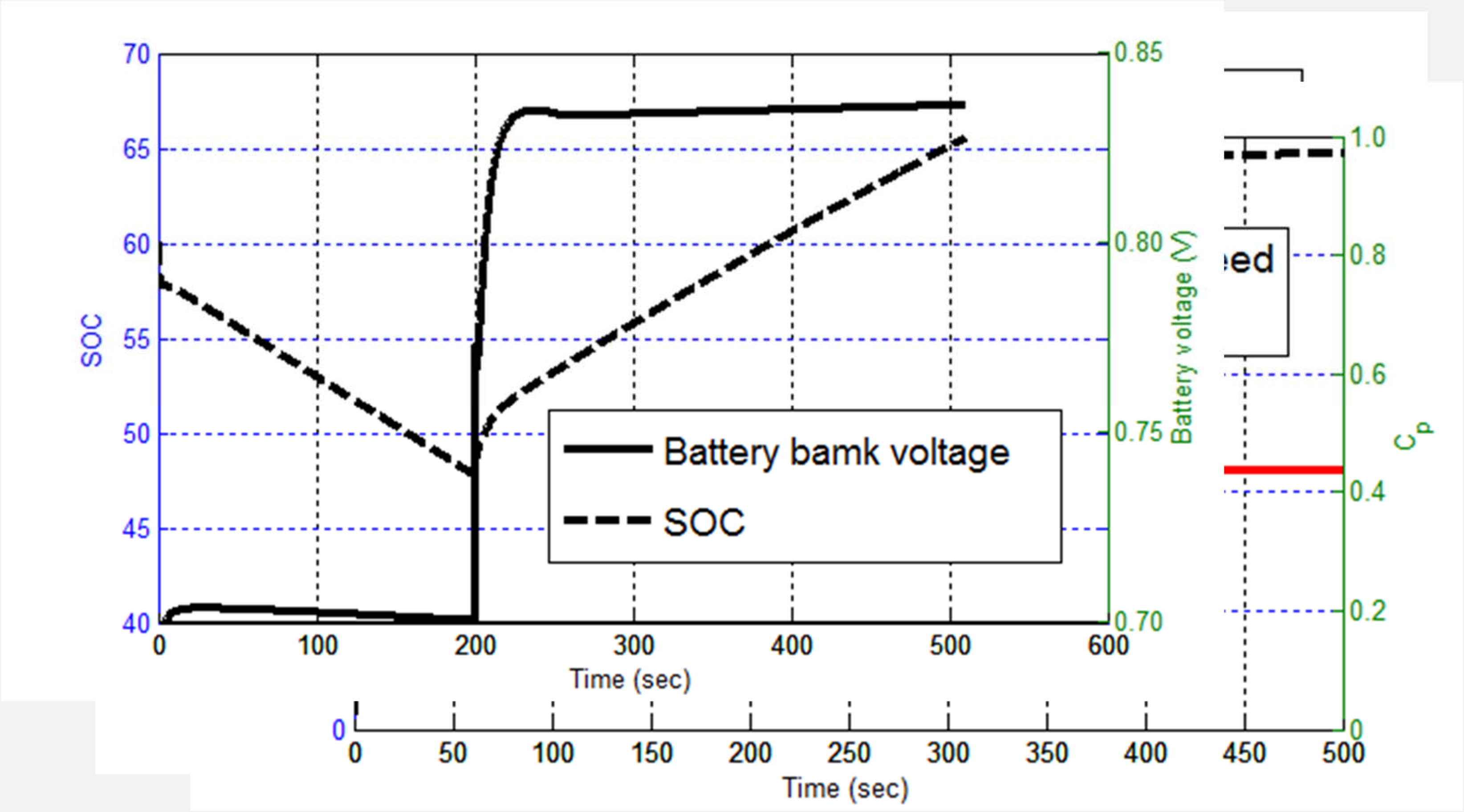
```
model HRES_Test
    Modelica.Blocks.Sources.Constant Sx(k = 1000.0);
    Modelica.Blocks.Sources.Constant Tx(k = 298.15);
    Modelica.Blocks.Sources.Constant Rx(k = 0.5);;
    Modelica.Blocks.Sources.Constant Ux(k = 12);
    Modelica.Blocks.Sources.TimeTable Beta(table = [0,0;1000,0]);
    Modelica.Blocks.Sources.TimeTable Ds(table =  [0,0.35;500,0..5]);
    Modelica.Blocks.Sources.TimeTable Dw(table =
[0,0.1;200,0.1;200.1,0.36;250,0.4;500,0.4]);
    HRES_wr hres;

equation
    connect(hres.Tx,Tx.y);
    connect(hres.Sx,Sx.y);
    connect(hres.Rx,Rx.y);
    connect(hres.Ux,Ux.y);
    connect(hres.beta,Beta.y);
    connect(hres.Dw,Dw.y);
    connect(hres.Ds,Ds.y);
end HRES_Test;
```

