Modeling Components of a Turbine-Generator System for Sub-Synchronous Oscillation Studies with Modelica

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Abstract

In power systems, sub-synchronous oscillations associated with the interaction between a mechanical rotor shaft and electrical system can lead to equipment damage if left unmitigated. This paper describes the development of a scalable, multi-mass torsional shaft model and a synchronous machine model that includes DC offset torque components using Modelica. When coupled, these models can be used to perform shaft torsional studies. Two methods of coupling the shaft with the rest of the turbine-generator system are devised and analyzed. A single-machine, infinite-bus test system using the torsional shaft model and generator model developed in this paper is proposed to observe the penetration of sub-synchronous oscillations throughout an electrical system. The test system is then modified to model sub-synchronous resonance leading to system instability. Analysis of the models described in this paper highlights the value of the Modelica_LinearSystems2 library in determining the torsional mode shapes and frequencies associated with a turbine-generator system model, which is not feasible with most power system simulation tools.

Keywords: OpenIPSL, power systems, turbine-generator, torsional shaft, SHAF25, GENDCO, sub-synchronous resonance, sub-synchronous oscillations, Modelica_LinearSystems2

1 Background

In the power system dynamic performance analysis of a turbine-generator system, the rotor shaft is generally represented as a single, lumped mass. While this is sufficient for many studies, the rotor of a turbine-generator system is much more complex. A more detailed representation employs several masses to characterize various components along the rotor, such as the turbine blades of different pressure stages, connected by shafts of varying cross-sectional diameters. This representation can aid in understanding the electromechanical dynamics resulting from torsional oscillations occurring between rotor shaft segments, with oscillations below the synchronous frequency translating to potentially disastrous interactions between the electrical system and mechanical rotor if unmitigated. These effects can include sub-synchronous resonance between the generator and series capacitor compensated lines ("Reader's guide to subsynchronous resonance" 1992) or torsional fatigue and material damage due to accumulated oscillations.

While the study of sub-synchronous resonance has been of practical interest following two shaft failures at the Mohave Generating Station in Nevada in 1970 and 1971 (Walker et al. 1975), challenges associated with these complex dynamics continue to emerge. For example, in July 2015, sub-synchronous oscillations originating from a wind farm in the Xinjiang Uygur Autonomous Region of China excited torsional vibrations in the shaft of a synchronous generator 300 km away. This caused torsional stress relays to trip three large thermal generation units offline and ultimately resulted in a sudden loss of approximately 1,280 MW of power (Shi, Nayanasiri, and Li 2020). In November 2015, torsional vibrations along the rotor shaft of a thermal generation unit in Ha Tinh province in Vietnam were exacerbated by sub-synchronous resonance. The unstable oscillations resulted in several cracks throughout the turbine-generator shaft (Duc Tung, Van Dai, and Cao Quyen 2019). More recently, in an isolated industrial area of Russia, torsional oscillations and sub-synchronous resonance have repeatedly caused protection systems to shut down all operating gas turbine generators in the area and led to widespread outages (Ilyushin and Kulikov 2021).

Incidents such as the ones listed above indicate how important it is to be able to adequately model the behavior of a turbine-generator rotor shaft system when investigating torsional oscillations or sub-synchronous oscillations. While a complete continuum model of the rotor subdivided into dozens of minute masses and connecting shafts is needed to capture the entire range of torsional oscillations, it is generally sufficient to represent the rotor as a lumped, multi-mass model if the oscillations of interest are sub-synchronous (Ong 1998). The oscillations associated with the torsional rotor shaft can also be exacerbated by the DC braking torque effect of the generator. When a symmetrical fault occurs in close proximity to a generator, the sudden disturbance has a tendency to cause the generator rotor to back swing. This effect could influence the angular displacement of the rotor and alter the torsional modes expressed by the rotor shaft (Shackshaft 1970).

While sub-synchronous resonance studies are generally performed in three-phase, electromagnetic transient simulation programs, there are still some instances in which a detailed positive sequence electrical system model with a simplified model of the interactions between the shaft and electrical dynamics is desirable. In these cases, a Modelica-based implementation can provide several beneficial features that are not available in other modeling languages or simulation tools. For example, the `Modelica_LinearSystems2` Library enables linearization and eigenvalue analysis of models to verify the modal quantities of a shaft without requiring the development of a separate model for linear analysis. Additionally, programs such as Dymola include functionality to easily compare the performance of different model implementations.

1.1 Motivation and Objectives

The Open-Instance Power System Library (OpenIPSL) was developed in part to provide Modelica implementations of standard phasor-domain power system models for research and teaching activities with a transparent library development framework. With the recent release of version 3.0.1, several models from the PSS®E Model Library that were missing from previous versions of OpenIPSL were added to the library (DeCastro Fernandes 2023). However, two component models critical to shaft torsional studies and sub-synchronous oscillation studies that are widely used in the industry have yet to be added. These models are a torsional shaft model with up to 25 masses, `SHAF25`, and a round rotor generator with a DC offset torque component, `GENDCO`. By developing Modelica implementations of these models, OpenIPSL can be used to develop power system models with richer dynamics suitable for investigating the effects of sub-synchronous oscillations and sub-synchronous resonance. After additional validation and testing, the models proposed in this paper will be added to a future release of OpenIPSL.

Finally, this work addresses a significant gap in power system dynamic modeling. According to the PSS®E Program Operation Manual, the `SHAF25` model is classified as a turbine-governor model (Siemens 2015a). It is therefore not possible to model turbine governor dynamics and the torsional dynamics of the `SHAF25` model simultaneously. Neglecting the turbine governor of a system restricts analysis of the impact of sub-synchronous resonance to the rotor shaft of the turbine-generator. By using components from OpenIPSL, the modeling approach proposed in this work allows for the dynamics of turbines, boilers, and governors to be modeled alongside the torsional dynamics of the shaft.

To summarize, the objectives of this work were to:

- Develop and validate a scalable, lumped mass torsional shaft model using the Modelica modeling language. This approach will allow for the dynamics of the shaft to be modeled simultaneously with the the dynamics of the turbine, boiler, and governor of the turbine-generator system, which is not possible with existing domain-specific tools.
- Develop and verify the behavior of a round rotor generator with quadratic saturation that includes a DC offset torque component.
- Demonstrate the functionality of the developed models by using an illustrative, single-machine infinite-bus (SMIB) test system to demonstrate the penetration of sub-synchronous resonance throughout a power grid.

1.2 Contributions and Organization

The primary contributions of this work are:

- The proposal and assessment two methods of coupling the electrical and mechanical dynamics of a turbine generator system.
- The development of a flexible implementation for modeling a torsional shaft with any number of masses that. The implementation enables the simultaneous modeling of turbine, boiler, and governor dynamics alongside the dynamics of the shaft.
- The implementation of a synchronous machine model with quadratic saturation and DC offset torque components for shaft torsional studies.
- A demonstration of the usefulness of the Modelica modeling language in developing power system models capable of simulating the effects of sub-synchronous resonance.

The remainder of the paper is organized as follows. Sections 2 and 3 detail the process of modeling and assessing two turbine-generator components respectively: 1) a scalable multi-mass torsional shaft; and 2) a round rotor generator model with a DC offset torque component. Section 4 demonstrates the use of these components to develop an illustrative power system example model to observe the penetration of sub-synchronous resonance throughout the grid. Finally, Section 5 summarizes the contributions of this work with concluding remarks and outlines planned future work for the models described throughout the paper.

2 Scalable Multi-Mass Shaft

2.1 SHAF25 Implementation Using Modelica

The `SHAF25` model found in the PSS®E Model Library (Siemens 2015b) is a lumped-mass torsional shaft model capable of representing up to 25 masses connected by weightless springs. Using the `Modelica Standard Library`, it is straightforward to assemble shaft models for a set number of masses by connecting an alternating sequence of rotational mechanical `inertia` and `springDamper` components. However, to be able to represent shafts with up to 25 masses, this approach would require maintaining a library with 25 separate shaft models. Alternatively, by using concepts from the

DOI 10.3384/ecp204541

ScalableTestSuite Library (Casella et al. 2015), a single shaft model can be developed with the number of masses on that shaft determined by a single integer parameter.

Listing 1 provides an excerpt of the text layer for the multi-mass torsional shaft model showing its scalability. The relevant parameters and components are all instantiated as arrays, and a for loop in the equation section iteratively connects the components in the correct order. As an added benefit, this scalable modeling approach allows the model to represent a shaft with any number of masses, effectively bypassing the 25 mass limit of the original SHAF25 model.

Listing 1. Excerpt of text layer for the scalable multi-mass torsional shaft model illustrating its scalability.

```
model ScalableShaft;
// Parameter declaration
parameter Integer N = 5 "Number of masses";
parameter SIunits.Inertia H[N] "Vector of p
    .u. moment of inertia values";
parameter SIunits.Inertia J[N] = H.*(
    SysData.S_b/wo^2);
parameter SIunits.RotationalSpringConstant
    K[N-1] "Vector of stiffness
    coefficients";
parameter SIunits.RotationalSpringConstant
    C[N-1] = K.*p^2*(SysData.S_b/(4*wo)) "
    Vector of stiffness coefficients in N-m
    /rad";
parameter SIunits.RotationalDampingConstant
     D[N-1] = fill(Modelica.Constants.small
    , N-1) "Vector of damping constant
    values in Nms/rad";
// Class Instantiation
Modelica.Mechanics.Rotational.Components.
    Inertia inertia[N](J=J);
Modelica.Mechanics.Rotational.Components.
    SpringDamper springdamper[N-1](c=C, d=D
    );
Modelica.Mechanics.Rotational.Sensors.
    RelAngleSensor relAngle[N];
// Model Equations
equation
  connect(inertia[1].flange_a, flange_a);
  for i in 1:(N-1) loop
    connect(inertia[i].flange_b,
        springdamper[i].flange_a);
    connect(springdamper[i].flange_b,
        inertia[i+1].flange_a);
    connect(relAngle[i].flange_b, inertia[i
        ].flange_a);
    connect(relAngle[i].flange_a, inertia[i
        ].flange_b);
  end for;
  connect(flange_b, inertia[N].flange_b);
  connect(relAngle[N].flange_b, inertia[N].
      flange_a);
  connect(relAngle[N].flange_a, inertia[N].
      flange_b);
end ScalableShaft;
```

In this work, and many other works in the literature, the damping coefficients of the springDamper components connecting the masses of the shaft are assumed to be negligible. It is generally acceptable to assume that the damped and undamped natural frequencies of the shaft are within 0.1 Hz of each other (**anderson:1999sub-synchronous**). As such, the damping coefficients for the shaft model shown here are all set to an arbitrarily small value, Modelica.Constants.small.

2.2 Model Validation

To verify the behavior of the multi-mass shaft model, eigenvalue analysis was used to observe the relative angular displacement between the segments of a five mass implementation of the component. The five mass shaft was parameterized using data from a four pole nuclear unit found in Section 15.1 of Prabaha Kundur's textbook, *Power System Stability and Control* (Kundur 1994). This procedure is aided and simplified through the use of the Modelica_LinearSystems2 library to generate a linearized electromechanical state-space model of the torsional shaft system. This library is also used to determine the frequencies of the modes exhibited by the system. From this model, it is straightforward to obtain an eigenvector matrix that describes the magnitude of the mode shapes. The resulting mode shapes are shown in Figure 1a. For comparison and validation, Figure 1b shows the mode shapes obtained in *Power System Stability and Control*(Kundur 1994).

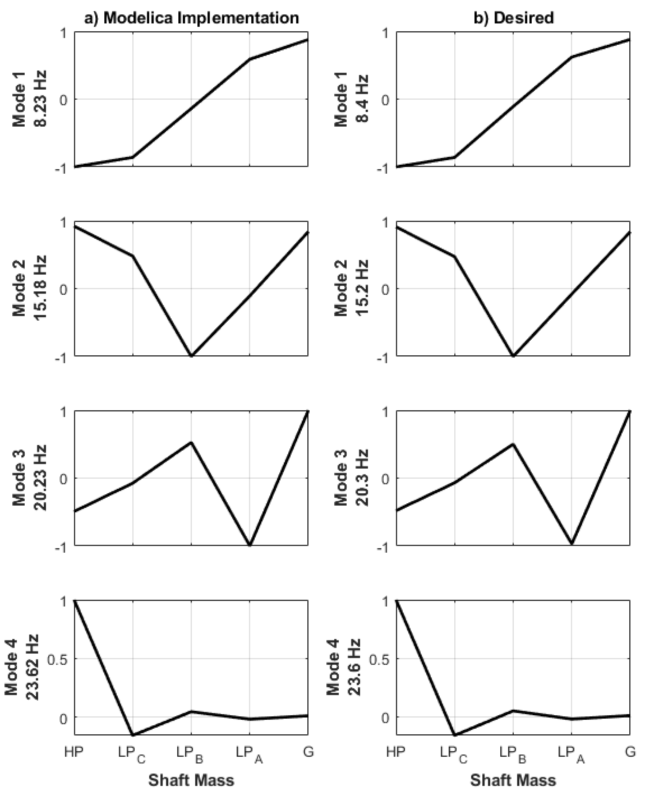

Figure 1. Mode shapes and frequencies obtained from a) the Modelica implementation of a five-mass torsional shaft, and b) the implementation found in *Power System Stability and Control* (Kundur 1994).

After normalizing each of the eigenvectors such that the magnitude of the largest element is 1.0, the overall trajectory of the mode shapes and modal frequencies of the two implementations are nearly identical, indicating that the Modelica multi-mass shaft implementation exhibits the expected behavior. While there are some minor discrepancies in the modal frequencies of the two implementations, this can likely be attributed to initialization differences in the Modelica implementation, as the states' precise initial values of the model from *Power System Stability and Control* are not known.

2.3 Coupling Mechanical Shaft Dynamics with Electrical System Dynamics

As a purely rotational mechanical model in Modelica, the multi-mass shaft has mechanical torque flange inputs and outputs. The PSS®E generator models in OpenIPSL through their extension of a `baseMachine` class, however, only accept real inputs for mechanical power and field voltage. Therefore, two methods were devised to interface the shaft model with the electrical system.

2.3.1 Modified Base Machine Class

The first approach to couple the mechanical and electrical dynamics of the system involved creating a variant of the `baseMachine` class included in OpenIPSL. Each of the PSS®E generator models in OpenIPSL extends the same `baseMachine` class. By altering this class to replace the mechanical power input with a mechanical torque flange input, the torsional shaft model can be simply connected to the rest of the electrical system through the electrical pin of the generator. For comparison, the icon layer of the original base machine and the modified base machine are shown in Figure 2.

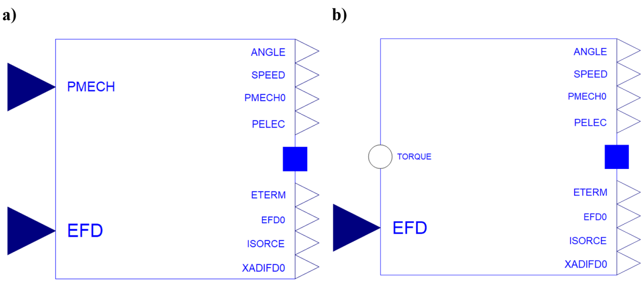

Figure 2. Comparison of the icon layer of a) the original base machine model from OpenIPSL, and b) the modified base machine model to accept a torque input from a torsional shaft model.

To facilitate this connection, two mathematical equations to explicitly calculate the mechanical power input to the generator from the mechanical torque input had to be added to the text layer of the model.

The first equation, shown in Equation 1, converts the per unit speed deviation of the rotor into mechanical speed:

$$\omega_m = \omega_b(1+\omega) \tag{1}$$

where ω_m is the mechanical speed of the rotor in radians per second, ω_b is the synchronous speed of the system in radians per second, and ω is the per unit mechanical speed deviation of the generator rotor.

The second equation, shown in Equation 2 uses this mechanical speed to convert the input mechanical torque into mechanical power:

$$P_m = \frac{\omega_m T_m}{M_b}, \tag{2}$$

where P_m is the per unit mechanical power input to the generator, T_m is the mechanical torque input to the generator from the torsional shaft in Newton-meters, and M_b is the system base power in volt-amperes.

By redefining the variable for mechanical power, the swing equation of the original `baseMachine` model can be left unaltered:

$$2H\frac{d\omega}{dt} = \frac{\omega_m - D\omega}{\omega+1} - T_e \tag{3}$$

2.3.2 Torque-to-Mechanical Power Interface

While the previous method to couple the electrical and mechanical dynamics of the turbine-generator system is relatively straightforward, it would require pervasive changes to OpenIPSL to implement, as individual models for each generator extending the new multi-domain base machine class would have to be developed. This would effectively require two of each generator model to be maintained.

An alternative approach is to create a standalone interface model that accepts a mechanical torque flange input and produces a real mechanical power output as shown in Figure 3 (F. J. Gómez et al. 2018; Aguilera, Vanfretti, Bogodorova, et al. 2019; Aguilera, Vanfretti, and F. Gómez 2018).

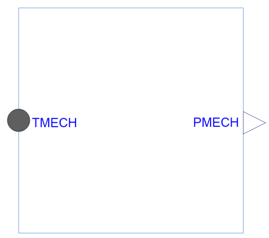

Figure 3. Icon layer of an interface to couple the mechanical dynamics of a torsional shaft with the electrical dynamics of a turbine-generator system.

Using this method, the per unit speed deviation of the rotor must be explicitly calculated by taking the derivative of the angular position of the shaft connected to the input of the interface:

$$\omega = \frac{d\phi}{dt}\frac{1}{\omega_b} \tag{4}$$

where ω is the per unit mechanical speed deviation of the rotor, ϕ is the relative angular position of the rotor in radians, and ω_b is the synchronous speed of the system in radians per second.

DOI 10.3384/ecp204541

The per unit mechanical speed deviation can then be used to calculate the mechanical speed of the rotor:

$$\omega_m = \omega_b(1+\omega) \tag{5}$$

where ω_m is the mechanical speed of the rotor in radians per second.

Finally, the mechanical speed of the rotor and torque input to the interface can be used to determine the mechanical power input to the generator:

$$P_m = \frac{\omega_m T_m}{M_b} \tag{6}$$

where P_m is the per unit mechanical power output from the interface, T_m is the mechanical torque input to the generator from the torsional shaft in Newton-meters, and M_b is the system base power in volt-amperes.

2.3.3 Comparison of Implementations

For comparison, Figure 4 shows the graphical layers for both methods of coupling the mechanical and electrical dynamics of a turbine-generator system. Both implementations include a representation of the boiler, turbine, and speed-governor modeled by an `IEEEG1` component; an IEEE Type 1 excitation system modeled using an `IEEET1` component; and a round rotor synchronous generator with quadratic saturation represented by a `GENROU` model.

To compare the efficacy of the two methods of interfacing the shaft model with the remainder of the turbine-generator model, the two models were initially simulated with an identical simulation configuration for 30 seconds using `DASSL`, a variable time-step solver. As shown in Figure 5, the error of the mechanical power input to the generator calculated between the two implementations appears to accumulate throughout the simulation. Using `Rkfix4`, a fixed step, fourth-order Runge-Kutta method solver, however, the mechanical power plotted for both implementations were identical, as shown in Figure 6.

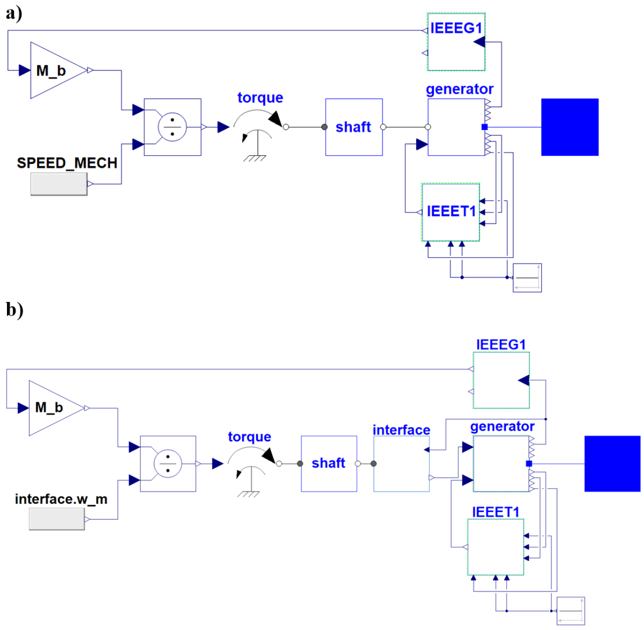

Figure 4. Comparison of the graphics layer of two methods to interface a torsional shaft model with an electrical system: a) A modified base machine directly accepts mechanical torque from the shaft and internally calculates mechanical power, b) An interface accepts a mechanical torque input from the shaft and produces a mechanical power output for the generator. Both approaches notably allow for a turbine-governor model, represented by the `IEEEG1` model, to be simulated in conjunction with the shaft model, which is not possible with many power system simulation tools.

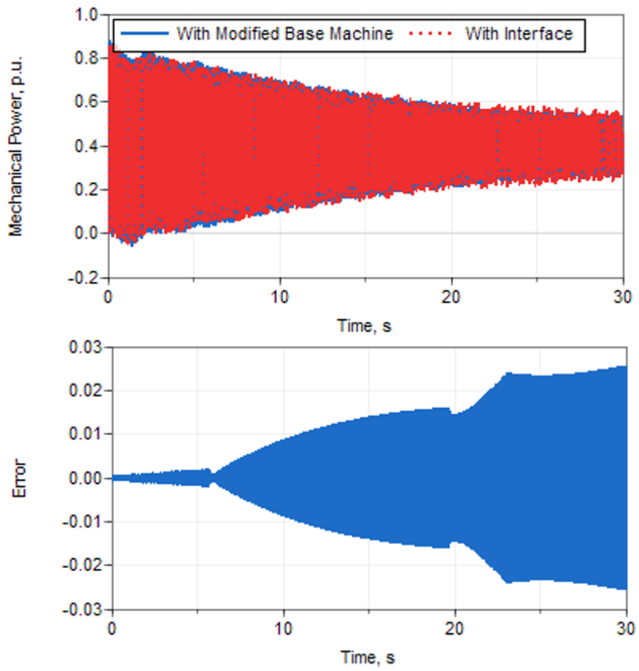

Figure 5. Plot of mechanical power input to the generator for both methods of interfacing the shaft model with the remainder of the turbine-generator model when simulated using the DASSL solver in Dymola and the error between the two.

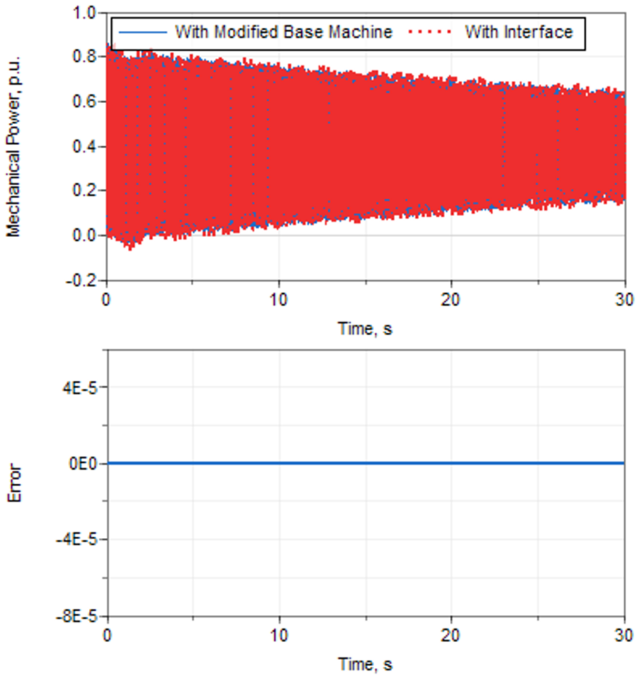

Figure 6. Plot of mechanical power input to the generator for both methods of interfacing the shaft model with the remainder of the turbine-generator model when simulated using the Rkfix4 solver with an integration step size of 0.00001 s in Dymola and the error between the two.

Generally, solutions obtained from variable-step solvers are more accurate, as the solver dynamically adjusts the size of the integration step size to match the speed at which the states of the model change. Fixed-step solvers, however, maintain the same integration step-size throughout the simulation. With a large step size, the simulation time can be greatly reduced, however, the accuracy of solutions may suffer as the solver cannot adjust its step size to match the stiffness of the system.

While the two implementations are modeled using the same equations and should therefore, in theory, produce identical solutions. However, the integration step size when using the `DASSL` solver does not vary identically for the implementations. As such, the solutions acquired by both implementations are not identical, as observed in Figure 5. When the same step size is enforced for both models, however, the solutions become identical, as shown in Figure 6. While the solution results may be identical for the two implementations, the accuracy of this solution is not guaranteed. Figure 7 shows a plot of the mechanical power for both implementations using an integration step size of 0.01 seconds.

While the plots of mechanical power from implementations agree with each other, it can be inferred that they are both inaccurate with respect to the actual result by comparing the resulting plot with the plots acquired from a variable-step solver or a fixed-step solver with a very small step size.

By enabling the `Generate block timers` flag in the simulation setup dialog of Dymola, the simulation

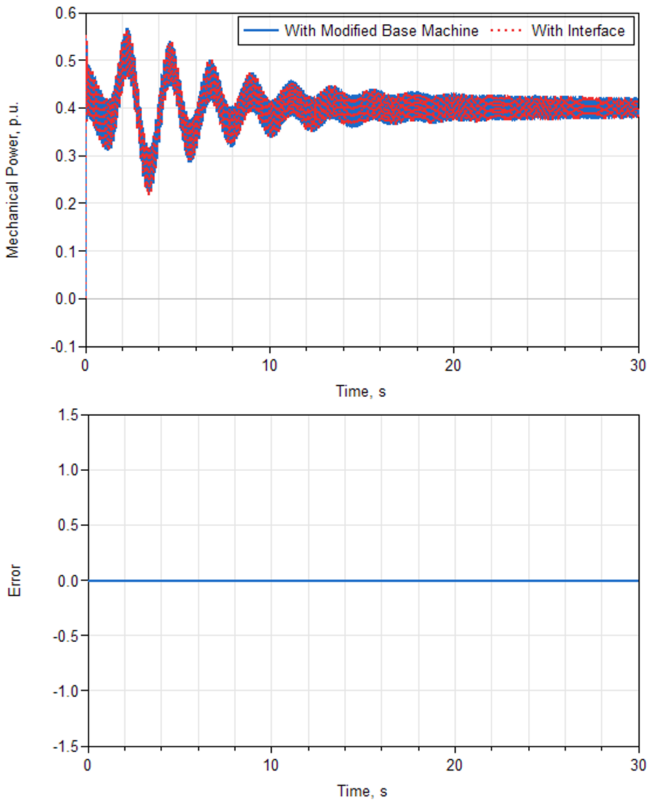

Figure 7. Plot of mechanical power input to the generator for both methods of interfacing the shaft model with the remainder of the turbine-generator model when simulated using the Rkfix4 solver with an integration step size of 0.01 s in Dymola and the error between the two.

time of the two implementations can be compared as shown in Table 1. Using the `Rkfix4` solver, the range of time steps that both implementations could successfully complete simulation for was between 0 seconds and 0.01 seconds. For each time step, it can be observed that the modified base machine implementation is slightly more computationally efficient. Using the variable time-step `DASSL` solver results in an even greater discrepancy between the computational cost of the two implementations, with the modified base machine method remaining the more efficient option.

The discrepancy in simulation time between the two implementations can be explained by examining the statistics of the translation log in Dymola, shown in Figure 8.

When translating a model, Dymola uses its state variables to create differential, linear, and non-linear systems to solve. As such, models with more states generally will take longer to simulate (Fish and Harrison 2017). The number of states can be approximated by examining the `Time-varying variables` and `Alias variables` entries of the translation statistics log (Horn 2020). Also of interest is the `Continuous time states` entry of the log which indicates the overall size

 DOI 10.3384/ecp204541

Table 1. Comparison of simulation time for two methods of coupling mechanical and electrical dynamics of a turbine-governor system using the Rkfix4 solver with various time steps and the DASSL solver.

Solver	Step Size (s)	Coupling Method	Simulation Time (s)
Rkfix4	0	Base Machine	328.835
		Interface	341.871
	0.0001	Base Machine	134.925
		Interface	135.096
	0.01	Base Machine	1.391
		Interface	1.638
DASSL	–	Base Machine	75.946
		Interface	80.161

of the model. From Figure 8 it can be observed that the modified base machine implementation contains fewer alias variables and continuous time states than the torque-to-power interface implementation, corresponding with the former's faster simulation time.

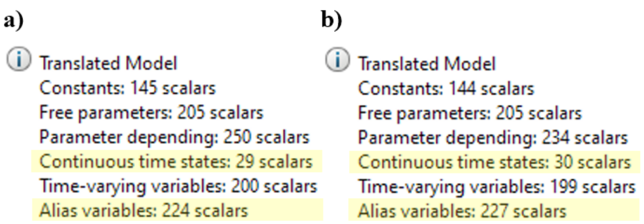

Figure 8. Comparison of excerpts from the translation statistics logs in Dymola for a) the modified base machine implementation, and b) the torque-to-power interface implementation. Highlighted statistics affect the simulation time of the implementations.

3 GENDCO

When performing power system studies involving shaft torsional dynamics in PSS®E, the `SHAF25` torsional shaft model must be coupled with a `GENDCO` generator model (Siemens 2015c). The `GENDCO` model is a round rotor generator model with quadratic saturation and DC offset torque components included. To model the effect of these DC offset components, the direct- and quadrature-axis armature-winding voltage equations of the generator were modified. The original equations used in the `GENROU` model are shown in Equation 9 and Equation 10 (Baudette et al. 2018):

$$v_d = -R_a i_d - \Psi_q \tag{7}$$

$$v_q = -R_a i_q + \Psi_d \tag{8}$$

where R_a is the machine armature resistance, i is the direct- or quadrature-axis current, and Ψ is the direct- or quadrature-axis stator flux linkage. The modified equations for the `GENDCO` model include the rate of change of stator flux linkages as shown in Equation 9 and Equation 10 (Dandeno et al. 2003):

$$v_d = -R_a i_d - \Psi_q + \frac{1}{\omega_0}\frac{d\Psi_d}{dt} \tag{9}$$

$$v_q = -R_a i_q + \Psi_d + \frac{1}{\omega_0}\frac{d\Psi_q}{dt} \tag{10}$$

where ω_0 is the synchronous electrical speed. These equations assume that the rotor speed never deviates from the synchronous rotor speed.

For `GENROU` and other generator models that ignore the effects of DC offset components, the air-gap torque of the generator following a disturbance will consist primarily of a unidirectional step change caused by stator resistance losses (Kundur 1994). For the `GENDCO` model, however, an additional decaying oscillatory component representing the DC offset component of current induced in the stator by the disturbance will be present. Figure 9 illustrates the difference in the air-gap torque response of a `GENROU` generator model from OpenIPSL that neglects the rate of change of stator flux linkages in the armature-winding voltage equations and the `GENDCO` generator model that includes them.

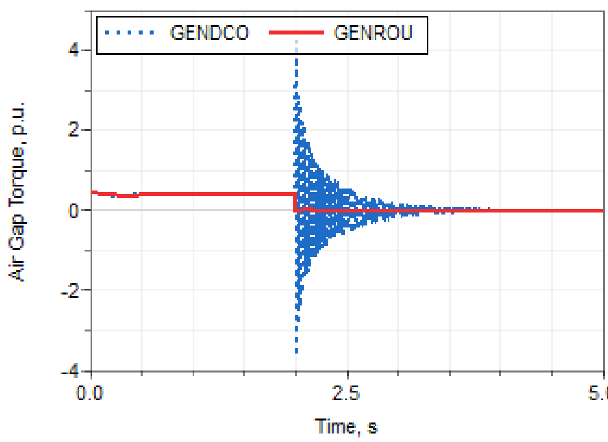

Figure 9. