Feasible Actuator Range Modifier (FARM) User Manual

Supervisory Control plugin for RAVEN

FARM-UM-1

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Contents

1 Introduction

Feasible Actuator Range Modifier (FARM) is a RAVEN ([1] and [2])plugin designed to solve the supervisory control problem in Integrated Energy System (IES) project. FARM utilizes the linear state-space representation (A,B,C matrices) of a model to predict the system state and output in the future time steps, and adjust the actuation variable to avoid the violation of implicit thermal mechanical constraints.

1.1 FARM Plugin: Reference Governor SIMO

The first external model in FARM plugin is a scalar Reference Governor([3] and [4]) for single input multiple output (SIMO) system. Assume the system has the following linear state space representation([5]) in **discrete** time domain:

- $\overrightarrow{x}[k+1] = \mathbf{A} * \overrightarrow{x}[k] + \mathbf{B} * u[k]$
- $\overrightarrow{y}[k+1] = \mathbf{C} * \overrightarrow{x}[k+1]$

where:

- $u \in \mathbb{R}$, is system actuation variable, scalar;
- $\overrightarrow{x} \in \mathbb{R}^n$, is system state vector, n elements;
- $\overrightarrow{y} \in \mathbb{R}^p$, is system output vector, p elements;
- $\mathbf{A} \in \mathbb{C}^{n\times n}$ is the state matrix;
- $\mathbf{B} \in \mathbb{C}^{n\times 1}$ is the input matrix;
- $\mathbf{C} \in \mathbb{C}^{p\times n}$ is the output matrix;

The Reference Governor SIMO use the linear matrices $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$ and the current system state vector $\overrightarrow{x}[k]$ to predict the system state vectors $\overrightarrow{x}[k+1], \overrightarrow{x}[k+2], ..., \overrightarrow{x}[k+g]$ and output vectors $\overrightarrow{y}[k+1]$, $\overrightarrow{y}[k+2]$, ..., $\overrightarrow{y}[k+g]$ for the next **g** time steps assuming a constant actuation variable u is applied to the system. In addition, the steady state vector $\overrightarrow{x}[\infty]$ and output vector $\overrightarrow{y}[\infty]$ under the same system actuation variable u is predicted.

With the knowledge of the constraints ($\overrightarrow{y_{min}}$ and $\overrightarrow{y_{max}}$) on system output vector $\overrightarrow{y}$, the predicted system output vectors ($\overrightarrow{y}[k+1]$, $\overrightarrow{y}[k+2], ...,$ $\overrightarrow{y}[k+g]$, and $\overrightarrow{y}[\infty]$) will be compared to the constraints element-wisely. Once a violation was found, the actuation variable u will be scaled down to avoid the violation.

In addition to the scaled down system actuation variable u, the admissible range of actuation variable (u_{min} and u_{max}) is also calculated. The actuation variable with a value within this admissible range will not cause any violation of the constraints in both the next consecutive **g** time steps and the steady state.

2 Input of FARM for RAVEN

In this section, the external matrices file structure, FARM model definition, and input/output file example will be discussed. In order to run FARM, two XML files are required:

- External Matrices File (See Section 2.1), and
- Input File (See Section 2.2)

Currently two version of Reference Governor SIMO are provided: paramterized version, and unparameterized version.

- Parameterized Version: Multiple state-space representations profiles are provided in the external matrices file, labeled by a parameter "ActuatorParameter". The FARM will select the closest profile based on the value of input variable "PwrSet".
- Unparameterized Version: Single state-space representation profile is provided, and will be used in all the time.

2.1 External Matrices File Structure

As discussed in 1.1, the state space matrices **A**, **B**, **C** are required for the FARM to run. In addition, the norminal values of u, $\overrightarrow{x}$, $\overrightarrow{y}$ needs to be known for the following equations at $k = 0$ to be satisfied:

- $\overrightarrow{x}[k+1] = \mathbf{A} * \overrightarrow{0} + \mathbf{B} * 0$
- $\overrightarrow{0} = \mathbf{C} * \overrightarrow{0}$

In addition, the latest value of $\overrightarrow{x}$ needs to be known as the current system state if no other values are provided in the Input File.

2.1.1 Parameterized External Matrices File

The following Listing 1 is a example external matrices file for Parameterized Reference Governor with necessary information:

Listing 1: Parameterized External Matrices File Example.

```
<DataObjectMetadata name="rom_stats">
  <DMDrom type="Static">
    <DMDcModel>
      <dmdTimeScale>1800 1810
      <UNorm>
        <realization ActuatorParameter="-1.15e+01"
           sample="0">-4.68e-02</realization>
```

```
    <realization ActuatorParameter="-3.45e+01"
       sample="1">-4.30e-01</realization>
  </UNorm>
  <XNorm>
    <realization ActuatorParameter="-1.15e+01"
       sample="0">2.55e+01 0.00e+00</realization>
    <realization ActuatorParameter="-3.45e+01"
       sample="1">2.55e+01 0.00e+00</realization>
  </XNorm>
  <YNorm>
    <realization ActuatorParameter="-1.15e+01"
       sample="0">3.20e+01 2.55e+01</realization>
    <realization ActuatorParameter="-3.45e+01"
       sample="1">3.20e+01 2.55e+01</realization>
  </YNorm>
  <XLast>
    <realization ActuatorParameter="-1.15e+01"
       sample="0">2.44e+01 4.12e+01</realization>
    <realization ActuatorParameter="-3.45e+01"
       sample="1">2.19e+01 1.38e+02</realization>
  </XLast>
  <Atilde>
    <realization ActuatorParameter="-1.15e+01" sample="0">
      <imaginary>0.00e+00 0.00e+00 0.00e+00
         0.00e+00</imaginary>
      <matrixShape>2,2</matrixShape>
      <real>1.00e+00 -1.18e-01 -6.25e-05 4.14e-03</real>
    </realization>
    <realization ActuatorParameter="-3.45e+01" sample="1">
      <imaginary>0.00e+00 0.00e+00 0.00e+00
         0.00e+00</imaginary>
      <matrixShape>2,2</matrixShape>
      <real>1.00e+00 -5.61e-02 -6.90e-05 1.32e-01</real>
    </realization>
  </Atilde>
  <Btilde>
    <realization ActuatorParameter="-1.15e+01" sample="0">
      <imaginary>0.00e+00 0.00e+00</imaginary>
      <matrixShape>2,1</matrixShape>
      <real>-2.01e-04 -4.21e+00</real>
    </realization>
    <realization ActuatorParameter="-3.45e+01" sample="1">
```

```
          <imaginary>0.00e+00 0.00e+00</imaginary>
          <matrixShape>2,1</matrixShape>
          <real>-2.31e-04 -3.71e+00</real>
        </realization>
      </Btilde>
      <Ctilde>
        <realization ActuatorParameter="-1.15e+01" sample="0">
          <imaginary>0.00e+00 0.00e+00 0.00e+00
             0.00e+00</imaginary>
          <matrixShape>2,2</matrixShape>
          <real>-1.00e+00 1.00e+00 -3.48e-10 1.10e-16</real>
        </realization>
        <realization ActuatorParameter="-3.45e+01" sample="1">
          <imaginary>0.00e+00 0.00e+00 0.00e+00
             0.00e+00</imaginary>
          <matrixShape>2,2</matrixShape>
          <real>-1.00e+00 1.00e+00 -5.85e-10 7.81e-18</real>
        </realization>
      </Ctilde>
    </DMDcModel>
  </DMDrom>
</DataObjectMetadata>
```

As one can see, all the required information for FARM are included in the <DMDcModel> block. Indeed, the name of this block and its parent blocks is flexible:

- <DataObjectMetadata>, Root element of XML file, other names are acceptable.
- <DMDrom>, Child 1 level element of XML file, other names are acceptable.
- <DMDcModel>, Child 2 level element of XML file, other names are acceptable.

As long as the following keywords and inputs are the Child 3 level elements of this XML file, the information can be processed for FARM execution:

- <dmdTimeScale>, ***float vector, required parameter***, the time step marks used in DMDc calculation. At least two consecutive time step value are required to calculate the discrete time interval;

Some items (<UNorm>, <XNorm>, <YNorm>, <XLast>, <Atilde>, <Btilde>, <Ctilde>) contains multiple <realization> nodes, in the format of <realization ActuatorParameter="some float value" sample="some integer value">, and the corresponding values are indexed by this ActuatorParameter.