The combined solar/wind plant Modelica model

```
class HRES_wr
     ...
     RealInput Sx "The solar irradiance (W/m2)";
     RealInput Tx "The ambient temperature (K)";
     RealInput Ux "The wind speed (m/s)";
     RealInput Rx "The load demand (ohm)";
     RealInput beta "The pitch angle (degree)";
     RealInput Ds "The boost converter duty-cycle [0,1]";
     RealInput Dw "The buck converter duty-cycle [0,1]";
     ...
equation
     der(Tc) = 1 / Ct * ((ta - eta) * Sx - Ul * (Tc - Tx));
     iPV = iph_Tc_Sx - i0_Tc * (exp((iPV * rs_Tc + vPV) / a_Tc) ;
     ...
     Tm = -(cP * (Ux / 12) ^ 3 * 24.3 * Pnom) / wr / 24.3;
     cP = (C1 * (C2 / lambdai - C3 * beta - C4) * exp(-C5 /lambdai)
     ...
     Te = -9.6 * iWIND * Dw;
     der(wr) = (Te - Tm - F * wr) / J;
     ...
     vBAT_STACK = Dw * ((1.35 * P * psi * sqrt(3) * ...;
     ...
algorithm
     when {change(chargeState) and not pre(chargeState)} then
         noOfEqCycles:=noOfEqCycles + 1 - soc;
     end when;
end HRES_wr;
```

Modeling as a flat HDAE using OpenModelica

Simulation results



Analysis and discussion

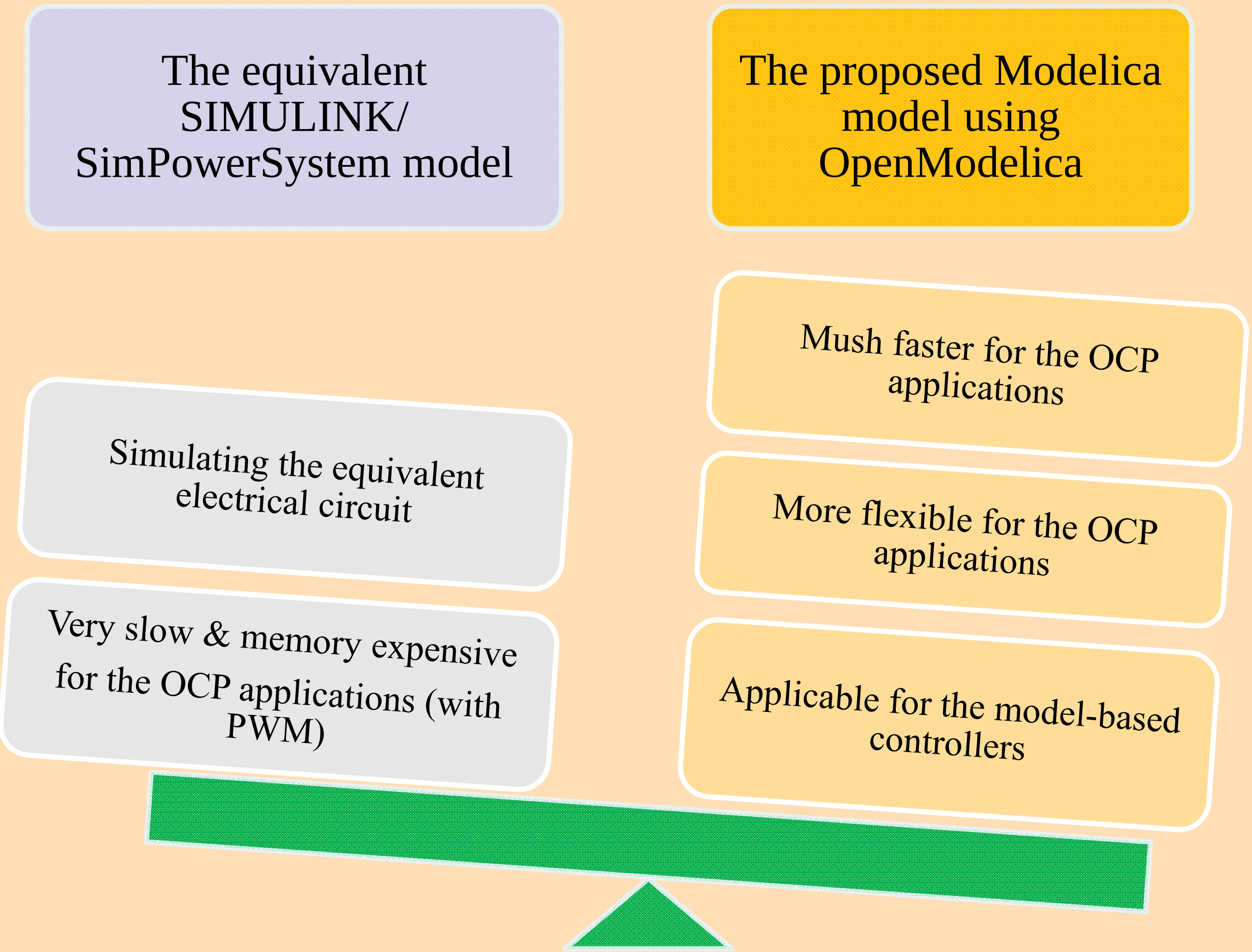
The proposed model vs. the equivalent SIMULINK/SimPowerSystem model for the optimal energy management problems

Performance criteria*	The equivalent SIMULINK/ SimPowerSystem model	The proposed Modelica model using OpenModelica
Simulation time (with the step-size of 100 nsec)**	Around 10 hrs for 3 sec of simulation	Around 8 hours for 3 sec of simulation
Simulation time (for 3600 sec)	Impractical : It is not easy to remove the PWM and make it fast.	Around 30 sec (with the step-size of 720 usec
Flexibility***	It cannot be integrated into the collocation method It is not easy to be integrated into the multiple shooting method	Adding the “smooth” function or converting to a MPCC problem, it can be used for the OCP applications

* It is just a **rough comparison** for this application. It is not the results of a systematic comparison.
** The equivalent SIMULINK model consists of **PWM** modules with the frequency of **100 KHz** that causes it to be very slow and memory expensive. While for this application, it is not straightforward to replace the converters with the average model in SIMULINK, it has been done in the proposed Modelica model that make it much faster.
*** For **OCP** applications

Analysis and discussion

The proposed model vs. the equivalent SIMULINK/SimPowerSystem model



The equivalent SIMULINK/ SimPowerSystem model

The proposed Modelica model using OpenModelica

Simulating the equivalent electrical circuit

Very slow & memory expensive for the OCP applications (with PWM)

Mush faster for the OCP applications

More flexible for the OCP applications

Applicable for the model-based controllers

Conclusion and Future works

Hybrid wind/solar energy system

Structure and characteristics

- **Wind branch**: Wind turbine + Generator + Rectifier + Converter
- **Solar branch**: PV panel + Converter
- **Storage**: Battery bank
- Nonlinear HDAE of Index-1

Modeling

- **Modelica** language has been employed.
- A **library** of the modelica components has been developed.
- A **flat HDAE** model has been developed as well.

Simulation results

- The **OpenModelica** tool has been used.
- The complete system has been **simulated**.
- The simulation results have been **verified** with the information available in datasheets.

