Control Course Project

Wind Turbine - Cistern - Super Capacitor Modeling and Simulation based on MATLAB/Octave

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Supported Features : Energy storage(cisterns + super capacitor, not battery), feedback control.

Introduction

Background

The stability of the grid is of vital importance, because many power devices, such as the induction motors, transformers, variable-frequency drives are sensitive to the voltage and frequency of the power supply. Without storage devices, the energy loss will be increased, which can lead to overheating when the heaksink systems are only designed for normal work load and TDP. In addition, unexpected oscillation and sudden load may damage the connected devices, especially for some inductive loads.

Components

The wind turbine generator is usually an Doubly Fed Induction Generator (DFIG), or dynamos. The DFIGs don't need a set of excitation capacitors, and the apperant power under zero-load working status is provided by the grid, so the details in normal induction motors are not included in the model.

For wind turbines with larger capacity (about 2MW), a synchronous generator with a variable-frequency drive is more likely to be used.

The given hybrid power supply system contains several components :

- **Wind Turbines**

  Provides electric power, the output is not stable and affected by the weather.

- **Energy Banks** (Batteries, molten salt cans or cisterns)

  Cisterns(stores extra potential/kinetic energy) and molten salt cans(common in solar-thermal power stations) got very large capacity and long lifespan(more than 10 years), but it is not flexible enough for sudden load because these energy storage system also contains mechanical components. In recent years, some of the solar-thermal plants has been equipped with molten salt cans ($\geq 800^{\circ}C$) and Stirling engines to get all-weather stablized power output and more than 30% efficiency in deserts, which is not suitable for cisterns and other engines with normal cooling systems.

  Batteries are easier for scheduling, but got smaller energy and power density and much more expensive than cisterns and molten salt cans. In addition, the lifespan of batteries are limited to about 1500 cycles even with the most advanced technology today, so it is not suitable for supplying large amount of current.

- **Super Capacitors**

  Provides the smallest energy storage capacity, but it is suitable for sudden current demands with its high power density and extremely long lifespan for rapid recharging applications.

By combining these sub-systems together, the power supply system got more robust and ready for more complicated situations.

Task 1 / Model of capacitor

The capacitor can be descripted in the following model :

$$i_C = C\frac{dU}{dt}, E_C = \frac{1}{2}CU^2 \tag{1}$$

The state of the capacitor can be fully descibed by its voltage, so $x = [Voltage]$.

$$\dot{x} = \frac{1}{C}u \tag{2}$$

Set the output as the voltage, $C = 1$

$$A = 0, B = \frac{1}{C}, C = 1, D = 0 \tag{3}$$

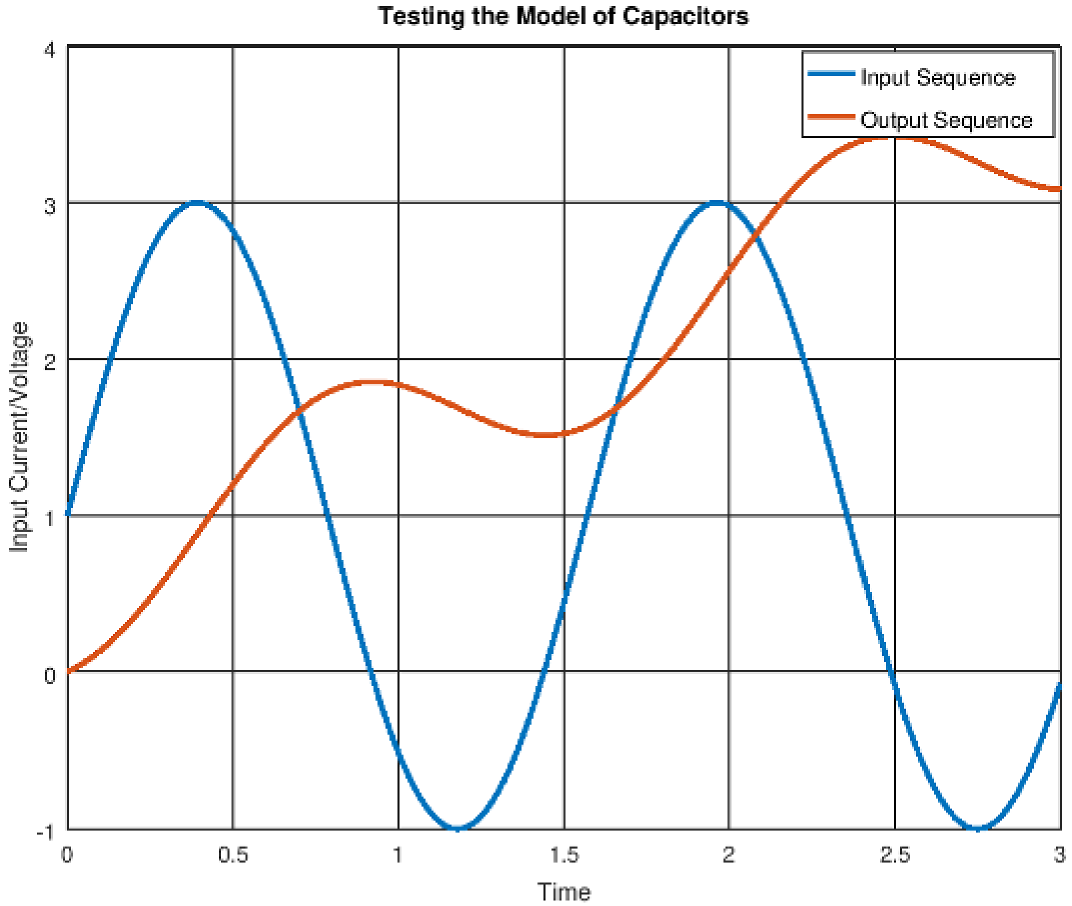
Building capacitor model in Matlab/Octave:

```
%% Capacitance
cap_C = 1.0;

%% State-space Model Matrices
mat_A = [0];
mat_B = [1.0/cap_C];
mat_C = [1];
mat_D = [0];

%% State-space System
sys_G = ss(mat_A,mat_B,mat_C,mat_D);
```

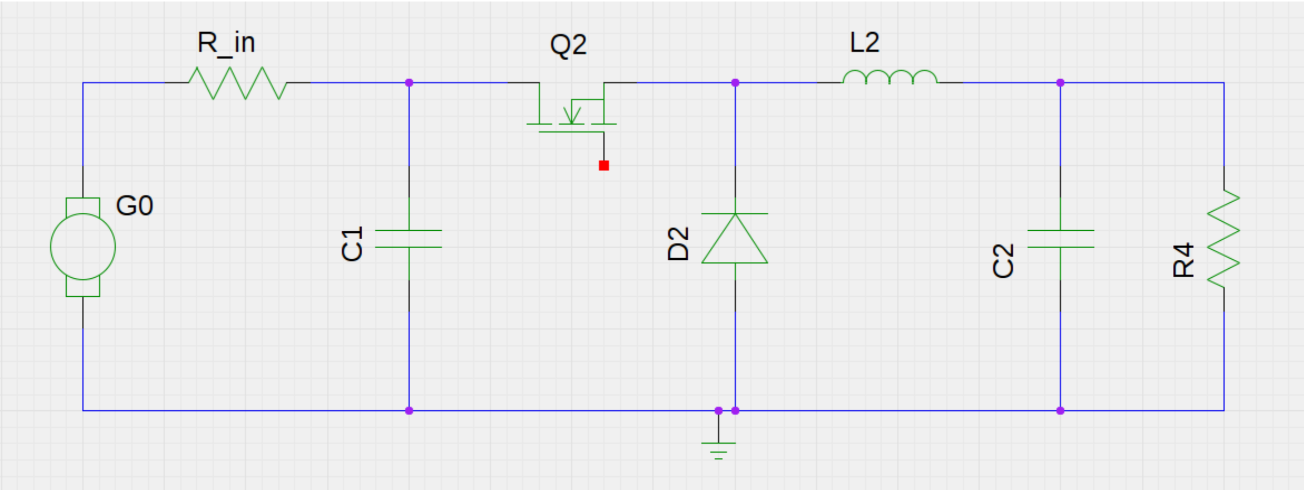
Result:


Testing the Model of Capacitors
Input Sequence
Output Sequence
Input Current/Voltage
Time
4
3
2
1
0
-1
0
0.5
1
1.5
2
2.5
3

Task 2 / Model of the system

Circuit Model

The circuit for the system model is shown below.



The main components are:

- Dynamos G_0

  The DC generator contains an ideal dynamo G_0 and a internal resistor R_{in}.