- – The <ActuatorParameter> attribute share the same unit with the input variable "PwrSet", and the parameterized Reference Governor SIMO will select the realization whose <ActuatorParameter> value is closest to the input variable "PwrSet";

  - The <sample> attribute contains a consecutive integer value starting from 0.

All the following items should share the same list of <ActuatorParameter> attribute:

- <UNorm>, ***float scalar, required parameter***, the norminal value of system actuation variable u;
- <XNorm>, ***float vector, required parameter***, the norminal value of system state vector $\overrightarrow{x} \in \mathbb{R}^n$;
- <YNorm>, ***float vector, required parameter***, the norminal value of system output vector $\overrightarrow{y} \in \mathbb{R}^p$;
  - Note: the <YNorm> must have at least realization that is within the range defined by "Min_Target" and "Max_Target" in the definition of Reference Governor SIMO EnternalModel. See Listing 3 in Section 2.2.1.
- <XLast>, ***float vector, required parameter***, the latest value of system state vector $\overrightarrow{x} \in \mathbb{R}^n$, **without norminal value subtraction**;
- <Atilde>, ***complex matrix, required parameter***, the state matrix $\mathbf{A} \in \mathbb{C}^{n\times n}$:
  - <imaginary>, ***float matrix, optional parameter***, the imaginary part of state matrix **A**. The matrix are flattened column-by-column, i.e. the order is
    $A_{11}A_{21}...A_{n1}\ A_{12}A_{22}...A_{n2}...$
  - <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
  - <real>, ***float matrix, required parameter***, the real part of state matrix **A**. The matrix are flattened column-by-column, i.e. the order is
    $A_{11}A_{21}...A_{n1}\ A_{12}A_{22}...A_{n2}...$
- <Btilde>, ***complex matrix, required parameter***, the input matrix $\mathbf{B} \in \mathbb{C}^{n\times 1}$:
  - <real>, ***float matrix, required parameter***, the real part of input matrix **B**. The matrix are flattened column-by-column, i.e. the order is
    $B_{11}B_{21}...B_{n1}\ B_{12}B_{22}...B_{n2}...$
  - <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
  - <imaginary>, ***float matrix, optional parameter***, the imaginary part of input matrix **B**. The matrix are flattened column-by-column, i.e. the order is
    $B_{11}B_{21}...B_{n1}\ B_{12}B_{22}...B_{n2}...$

- <Ctilde>, ***complex matrix, required parameter***, the output matrix $\mathbf{C} \in \mathbb{C}^{p\times n}$:
  - <real>, ***float matrix, required parameter***, the real part of output matrix $\mathbf{C}$. The matrix are flattened column-by-column, i.e. the order is $C_{11}C_{21}...C_{n1}\ C_{12}C_{22}...C_{n2}...$
  - <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
  - <imaginary>, ***float matrix, optional parameter***, the imaginary part of output matrix $\mathbf{C}$. The matrix are flattened column-by-column, i.e. the order is $C_{11}C_{21}...C_{n1}\ C_{12}C_{22}...C_{n2}...$

This external matrices file example can be found in the following directory, which is automatically generated by a Dynamic Mode Decomposition with Control (DMDC)([6] and [7]) post processor, and contains some information that is not necessary for FARM:

- /raven/plugins/FARM/tests/RefGov_para_xmlABC_Test/DMDcCxCoeff_TES_para.xml

This external matrices file represents a thermal energy storage (TES) model, with:

- One(1) system actuation variable u
  - Power set point, measured in Mega Watts (MW);
- Two(2)-element system state vector $\overrightarrow{x} \in \mathbb{R}^2$
- Two(2)-element system output vector $\overrightarrow{y} \in \mathbb{R}^2$
  - y_1, Hot fluid tank height, measured in Meter (m);
  - y_2, Cold fluid tank height, measured in Meter (m);

In addition, the state-space representations are parameterized by 20 charging(-)/discharging(+) power levels, and the values in <ActuatorParameter> attribute are measured in Mega Watts (MW).

2.1.2 Unparameterized External Matrices File

The following Listing 2 is a example external matrices file for Unparameterized Reference Governor with necessary information:

Listing 2: Unparameterized External Matrices File Example.

```
<DataObjectMetadata name="rom_stats">
  <DMDrom type="Static">
    <DMDcModel>
      <dmdTimeScale>1800 1810
      <UNorm>
```

```
        <realization sample="0">-3.50e+00</realization>
      </UNorm>
      <XNorm>
        <realization sample="0">2.55e+01 0.00e+00</realization>
      </XNorm>
      <XLast>
        <realization sample="0">2.09e+00 9.15e+02</realization>
      </XLast>
      <YNorm>
        <realization sample="0">3.20e+01 2.55e+01</realization>
      </YNorm>
      <Atilde>
        <realization sample="0">
          <imaginary>0.00e+00 0.00e+00 0.00e+00
             0.00e+00</imaginary>
          <matrixShape>2,2</matrixShape>
          <real>1.00e+00 -1.33e-02 -5.56e-05 -4.57e-01</real>
        </realization>
      </Atilde>
      <Btilde>
        <realization sample="0">
          <imaginary>0.00e+00 0.00e+00</imaginary>
          <matrixShape>2,1</matrixShape>
          <real>-1.75e-04 -6.25e+00</real>
        </realization>
      </Btilde>
      <Ctilde>
        <realization sample="0">
          <imaginary>0.00e+00 0.00e+00 0.00e+00
             0.00e+00</imaginary>
          <matrixShape>2,2</matrixShape>
          <real>-1.00e+00 1.00e+00 -3.76e-11 -4.86e-17</real>
        </realization>
      </Ctilde>
    </DMDcModel>
  </DMDrom>
</DataObjectMetadata>
```

As one can see, all the required information for FARM are included in the <DMDcModel> block. Indeed, the name of this block and its parent blocks is flexible:

- <DataObjectMetadata>, Root element of XML file, other names are acceptable.
- <DMDrom>, Child 1 level element of XML file, other names are acceptable.

- <DMDcModel>, Child 2 level element of XML file, other names are acceptable.

As long as the following keywords and inputs are the Child 3 level elements of this XML file, the information can be processed for FARM execution:

- <dmdTimeScale>, ***float vector, required parameter***, the time step marks used in DMDc calculation. At least two consecutive time step value are required to calculate the discrete time interval;

Some items (<UNorm>, <XNorm>, <YNorm>, <XLast>, <Atilde>, <Btilde>, <Ctilde>) contains one <realization> nodes, in the format of <realization sample="0">, and the corresponding value are contained in the <realization> node.
All the following items have the <realization sample="0"> node:

- <UNorm>, ***float scalar, required parameter***, the norminal value of system actuation variable u;
- <XNorm>, ***float vector, required parameter***, the norminal value of system state vector $\overrightarrow{x} \in \mathbb{R}^n$;
- <YNorm>, ***float vector, required parameter***, the norminal value of system output vector $\overrightarrow{y} \in \mathbb{R}^p$;
  - Note: the <YNorm> values must be within the range defined by "Min_Target" and "Max_Target" in the definition of Reference Governor SIMO EnternalModel. See Listing 4 in Section **??**.
- <XLast>, ***float vector, required parameter***, the latest value of system state vector $\overrightarrow{x} \in \mathbb{R}^n$, **without norminal value subtraction**;
- <Atilde>, ***complex matrix, required parameter***, the state matrix $\mathbf{A} \in \mathbb{C}^{n\times n}$:
  - <imaginary>, ***float matrix, optional parameter***, the imaginary part of state matrix $\mathbf{A}$. The matrix are flattened column-by-column, i.e. the order is $A_{11}A_{21}...A_{n1}\ A_{12}A_{22}...A_{n2}...$
  - <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
  - <real>, ***float matrix, required parameter***, the real part of state matrix $\mathbf{A}$. The matrix are flattened column-by-column, i.e. the order is $A_{11}A_{21}...A_{n1}\ A_{12}A_{22}...A_{n2}...$
- <Btilde>, ***complex matrix, required parameter***, the input matrix $\mathbf{B} \in \mathbb{C}^{n\times 1}$:
  - <real>, ***float matrix, required parameter***, the real part of input matrix $\mathbf{B}$. The matrix are flattened column-by-column, i.e. the order is $B_{11}B_{21}...B_{n1}\ B_{12}B_{22}...B_{n2}...$

- <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
- <imaginary>, ***float matrix, optional parameter***, the imaginary part of input matrix **B**. The matrix are flattened column-by-column, i.e. the order is $B_{11}B_{21}...B_{n1}\ B_{12}B_{22}...B_{n2}...$

- <Ctilde>, ***complex matrix, required parameter***, the output matrix $\mathbf{C} \in \mathbb{C}^{p\times n}$:
  - <real>, ***float matrix, required parameter***, the real part of output matrix **C**. The matrix are flattened column-by-column, i.e. the order is $C_{11}C_{21}...C_{n1}\ C_{12}C_{22}...C_{n2}...$
  - <matrixShape>, ***int vector, required parameter***, the shape of matrix, defined as <matrixShape>Number of Rows,Number of Columns</matrixShape>
  - <imaginary>, ***float matrix, optional parameter***, the imaginary part of output matrix **C**. The matrix are flattened column-by-column, i.e. the order is $C_{11}C_{21}...C_{n1}\ C_{12}C_{22}...C_{n2}...$

This external matrices file example can be found in the following directory, which is automatically generated by a Dynamic Mode Decomposition with Control (DMDC)([6] and [7]) post processor, and contains some information that is not necessary for FARM:

- /raven/plugins/FARM/tests/RefGov_unpara_xmlABC_Test/DMDcCxCoeff_TES_unpara.xml

This external matrices file represents a thermal energy storage (TES) model, with:

- One(1) system actuation variable u
  - Charging(-)/Discharging(+) Power setpoint, measured in Mega Watts (MW);
- Two(2)-element system state vector $\overrightarrow{x} \in \mathbb{R}^2$
- Two(2)-element system output vector $\overrightarrow{y} \in \mathbb{R}^2$
  - y_1, Hot fluid tank height, measured in Meter (m);
  - y_2, Cold fluid tank height, measured in Meter (m);

The state-space representation listed in this external matrices file is linearized at a charging power of 218.5 MW.

2.2 Input of Reference Governor SIMO ExternalModel

The input of Reference Governor SIMO is an XML file.

2.2.1 Input File for Parameterized Reference Governor SIMO ExternalModel

An example of the input structure is given in Listing 3. The following section will discuss the different keywords in the input and describe how they are used in this FARM plugin.

Listing 3: Reference Governor SIMO ExternalModel Example.

```xml
<ExternalModel name="RG1"
   subType="FARM.RefGov_parameterized_SIMO">
  <outputVariables>V, V_min, V_max</outputVariables>
  <variables>PwrSet, V, V_min, V_max</variables>
  <constant varName="MOASsteps"> 360 </constant>
  <constant varName="Min_Target1"> 2.5 </constant>
  <constant varName="Max_Target1"> 55. </constant>
  <constant varName="Min_Target2"> 2.5 </constant>
  <constant varName="Max_Target2"> 55. </constant>
  <constant varName="Sys_State_x"> 30., 0 </constant>
</ExternalModel>
```

As one can see, all the specifications of the Reference Governor SIMO plugin are given in the `<ExternalModel>` block.

- The `<subType>` attribute should be set as "FARM.RefGov_parameterized_SIMO" to call the parameterized Reference Governor SIMO external model.

Inside the `<ExternalModel>` block, the XML nodes that belong to this plugin only (and not to the ExternalModel) are:

- `<outputVariables>`, ***3-element string, required parameter***, the names of output variables:
  - Adjusted actuation variable u, any user-defined name is allowed(e.g. V);
  - Lower limit of adjusted actuation variable u, any user-defined name is allowed (e.g. V_min);
  - Upper limit of adjusted actuation variable u, any user-defined name is allowed (e.g. V_max);

  The order of the 3 variables should be strictly followed.

- `<variables>`, ***4-element string, required parameter***, the names of:
  - Original actuation variable r, any user-defined name is allowed (e.g. PwrSet);
  - The 3 output variables in `<outputVariables>`

  The order of the 4 variables should be strictly followed.