Future works

- Combining OpenModelica and CasAdi to design nonlinear optimal controllers
- Optimal energy management

northumbria UNIVERSITY

LINKÖPINGS UNIVERSITET

References

[1] A. M. Dizqah, K. Busawon, P. Fritzson. Acausal Modeling and Simulation of the Standalone Solar Power Systems as Hybrid DAEs, The 53rd Intl. Conf. Of the Scandinavian Simulation Society (SIMS), 2012.
[2] I. H. Altas, and A. M. Sharaf. A photovoltaic array simulation model for matlab-Simulink GUI environment. In Proc. Intl. Conf. Clean Elect. Power (ICCEP), pages 341–345, 2007.
[3] M. Buresch. Photovoltaic Energy Systems Design and Installation. McGraw-Hill, New York, 1983.
[4] M. G. Villalva, J. R. Gazoli, and E. R. Filho. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Transactions on Power Electronics, 24:1198–1208, 2009.
[5] F. M. Petcut, and T. L. Dragomir. Solar cell parameter identification using genetic algorithms. Journal of Control Engineering and Applied Informatics, 12:30–37, 2010.
[6] C. Carrero, J. Amador, and S. Arnaltes. A single procedure for helping PV designers to select silicon PV modules and evaluate the loss resistances. Journal of Renewable Energy, 32:2579–2589, 2007.
[7] D. Guasch, and S. Silvestre. Dynamic battery model for photovoltaic applications. Progress in Photovoltaics: Research and Applications, 11:193–206, 2003.
[8] O. Tremblay ,and L. Dessaint. Experimental validation of a battery dynamic model for ev applications. World Electric Vehicle Journal, 3:10–15, 2009.
[9] M. Najafi,and R. Nikoukhah. Modeling and simulation of differential equations in scicos. In The Modelica Association, editor, Modelica Conference, 2006.
[10] H. Lundvall, P. Fritzson, and B. Bachmann. Event handling in the openmodelica compiler and runtime system. In the 46th Conference on Simulation and Modeling (SIMS 2005), Trondheim, Norway, 2005.
[11] M. K. Deshmukh, and S. S. Deshmukh. Modelling of hybrid renewable energy system. Renewable And Sustainable Energy Reviews, 12:235–249, 2008.
[12] J. J. Soon, and K. S. Low. Photovoltaic model identification using particle swarm optimization with inverse barrier constraints. IEEE Transactions on Power Electronics, 27:3975–3983, 2012.
[13] K. Ishaque, Z. Salam, and H. Taheri. Simple, fast and accurate two-diode model for photovoltaic modules. Journal of Solar Energy Materials and Solar Cells, 95:586–594, 2011.
[14] Q. Kou, S. A. Klein, and W. A. Beckman. A method for estimating the long-term performance of direct-coupled PV pumping systems. Journal of Solar Energy, 64:33– 40, 1998.
[15] R. D. Middledbrook,and S. Cuk. A general unified approach to modelling switching-converter power stages. In Proc. of IEEE Power Electronics Specialist conference, 1976.
[16] M. Beaudin, H. Zareipour, A. Schellenberglabe, and W. Rosehart. Energy storage for mitigating the variability of renewable electricity sources: An updated review. Energy for Sustainable Development, 14:302–314, 2010.
[17] K. C. Divya, and J. Ostergaard. Battery energy storage technology for power systems an overview. Electric Power Systems Research, 79:511–520, 2009.
[18] SUNDIALS. Suite of nonlinear and differential/algebraic equation solver. https://computation.llnl.gov/casc/sundials/.
[19] DAETS. Defferential-algebraic equations by taylor series. www.cas.mcmaster.ca/ nedialk/dates/.
[20] DASSL. Defferential algebraic system solver. www.cs.ucsb.edu/ cse/.
[21] Modelica. Modelica association. www.modelica.org.
[22] P. Fritzson. Introduction to modelling and Simulation of Technical and Physical Systems with Modelica. John Wiley & Sons, New York, 2011.
[23] OpenModelica. Open-source modelica-based modeling and simulation env. www.openmodelica.org.
[24] Kyocera. KC200GT, high efficiency multicrystal photovoltaic module. www.kyocerasolar.com/assets/001/5195.pdf, 2012.
[25] Panasonic. LC-R127R2PG, panasonic batteries. www.farnell.com/datasheets/1624915.pdf.

Thank You