- Super Capacitor C_1

  The capacitor must be connected on the input stage of the buck converter to ensure it works in CCM.

- DC-DC Buck Converter

  The DC-DC Buck Converter is cascaded after the dynamo.

- Load

  The load is a simple resistor.

- Energy Bank, aka Cisterns, not battery, not shown in schematic.

  Cistern and generator/motor, scheduled by voltage feedback.

State-Space Average Model

AC-DC converting involves generalized state-space average(GSSA) model or SSEM and greatly increase the complexity for the analysis of the system. So that DC dynamo is used in building up the system.

By using the state-space average(SSA) model, the DC-DC buck converter can be treated as a linear system, by ignoring the high frequency components(>10kHz) caused by the PWM control signal.

The state vector $\mathbf{x}$ and input $\mathbf{u}$ can be descripted as:

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} \omega \\ U_{Csuper} \\ U_{Cbuck} \\ I_{Lbuck} \end{bmatrix}, \mathbf{u} = \begin{bmatrix} \tau \\ U_{ref} \end{bmatrix} \tag{4}$$

The parameters contains:

$$C_{super}, C_{buck}, L_{buck}, D_{PWM}, J_G, K_m, K_e, K_L, f_{air}, R_{in}, R_L \tag{5}$$

C_{super} : Capacitance of the super capacitor.

C_{buck} : Capacitance of the capacitor in DC-DC Buck converter.

L_{buck} : Inductance of the inductor in DC-DC Buck converter.

D_{PWM} : PWM control signal duty-cycle.

J_G : Moment of inertia of the rotor in the dynamo.

K_m : The current-torque relationship in the dynamo.

K_e : The speed-voltage relationship in the dynamo.

K_{SL} : The parameter for cistern water pump - centrifugal governor in the dynamo, aka speed limit.

f_{air} : The air and mechanical friction parameter.

R_x : Equavalent resistors

SSA Model | System with MOSFET-Triode State

The system equations are shown below:

$$I_{Lbuck} = C_{buck}\frac{dU_{Cbuck}}{dt} + \frac{U_{Cbuck}}{R_L} \tag{6}$$

$$-K_m(\frac{K_e\omega - U_{Csuper}}{R_{in}}) - f_{air}\omega + \tau - K_{SL}(U_{Cbuck} - U_{ref}) = J_G\frac{d\omega}{dt} \tag{7}$$

$$K_e\omega = (I_{Lbuck} + C_{super}\frac{dU_{Csuper}}{dt})R_{in} + U_{Csuper} \tag{8}$$

$$U_{Csuper} - U_{Cbuck} = L_{buck}\frac{dI_{Lbuck}}{dt} \tag{9}$$

The matrices can be obtained by following equations:

$$\dot{x}_1 = (-\frac{K_mK_e}{R_{in}J_G} - \frac{f_{air}}{J_G})x_1 + \frac{K_m}{J_GR_{in}}x_2 - \frac{K_{SL}}{J_G}x_3 + \frac{1}{J_G}u_1 + \frac{K_{SL}}{J_G}u_2 \tag{10}$$

$$\dot{x}_2 = \frac{K_e}{C_{super}R_{in}}x_1 + \frac{1}{C_{super}R_{in}}x_2 - \frac{1}{C_{super}}x_4 \tag{11}$$

$$\dot{x}_3 = -\frac{1}{C_{buck}R_L}x_3 + \frac{1}{C_{buck}}x_4 \tag{12}$$

$$\dot{x}_4 = \frac{1}{L_{buck}}x_2 - \frac{1}{L_{buck}}x_3 \tag{13}$$

The matrices:

$$A = \begin{bmatrix} -\frac{K_m K_e}{J_G R_{in}} - \frac{f_{air}}{J_G} & \frac{K_m}{J_G R_{in}} & -\frac{K_{SL}}{J_G} & 0 \\ \frac{K_e}{C_{super} R_{in}} & \frac{1}{C_{super} R_{in}} & 0 & -\frac{1}{C_{super}} \\ 0 & 0 & -\frac{1}{C_{buck} R_L} & \frac{1}{C_{buck}} \\ 0 & \frac{1}{L_{buck}} & -\frac{1}{L_{buck}} & 0 \end{bmatrix} \tag{14}$$

$$B = \begin{bmatrix} \frac{1}{J_G} & \frac{K_{SL}}{J_G} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix} \tag{15}$$

SSA Model | System with MOSFET-Cutoff State

$$K_e \omega = U_{Csuper} + C_{super} R_{in} \frac{dU_{Csuper}}{dt} \tag{16}$$

$$I_{Lbuck} = \frac{U_{Cbuck}}{R_L} + C_{buck} \frac{dU_{Cbuck}}{dt} \tag{17}$$

$$L_{buck} \frac{dI_{Lbuck}}{dt} = U_{Cbuck} \tag{18}$$

$$J_G \frac{d\omega}{dt} = -K_m \frac{K_e \omega - U_{Csuper}}{R_{in}} - f_{air} \omega + \tau \tag{19}$$

The matrices can be obtained by following equations:

$$\dot{x}_1 = (-\frac{K_m K_e}{J_G R_{in}} - \frac{f_{air}}{J_G}) x_1 + \frac{K_m}{J_G R_{in}} x_2 + \frac{u}{J_G} \tag{20}$$

$$\dot{x}_2 = \frac{K_e}{R_{in} C_{super}} x_1 - \frac{1}{R_{in} C_{super}} x_2 \tag{21}$$

$$\dot{x}_3 = \frac{1}{C_{buck}} (x_4 - \frac{x_3}{R_L}) \tag{22}$$

$$\dot{x}_4 = -\frac{1}{L_{buck}} x_3 \tag{23}$$

The matrices:

$$A = \begin{bmatrix} -\frac{K_m K_e}{J_G R_{in}} - \frac{f_{air}}{J_G} & \frac{K_m}{J_G R_{in}} & 0 & 0 \\ \frac{K_e}{C_{super} R_{in}} & \frac{1}{C_{super} R_{in}} & 0 & 0 \\ 0 & 0 & -\frac{1}{C_{buck} R_L} & \frac{1}{C_{buck}} \\ 0 & 0 & -\frac{1}{L_{buck}} & 0 \end{bmatrix} \tag{24}$$

$$B = \begin{bmatrix} \frac{1}{J_G} \\ 0 \\ 0 \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}, D = \begin{bmatrix} 0 \end{bmatrix} \tag{25}$$

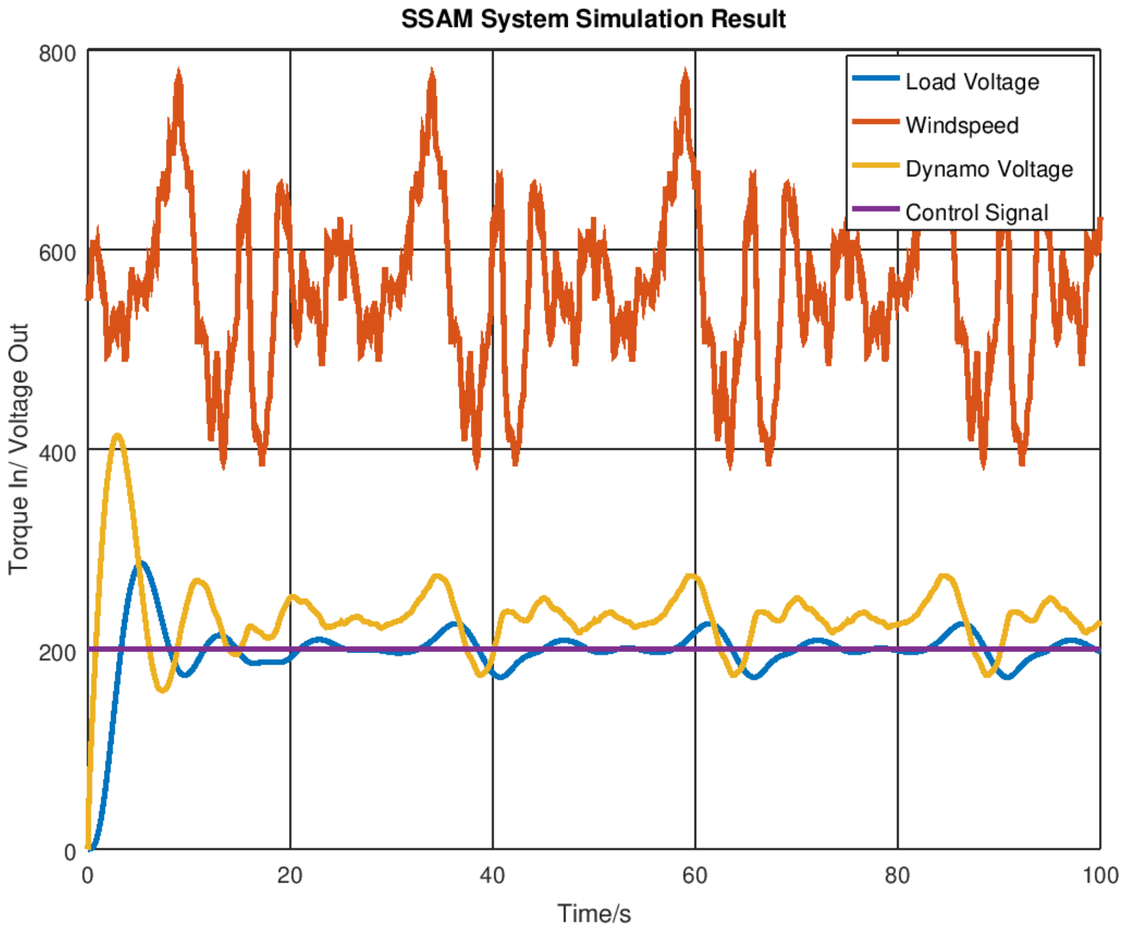
SSA Model | Summarize

$$\mathbf{A}_{SSA} = D\mathbf{A}_{triode} + (D-1)\mathbf{A}_{cut-off} \tag{26}$$

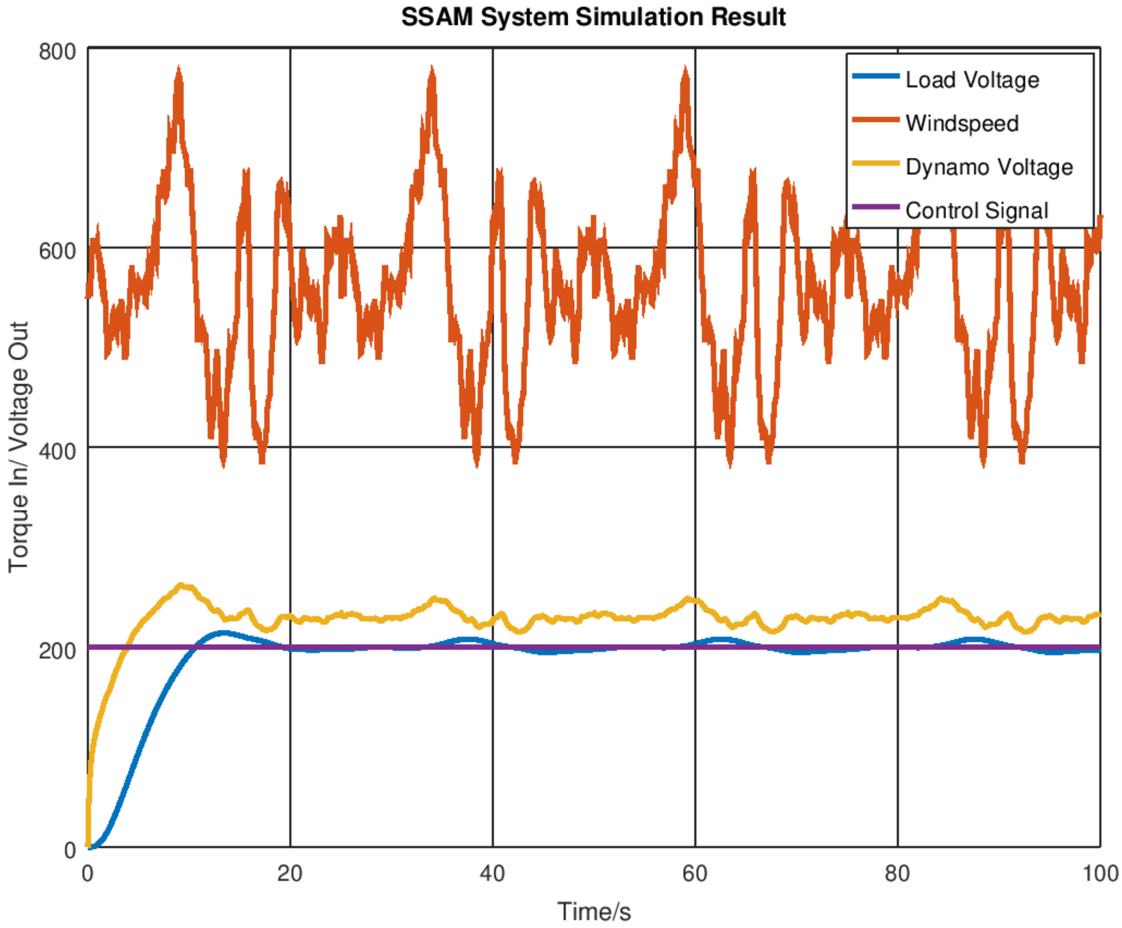
Simulation Result

Reminder: All the simulation uses the wind data from the given CSV file.

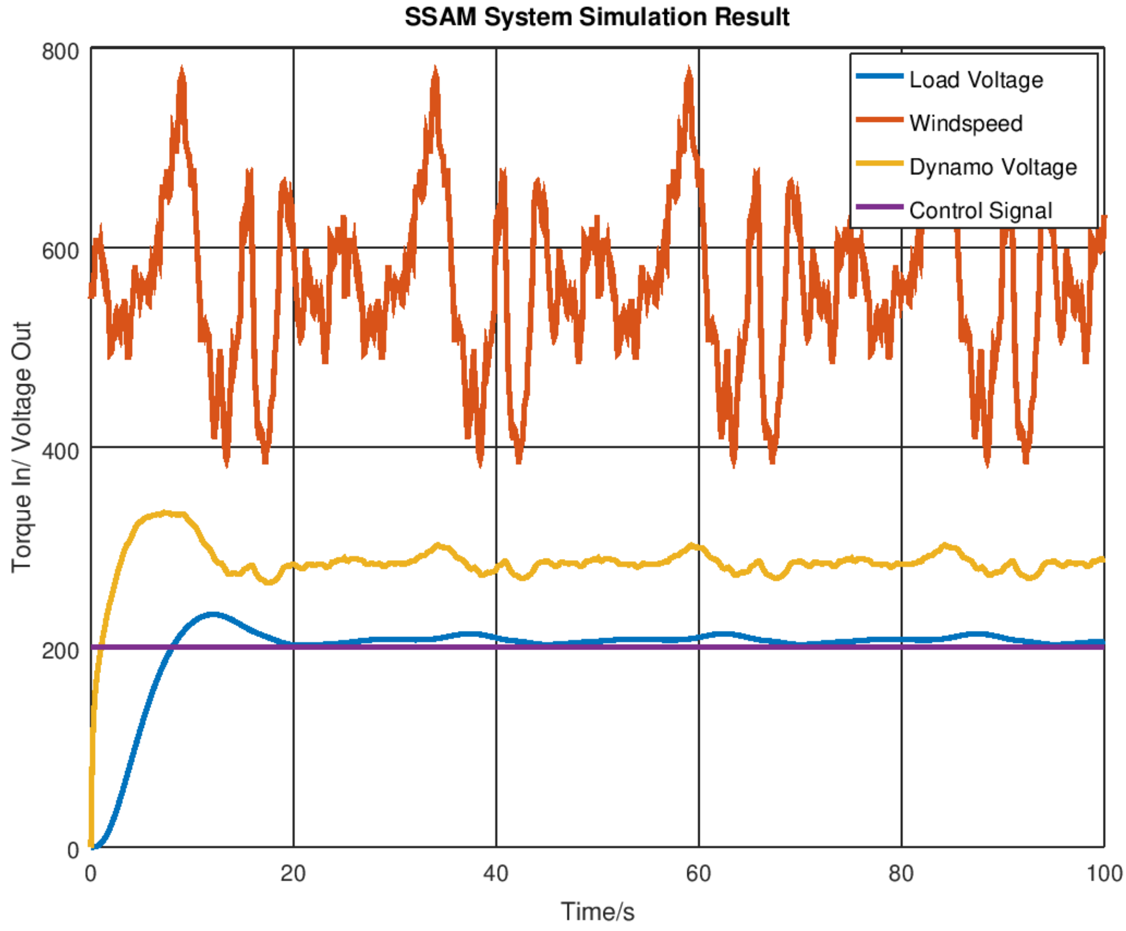
using 10C super capacitor, D = 1



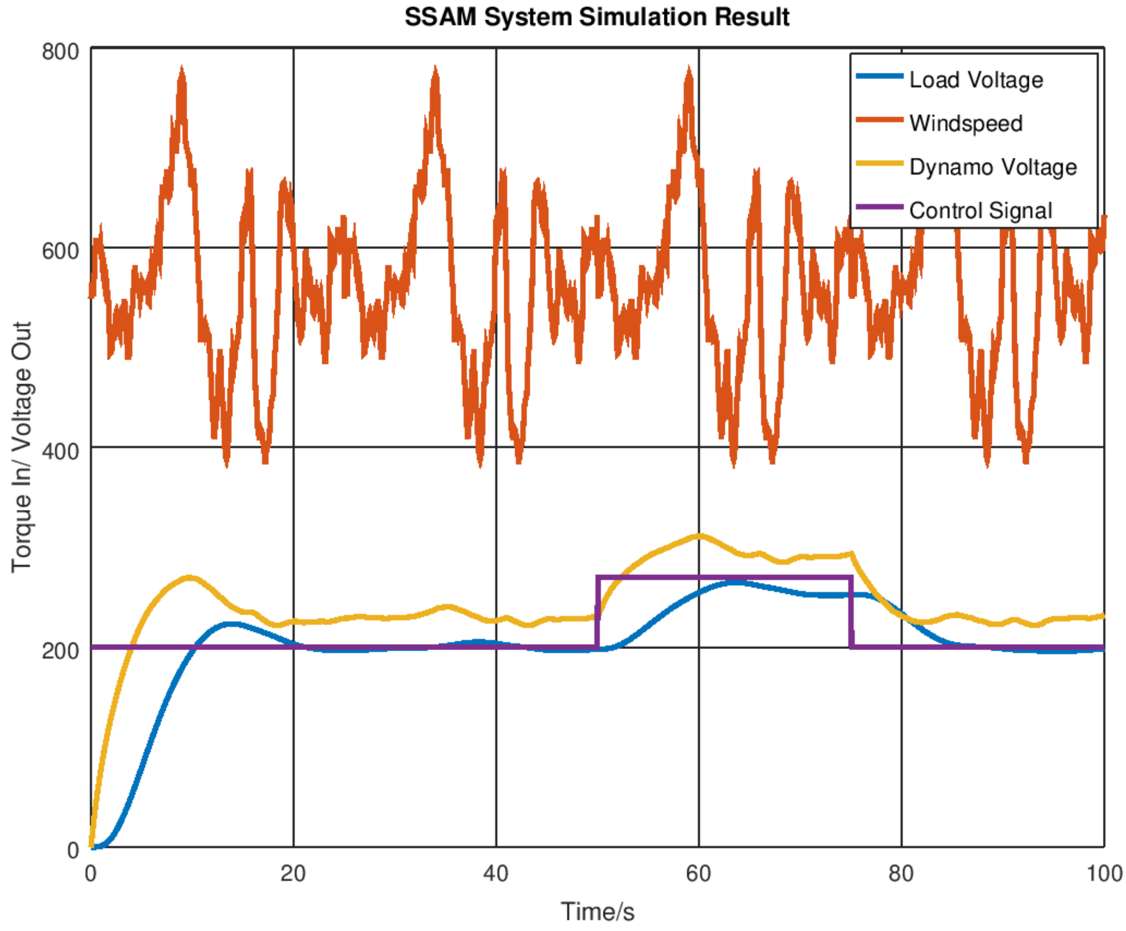
using 70C super capacitor, D = 1



using 70C super capacitor, buck converter PWM duty-cycle D = 0.6



Sudden voltage demand test, using 70C super capacitor, D = 1


SSAM System Simulation Result
Load Voltage
Windspeed
Dynamo Voltage
Control Signal
Torque In/ Voltage Out
800
600
400
200
0
0
20
40
60
80
100
Time/s

Summary

Control Strategies for Load/Demand Changes

- Control the electro-magnetical or mechanical load.

  Mechanical loads, such as the water pump of a cistern, can be attached to the dynamo's rotor to store the exceeded energy into energy banks and limit the speed of the dynamo (scheduled by a centrifugal governor), which has already been adopted in real application.

  This feature is implemeted in the SSA model.

For Wind Changes, or for Higher Efficiency

- Control the Buck Converter D_{PWM}

  The PWM control signal of the buck converter can be used to adjust the speed-voltage relationship between load and the dynamo, which can be used to limit the speed and let the dynamo runs in speed region with higher efficiency and longer lifespan.

  The simulation can not be directly implemeted in the SSA model.