- `<constant varName="MOASsteps">`, ***integer, required parameter***, the **g** value of steps to predict in the future (e.g. 360);
- And 2*p blocks of `<constant>` regarding the constraints on system output vector $\overrightarrow{y} \in \mathbb{R}^p$
  - `<constant varName="Min_Target1">`, ***float, required parameter***, the lower constraint on output y_1 (e.g. 2.5);
  - `<constant varName="Max_Target1">`, ***float, required parameter***, the upper constraint on output y_1 (e.g. 50.);
  - `<constant varName="Min_Target2">`, ***float, required parameter***, the lower constraint on output y_2 (e.g. 2.5);
  - `<constant varName="Max_Target2">`, ***float, required parameter***, the upper constraint on output y_2 (e.g. 50.);
  - ...
  - `<constant varName="Min_Targetp">`, ***float, required parameter***, the lower constraint on output y_p (not shown in Listing 3 due to $p = 2$);
  - `<constant varName="Max_Targetp">`, ***float, required parameter***, the upper constraint on output y_p (not shown in Listing 3 due to $p = 2$);
- `<constant varName="Sys_State_x">`, ***float vector, optional parameter***, the current system state vector x (e.g. 30., 0) before subtracting the value in `<XNorm>` in the External Matrice File (See Section 2.1.1). If not supplied, the FARM will automatically use the the value in `<XLast>` in the External Matrice File (See Section 2.1.1).

This external model definition example can be found in the following directory:

- /raven/plugins/FARM/tests/test_RefGov_para_xmlABC.xml

and it is designed for a thermal energy storage (TES) simulation, with:

- One(1) input variable:
  - PwrSet, Charging(-)/Discharging(+) Power setpoint, measured in Mega Watts (MW);
- Three(3) output variables:
  - V, Adjusted Charging(-)/Discharging(+) Power setpoint, measured in Mega Watts (MW);
  - V_min, Admissible power setpoint lower limit, measured in Mega Watts (MW);
  - V_max, Admissible power setpoint upper limit, measured in Mega Watts (MW);
- MOASsteps $g = 360$, will project for the next 360 discrete time steps;

- Two(2) pairs of system output constraints:
  - y_1, Hot fluid tank height, measured in Meter (m);
  - y_2, Cold fluid tank height, measured in Meter (m);

2.2.2 Input File for Unparameterized Reference Governor SIMO ExternalModel

An example of the input structure is given in Listing 4. The following section will discuss the different keywords in the input and describe how they are used in this FARM plugin.

Listing 4: Reference Governor SIMO ExternalModel Example.

```
<ExternalModel name="RG1"
   subType="FARM.RefGov_unparameterized_SIMO">
  <outputVariables>V, V_min, V_max</outputVariables>
  <variables>PwrSet, V, V_min, V_max</variables>
  <constant varName="MOASsteps"> 360 </constant>
  <constant varName="Min_Target1"> 2.5 </constant>
  <constant varName="Max_Target1"> 55. </constant>
  <constant varName="Min_Target2"> 2.5 </constant>
  <constant varName="Max_Target2"> 55. </constant>
  <constant varName="Sys_State_x"> 30., 0 </constant>
</ExternalModel>
```

Being similar to Listing 3, all the specifications of the Reference Governor SIMO plugin are given in the <ExternalModel> block. The only difference is

- The <subType> attribute should be set as "FARM.RefGov_unparameterized_SIMO" to call the unparameterized Reference Governor SIMO external model.

This external model definition example can be found in the following directory:

- /raven/plugins/FARM/tests/test_RefGov_unpara_xmlABC.xml

and it is designed for the same thermal energy storage (TES) simulation described in Section 2.2.1.

2.3 Input File Example with FARM.RefGov_parameterized_SIMO ExternalModel

A complete input file example using the external model "FARM.RefGov_parameterized_SIMO" can be found in the following directory, and it will be discussed in this section:

- /raven/plugins/FARM/tests/test_RefGov_para_xmlABC.xml

This RAVEN input file simulates the feedback from RefGov_parameterized_SIMO ExternalModel. The key factors are:

- External matrices file in Listing 1 is used;
- External model defined in Listing 3 is used;
- Twenty(20) random input values (uniformly distributed over range [-2000, +2000] MegaWatts) will be generated, and fed into the external model as ”PwrSet”;
- The external model will perform the calculation, and print the three(3) outputs(V, V_min, V_max) associated with each input value of PwrSet to a file ”RefGovOutput.csv”.

The example input file is shown in Listing 5:

Listing 5: Input File Example using RefGov.RefGov_SIMO ExternalModel.

```
<Simulation verbosity="silent">
  <TestInfo>
    <name>plugins/FARM.RefGov_parameterized_SIMO</name>
    <author>HaoyuWang</author>
    <created>2021-02-01</created>
    <classesTested>Models.ExternalModel</classesTested>
    <description>
      This is a test run of parameterized reference governor.
         It loads ABC matrices from external xml file and
         calculate the feedback from RefGov_parameterized_SIMO
         external model.
    </description>
    <requirements> </requirements>
  </TestInfo>
  <!-- TestInfo is the description part of input xml file,
     won't run -->

  <RunInfo>
    <WorkingDir>RefGov_para_xmlABC_Test</WorkingDir>
    <Sequence>
      RGrun,
      printTOfile
    </Sequence>
  </RunInfo>

  <Files>
    <Input name="ABCMatrices"
       type="">DMDcCxCoeff_TES_para.xml</Input>
  </Files>
```

```xml
<Models>
  <ExternalModel name="RG1"
     subType="FARM.RefGov_parameterized_SIMO">
    <!-- 3 output variables -->
    <outputVariables>V, V_min, V_max </outputVariables>
    <!-- 4 variables: Issued Setpoint(PwrSet), Adjusted
       Setpoint(V1), bounds of V1(V1min & V1max) -->
    <variables> PwrSet, V, V_min, V_max </variables>
    <!-- steps in MOAS calculation, "g" value -->
    <constant varName="MOASsteps"> 360 </constant>
    <!-- lower and upper bounds for y vector, will be
       internally checked -->
    <constant varName="Min_Target1"> 2.5 </constant>
    <constant varName="Max_Target1"> 55. </constant>
    <constant varName="Min_Target2"> 2.5 </constant>
    <constant varName="Max_Target2"> 55. </constant>
    <!-- System state vector "x", optional, with elements
       separated by comma(,) -->
    <constant varName="Sys_State_x"> 30.,0 </constant>
  </ExternalModel>
</Models>

<Distributions>
  <Uniform name="one">
    <lowerBound>-2000</lowerBound>
    <upperBound>2000</upperBound>
  </Uniform>
<!-- distribution for PwrSet sampling -->
</Distributions>

<Samplers>
  <MonteCarlo name="RG_Sampler">
    <samplerInit>
      <limit>20</limit>
    </samplerInit>
    <variable name="PwrSet">
      <distribution>one</distribution>
    </variable>
  </MonteCarlo>
<!-- A MonteCarlo sampler for PwrSet sampling  -->
</Samplers>
```

```
  <DataObjects>
    <PointSet name="RGInput">
      <Input>PwrSet </Input>
      <Output>OutputPlaceHolder</Output>
    </PointSet>
    <PointSet name="RGOutput">
      <Input>PwrSet </Input>
      <Output>V, V_min, V_max </Output>
    </PointSet>
  <!-- input and output pointsets for RG -->
  </DataObjects>

  <Steps>
    <MultiRun name="RGrun">
      <Input  class="DataObjects"
         type="PointSet">RGInput</Input>
      <Input  class="Files" type="">ABCMatrices</Input>
      <Model  class="Models"  type="ExternalModel">RG1</Model>
      <Sampler  class="Samplers"
         type="MonteCarlo">RG_Sampler</Sampler>
      <Output class="DataObjects"
         type="PointSet">RGOutput</Output>
    </MultiRun>
    <!-- MultiRun step to execute the plugin for multiple
       times -->
    <IOStep name="printTOfile">
      <Input  class="DataObjects"
         type="PointSet">RGOutput</Input>
      <Output class="OutStreams"
         type="Print">RefGovOutput</Output>
  </IOStep>
  <!-- IOStep to dump the RGOutput to RefGovOutput.csv-->
  </Steps>

  <OutStreams>
    <Print name="RefGovOutput">
      <type>csv</type>
      <source>RGOutput</source>
      <what>input,output</what>
    </Print>
  </OutStreams>
</Simulation>
```

The output is a csv file, containing 10 rows of input-outputs (PwrSet - V - V_min - V_max). The data and plot are included in Figure 1.

As one can see, the V_min and V_max placed limits on the adjusted actuation variable V:

- when original actuation variable(PwrSet) exceeds the upper limit(V_max), the actuation variable(V) is adjusted to V_max;
- when original actuation variable(PwrSet) undergoes the lower limit(V_min), the actuation variable(V) is adjusted to V_min;
- when original actuation variable(PwrSet) is within the range of [V_min, V_max], the actuation variable V has the same value as PwrSet.

PwrSet	V	V_min	V_max
537.7024	537.7024	-1188.97	1086.535
-1101.34	-1101.34	-1195.97	1079.542
248.3486	248.3486	-1188.97	1086.535
1417.471	1086.535	-1188.97	1086.535
1570.537	1086.535	-1188.97	1086.535
1828.986	1086.535	-1188.97	1086.535
565.3647	565.3647	-1188.97	1086.535
85.37771	85.37771	-1191.27	1084.235
-342.28	-342.28	-1195.97	1079.542
-1999.13	-1195.97	-1195.97	1079.542
-1960.83	-1195.97	-1195.97	1079.542
265.878	265.878	-1188.97	1086.535
985.9726	985.9726	-1188.97	1086.535
60.37677	60.37677	-1191.66	1083.852
786.1524	786.1524	-1188.97	1086.535
1083.584	1083.584	-1188.97	1086.535
-298.547	-298.547	-1195.97	1079.542
129.1419	129.1419	-1190.51	1085.002
835.4508	835.4508	-1188.97	1086.535
825.2659	825.2659	-1188.97	1086.535

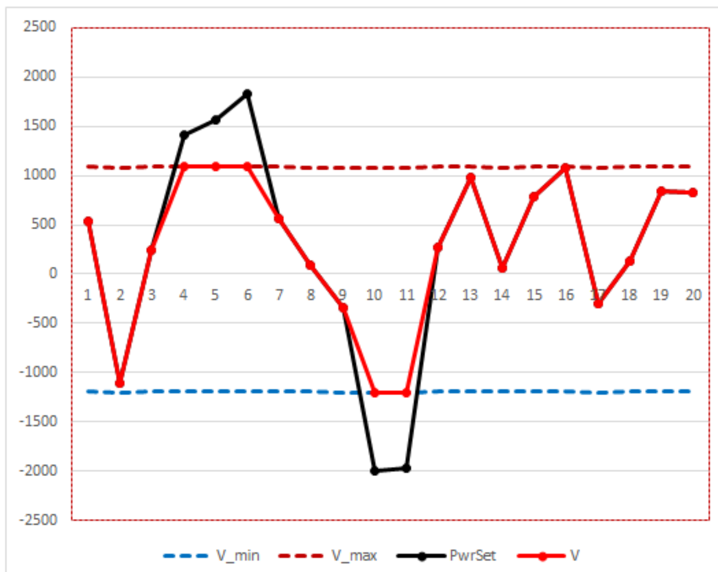

Figure 1: Data and Plot from example RefGov_parameterized_SIMO input file.

3 Document Version Information

This document has been compiled using the following version of the plug-in git repository:

References

[1] C. Rabiti, A. Alfonsi, J. Cogliati, D. Mandelli, R. Kinoshita, S. Sen, C. Wang, and J. Chen, "Raven user manual," Tech. Rep. INL/EXT-15-34123, Idaho National Laboratory (INL), March 2017.

[2] A. Alfonsi, C. Rabiti, D. Mandelli, J. Cogliati, C. Wang, P. W. Talbot, D. P. Maljovec, and C. Smith, "Raven theory manual and user guide," tech. rep., Idaho National Laboratory (INL), 2017.

[3] I. Kolmanovsky, E. Garone, and S. Di Cairano, "Reference and command governors: A tutorial on their theory and automotive applications," in *2014 American Control Conference*, pp. 226–241, IEEE, 2014.

[4] E. Garone, S. Di Cairano, and I. Kolmanovsky, "Reference and command governors for systems with constraints: A survey on theory and applications," *Automatica*, vol. 75, pp. 306–328, 2017.

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[6] J. L. Proctor, S. L. Brunton, and J. N. Kutz, "Dynamic mode decomposition with control," *SIAM Journal on Applied Dynamical Systems*, vol. 15, no. 1, pp. 142–161, 2016.

[7] H. Wang, R. Ponciroli, A. Alfonsi, and R. Vilim, "Development of control system functional capabilities within the ies plug-and-play simulation environment," Tech. Rep. ANL/NSE-20/35, Argonne National laboratory (ANL), September 2020.