Modeling of Custom Hydro Turbine and Governor Models for Real-Time Simulation

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***Abstract*—This article develops three different hydro turbine and governor (HTG) models to fulfill adequate modeling requirements for the representation of hydro power generation in the Nordic grid. To validate the performance of the developed models, both off-line and real-time simulation studies on a single-machine infinite-bus (SMIB) system are carried out. Apart from SMIB system, real-time simulations are also executed for a larger scale power system—the IEEE Reliability Test System 1996 (IEEE RTS 96) in this article to determine the models' dynamic performance in larger and more complex networks. In addition, how to properly transfer an off-line models developed in SimPowerSystems (SPS) for real-time simulation in RT-LAB is addressed; including valuable experiences obtained from these simulation exercises.**

***Index Terms*—Hydro Turbine and Governor, Real-Time Simulation**

I. INTRODUCTION

TOday, hydro-power accounts for one half of Sweden's electricity net production of electrical power generation and 56% of Nordic system [1], respectively. As one of the most important energy sources, the exploitation of hydro-power has naturally attracted more and more attention particularly in the Nordic region [2]. In hydro power production systems, it is not possible to neglect turbine and governor's functions, which participate in the primary frequency control of synchronous machines. With the continuous development of power system simulation software, engineers have more choices for including various components in simulation, however, there are still many cases that custom HTG models need to be designed and implemented to meet particular modeling and simulation requirements.

The purpose of this article is to develop three different HTG models to fulfill adequate modeling requirements for the representation of hydro power generation in the Nordic grid. Different scales of test systems, the SMIB system and IEEE RTS 96 system, are used to validate the models' performance. In addition, real-time simulations for both test systems are carried out, which allows for future hardware-in-the-loop (HIL) testing of prototype turbine controls [3]. As supplementary, valuable experiences obtained from these simulation exercises are shared at last.

II. MODELING OF HYDRO TURBINES AND GOVERNORS

The hydro turbine and its governor are normally combined together for representation. When the output of turbine governor is the gate position, it can connect with the hydro turbine directly. However, for some cases, the output is the derivative of the gate position, which does not match the input of the turbine, therefore, a desired gate position reference is applied to add to the gate position derivative. In this section, three custom HTGs are introduced with the structural diagrams and initialization. In addition, for reference, the HTG model provided in SPS is also presented following other three models.

A. Model 1

The structural diagram of Model 1 is shown in Fig. 1. It consists of a typical hydro turbine governor model [4] [5] and a linearized hydro turbine model [4] [5]. The output of turbine governor is the gate position derivative (ΔG), while the input of the turbine is the gate position (G). Consequently, a position reference G_{ref}, which is regarded as equal to P_{ref}, is required between them.

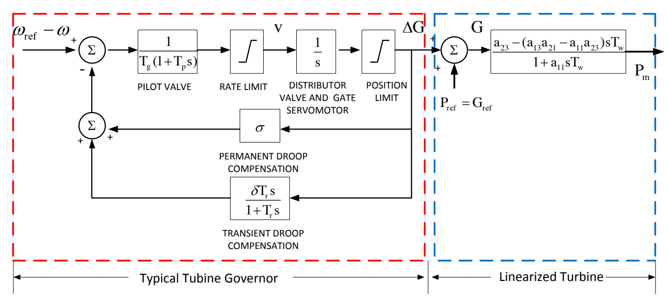

Fig. 1. Diagram showing the general structure of Model 1

To implement models in computer software and determine its future behaviors under different scenarios, normally, a set of state variables that consist of coupled first-order differential equations are necessary. However, it is hard to determine the state variables in the structural diagram. The solution is to utilize a canonical realization by redrawing the models using single integrators and gain blocks. In this way, along the signal flow each state variable is located behind each integrator, while the derivative of state variable in the front (see in Fig. 2).

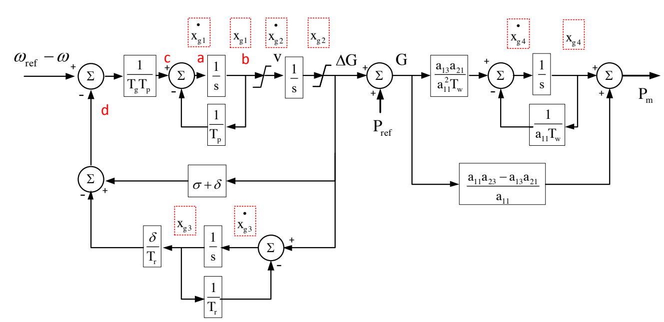

Fig. 2. Block Diagram Realization of Model 1

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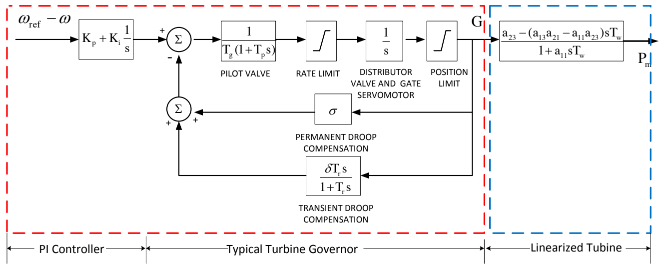

Fig. 3. Diagram Showing the General Structure of Model 2

From the block diagram realization in Fig. 2, the differential algebraic equation (DAE) set can be derived and utilized for calculating the integrators' initial values. The derived DAEs are

$$\dot{x}_{g1} = \frac{1}{T_g T_p}\left[(\omega_{ref} - \omega) - (\sigma + \delta)\Delta G + \frac{\delta}{T_r} x_{g3}\right] - \frac{1}{T_p} x_{g1}$$

$$\dot{x}_{g2} = v = \begin{cases} x_{g1} & \text{if } v_{max} \geq x_{g1} \geq v_{min} \\ v_{max} & \text{if } v_{max} < x_{g1} \\ v_{min} & \text{if } v_{min} > x_{g1} \end{cases}$$

$$\dot{x}_{g3} = \Delta G - \frac{1}{T_r} x_{g3}$$

$$\dot{x}_{g4} = \frac{a_{13}a_{21}}{{a_{11}}^2 T_w}(\Delta G + P_{ref}) - \frac{1}{a_{11}T_w} x_{g4}$$

$$\Delta G = \begin{cases} x_{g2} & \text{if } G_{max} - P_{ref} \geq x_{g2} \geq G_{min} - P_{ref} \\ G_{max} - P_{ref} & \text{if } G_{max} - P_{ref} < x_{g2} \\ G_{min} - P_{ref} & \text{if } G_{min} - P_{ref} > x_{g2} \end{cases}$$

$$P_m = x_{g4} + \frac{a_{11}a_{23} - a_{13}a_{21}}{a_{11}}(\Delta G + P_{ref}).$$

When the system is in steady state, $\omega = \omega_{ref}$, the rate of the gate movement $v = 0$, and the gate is fixed as $\Delta G = 0$. The initial values for Model 1 can be obtained by setting the derivatives to zero:

$$x_{g1} = x_{g2} = x_{g3} = 0, x_{g4} = \frac{a_{13}a_{21}}{a_{11}} P_{ref}, P_m = a_{23} P_{ref}.$$

This initial values can also be determined by analyzing Fig. 2. When the system is in steady state, $\omega = \omega_{ref}$, all the derivatives of all state variables are zero. Consequently, as we can see, point a and b are zero. Because $c - b = a$, c is accordingly equal to zero. Similarly, point d is also zero as $(\omega_{ref} - \omega)$ and c are zero. With this recurrence method, it is possible to obtain all the state variables' initial values that are as those obtained with the DAEs, and hence, this method can be used to check if the DAE initialization is correct.

B. Model 2

As shown in Fig. 3, the difference between Model 2 to Model 1 is a simple PI controller added in the front of the turbine governor [6] [7]. The integrator in the PI controller computes the integral of the error between ω_{ref} and ω, which affects the input of turbine governor model. In this case the output of turbine governor becomes the gate position itself, which is also the input of the turbine model. The integrators initial values in Model 2 can be obtained from its DAEs:

$$G = P_{ref}, x_{g1} = \sigma P_{ref}, x_{g2} = 0, x_{g3} = P_{ref},$$
$$x_{g4} = T_r P_{ref}, x_{g5} = \frac{a_{13}a_{21}}{a_{11}} P_{ref}, P_m = P_{ref}.$$

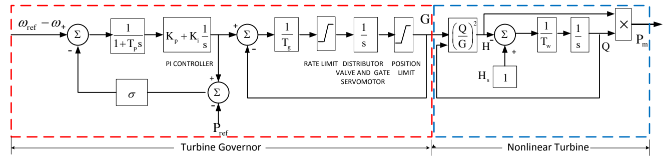

Fig. 4. Diagram Showing the General Structure of Model 3

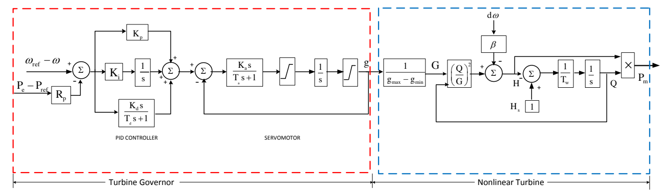

Fig. 5. Block Diagram Showing the General Structure of Model 4

C. Model 3

Model 3 is taken from [8], in which the main difference to the previous models is that a nonlinear turbine model is used. For nonlinear turbine models, when calculating Jacobian matrices, the partial derivatives of the differential function f with respect to state variables x still contain state variables, which means that the partial derivatives change with time. This translates to different performances when compared with linear turbine models. When the system is in steady state, $\omega = \omega_{ref}$, all differential variables are equal to zero, thus M and G are equal to P_{ref}. The calculation results for integrators' initial values are

$$G = P_{ref}, x_{g1} = 0, x_{g2} = P_{ref},$$
$$x_{g3} = P_{ref}, x_{g4} = P_{ref}, P_m = P_{ref}.$$

D. Model 4

The HTG model in SPS is encapsulated into one block named HTG, which contains a nonlinear hydro turbine model, a PID governor system, and a servomotor. An additional distinction is that this model makes use of $\dot{\omega}$ as another input to the turbine, which can accelerate the system reaction when it is subjected to a large transient perturbation. The turbine and governor model can be transfered into the diagram shown in Fig.5. The integrators' initial values are calculated from

$$G = P_{ref}, x_{g1} = g = (g_{max} - g_{min}) * P_{ref}, x_{g2} = x_{g3} = 0,$$
$$x_{g4} = g = (g_{max} - g_{min}) * P_{ref}, x_{g5} = P_{ref}, P_m = P_{ref}.$$

III. Simulation of Custom Hydro Turbine and Governor Models in a SMIB System

Next, the off-line and real-time performances of the developed HTG models in a SMIB system are examined. The evaluation of a power system's performance is concerned with the stability of that system: i.e. if it remains in an equilibrium after being subjected to a disturbance [9]. Off-line simulation makes use of variable step solvers to compute the next simulation time as the sum of the current simulation time and a variable step size. Variable step size solvers can take flexible steps along with the variables varying rapidly or slowly. This ability to change step sizes to meet the error tolerances can increase computational efficiency. However, variable step size solvers are not appropriate for deterministic real-time applications because the variable step size can not be mapped to a real-time clock, which is important in HIL tests.

Compared to conventional hardware prototype testing, HIL real-time simulation takes advantage of decreasing damage on equipment, reducing expense as well as extending simulation time during the development process of a product [10]. For real-time simulation, the amount of time spent calculating the solution for a given time step must be fixed, and moreover, it should be less than the length of that time step. In this case, a fixed-step solver must be used instead of a variable step size solver for real-time simulation. To ensure that the results obtained with the fixed-step solver are accurate and the fixed step size is suitable, the off-line simulation with a variable step solver will be set as the reference.

The real-time simulations shown in this article are performed in the SmarTS Lab at KTH, which includes two real-time targets of Opal-RT's eMegaSim real-time simulator [11].

A. Introduction for the SMIB system

Figure 6 shows a SMIB system consisting of one 991 MVA, 20 kV, 50 Hz generator, one transformer operating 20 kV on the primary and 230 kV on the secondary, two lines with reactance of 0.1 p.u. and an infinite bus.

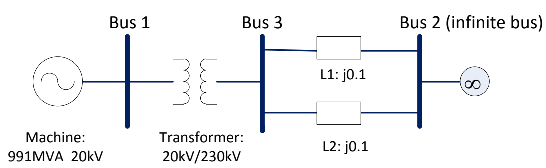

Fig. 6. The SMIB system

B. Off-line simulation for each SMIB system

A three-phase fault is applied at Bus 3 at $t = 5$ s and removed at $t = 5.02$ s. After computing the power flow, time-domain simulations show the model responses in SPS. Figure 7 depicts the generator rotor speed of off-line simulation results for SMIB systems with each HTG model in SPS.

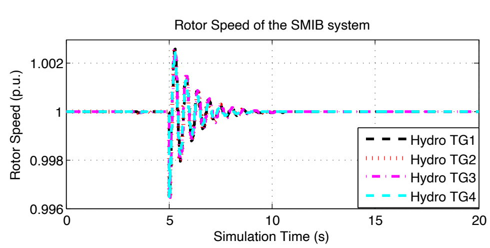

Fig. 7. Off-line simulation results for SMIB systems with HTG models

C. Real-time simulation for each SMIB system

Figure 8, 9, 10, 11, 12 show the real-time simulation results for the SMIB system with each HTG model. All the real-time simulation data can be written to a MATLAB file by the "OpWriteFile" block. As depicted in Fig. 8, all the SMIB

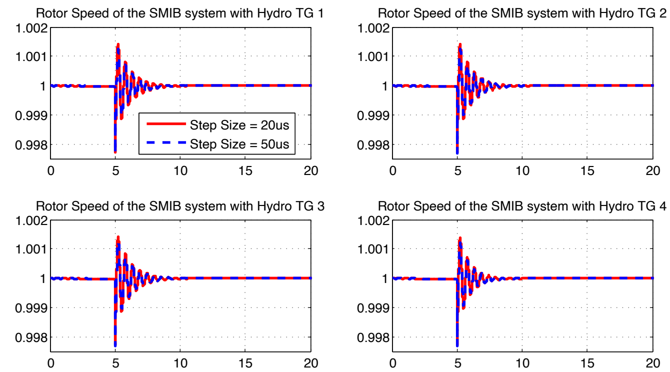

Fig. 8. Rotor speed of the SMIB system for different HTG models

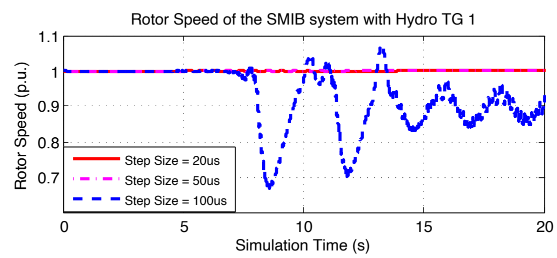

Fig. 9. Rotor speed of the SMIB system with HTG1 for different step sizes

systems with different HTG models show the nearly same performances with the off-line simulation above. At the same time, these results indicate that the applied step sizes (50 μs, 20 μs) are capable for running this real-time simulations. By contrast, 100 μs is too large to capture the true real-time dynamic performance and finally results in the numerical instability shown in Fig. 9. This is an intuitive instance to show how the fixed step size significantly influences the simulation performance. But it does not mean that the shorter step size, the better solution, particularly when the given step size is shorter than the time for computing the solution (referred as overruns). Generally speaking, decreasing step size increases the accuracy of the results while increasing the computational resources required to simulate the system up to the limits imposed by Amdahl's law.

In order to obtain the accurate timing information of real-time simulation, the RT-LAB library is equipped with a set of system monitoring blocks. For instance, the OpMonitor block provides timing information including "Computation time", "Real step size", "Idle time" and "Number of overruns" [12], which could be used to analyze if the current step size is appropriate for real-time simulation and if there is still space to reduce the step size for better performance. According to Figs. 10 and 11, the computation time is far smaller than the step size only except when a fault occurs, which guarantees very small amount of overruns during real-time simulation as shown in Fig. 12.

IV. Real-time simulation of custom hydro turbine and governor models in IEEE RTS 96 System

A. Introduction for the IEEE Reliability Test System 1996

The IEEE RTS 96 system was developed and published with the objective of assessing deterrent reliability modeling

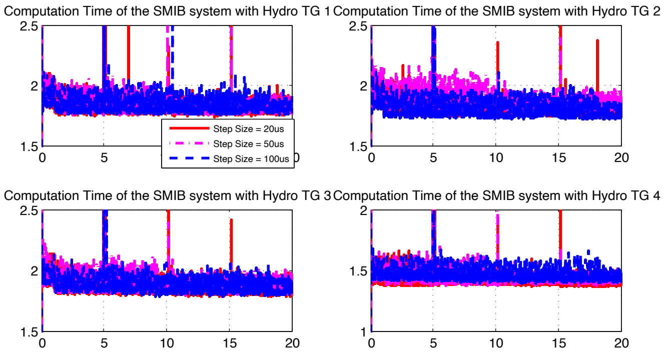

Fig. 10. Computation time for the SMIB system with different HTG models (enlargement)

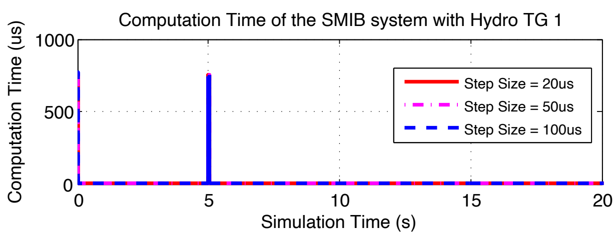

Fig. 11. Computation time overview of the SMIB system with HTG1

and evaluation methodologies as well as meeting the new changes in the electric utility industry [13]. The single line diagram of IEEE RTS 96 system which has been carried out in SPS for a new implementation is shown in Fig. 13. This system comprises of 10 synchronous generators, 66 lines and 34 buses; it consists of 24 substations, with configurations such as Single Bus Single Breaker, Double Bus Double Breaker, Breaker and a Half, and Ring [14].

B. Real-time simulation for the IEEE Reliability Test System 1996

The (modified) IEEE RTS 96 system is divided into 9 subsystems as shown in the Fig. 13, called Area 1 to 9. Adding the console subsystem, which contains all the scopes and controllers and plays the role of interfacing between the running model and the host monitoring console, there are 10 subsystems for the whole model in RT-LAB. Each subsystem will take account for one core in the real-time simulator, where there are 12 in total.

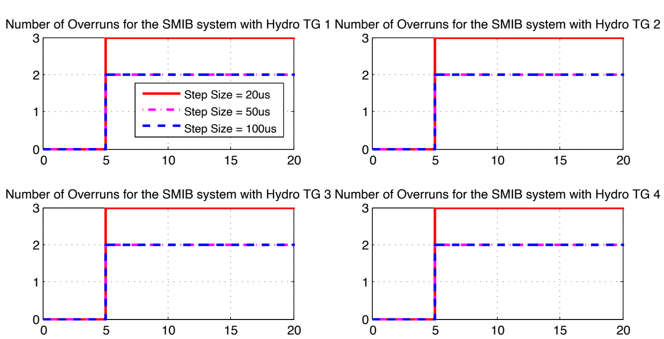

Fig. 12. Number of overruns for the Master Subsystem in the SMIB system with HTG models

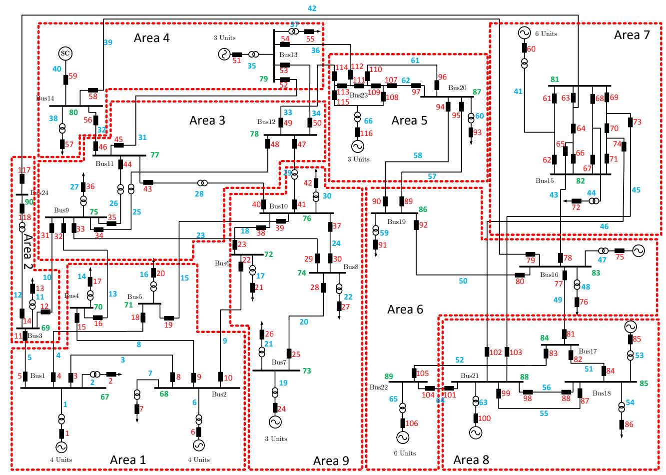

Fig. 13. One area of the modified IEEE Reliability Test System 1996 (taken from [14])

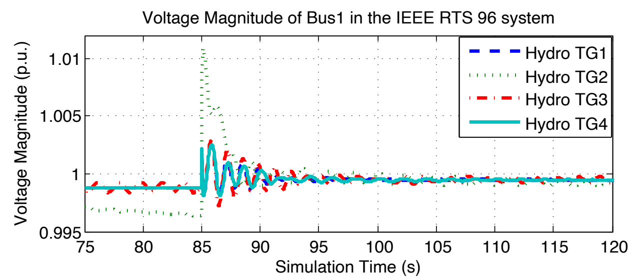

Fig. 14. Voltage Magnitude of Bus 1 in the modified IEEE RTS 96 system with HTG models

In this article the IEEE RTS 96 system implements HTGs for all the 10 generators and carries out the real-time simulation with fixed step size 50 μs. The designed test scenario is to open the breaker 18 at 85 s. Since bus 1 and bus 5 are two directly connected buses with breaker 18, the voltage magnitude of bus 1 and bus 5 are depicted in Fig. 14 and Fig. 16, respectively, to analyze the IEEE RTS 96 system stability particularly with the HTGs. While Fig. 15 focuses on the instant when the fault occurs.

Implemented in a large scale power system, the HTG models perform differently. Instead of directly inputting a power reference or gate reference signal, HTG of Model 2 (Fig. 3) utilizes a PI controller to integrate the error until the reference value is reached. Depending on the controller parameters, there is a risk in that the response will largely deviate from the reference, and therefore, the HTG of Model2

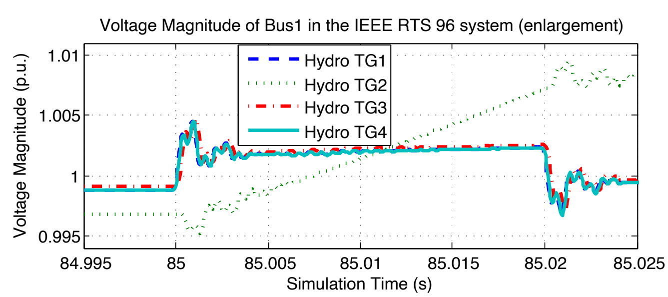

Fig. 15. Voltage Magnitude of Bus 1 in the modified IEEE RTS 96 system with HTG models (enlargement)

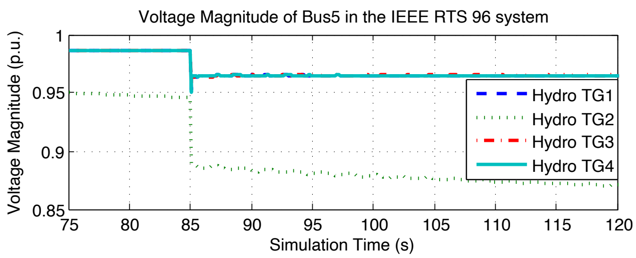

Fig. 16. Voltage Magnitude of Bus 5 in the modified IEEE RTS 96 system with HTG models

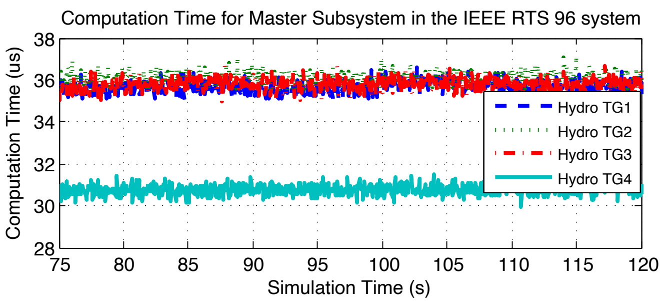

Fig. 17. Computation time for the modified IEEE RTS 96 system with HTG models

is more sensitive to the perturbation. Containing a nonlinear turbine component, the HTG of Model 3 (Fig. 4) results in a slower response. The obvious phenomenon is sustaining small oscillations around steady state. An improvement in HTG of Model 4 (Fig. 5) is to introduce the derivative of rotor speed, which increases the reaction speed.

As seen from Fig. 17, the computation time is below 50 μs for all the cases, which guarantees that the overruns are kept low and take place only when the system initializes or the breaker opens.

V. Issues related to real-time performance

To transfer an off-line model developed in SPS to real-time simulation in RT-LAB (the software used by the Opal-RT real-time simulator), some changes have to be considered. The first task is to regroup the SPS model into subsystems according to RT-LAB rules. As mentioned before, each subsystem will take account for one core in the simulator and only one master subsystem is allowed in one single model. Master subsystem (SM) and slave subsystem (SS) contain all the computational elements, mathematical operations, I/O blocks, signal generators, etc. Since the console subsystem (SC) is not linked to a computation core, it is not allowed to include any signal generation or important mathematical operations but all user interface blocks, such as scopes, displays, switches. Another significant difference to the SPS model is RT-LAB uses "OpComm" block to enable the communication between subsystems. Any input from other subsystems has to go through an "OpComm" block before further local operation.

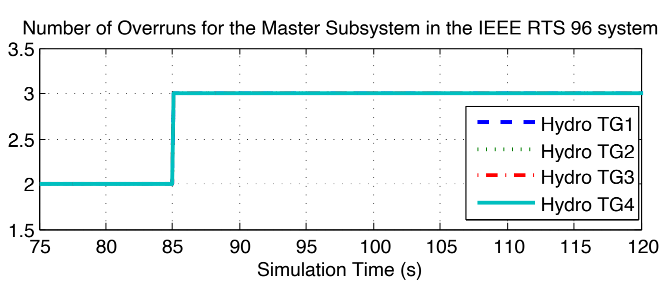

Fig. 18. Number of overruns for the Master Subsystem in the modified IEEE RTS 96 system with HTG models

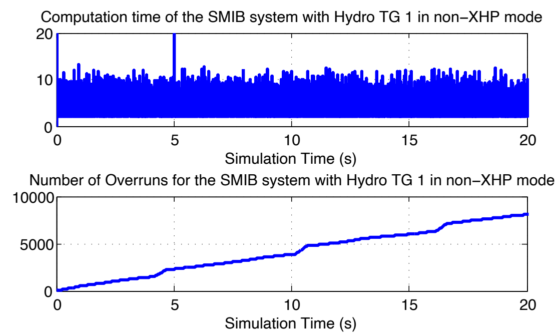

Fig. 19. Real-time simulation results for SMIB system in non-XHP mode

In addition, choosing suitable fixed step size is of critical importance. The corresponding aim is to reduce the overruns as much as possible, and to make sure the real-time simulation performance is as close as possible to the off-line simulation. Some tools provided by RT-LAB can help to obtain better real-time performance. For instance, the use of a fixed step size solver from the ARTEMIS guide block takes advantage of the sparse matrix properties to optimize the computation time, and applies unique interpolation techniques.

There is one simulation mode called eXtreme High Performance (XHP) which "disables the default operating system scheduler and prevents other processes from getting to the processor" [15]. Therefore, the latencies caused by harmful jitter can be removed and the subsystem can run on each core jitter-free, which will maximize the computation ability within each step. The real-time simulation in non-XHP mode for the SMIB system with HTG 1 is carried out and the timing information is shown in Fig. 19. By comparing with the results running in XHP mode for the HTG1 with 20 μs step size shown in Fig. 10 and 12, it is obvious that the XHP mode allows the user to significantly improve real-time simulation performance. All the real-time simulations shown in this article perform in XHP mode if no particular notice mentioned.

When some events and changes occur in the system instantaneously, the fixed step solver might be unable to follow such rapid changes and fails to find the right solution, which may result in numerical instability of the solver [16]. In order to study these events and select suitble step size, the timing information during real-time simulation is valuable. The OpMonitor block can provide accurate and adequate information for monitoring and analysis, since RT-LAB 10.1, a new monitoring feature is available. By using the "Enable Monitoring" option in the "Diagnostic" tab, each part of a computation step can be monitored during the real-time simulation.

Apart from the above experiences with real-time simulation, a couple of necessary considerations for model conversion from the off-line simulation environment into the real-time environment need to be noticed as well. For instance, a system

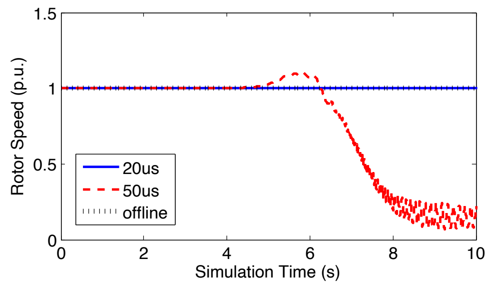

Fig. 20. Real-time simulation results for SMIB system with smaller RLC parameters

containing elements with small time constants requires a small step size so that the fixed step solvers can compute the solution accurately in each step. [16] indicates several relevant cases where small step size should be applied, including a small time constant in small masses attached to stiff springs with minimal damping, electrical circuits with small capacitance and inductance and low resistance and hydraulic circuits with small compressible volumes. Here an example with smaller capacitance and inductance and lower resistance by modifying the parameters of the transformer in the SMIB system is presented.

As shown in the Fig. 20, the simulation of the modified SMIB system suffers from numerical instability when the fixed step size is set to 50 μs, while this step size is sufficiently short to guarantee the accuracy of real-time simulation in the original SMIB system. Consequently, proper modifications have to be considered when transferring the model from the off-line simulation environment into the real-time simulation environment, even though the model achieves perfect off-line simulation performance.

VI. Conclusion

This article presents three custom HTG models as a reference for engineers to develop specific models for off-line and real-time simulation. To examine the performance of newly developed models, power systems of different scales are studied including the SMIB system and IEEE RTS 96 system. Apart from off-line simulations in SPS, the highlight of this article is on real-time simulation in RT-LAB using different fixed step sizes. In addition, how to transfer a model from the off-line into the real-time simulation environment, and the considerations to take into account during this process were also addressed with the aim of providing feedback on real-time simulation practices to other users.

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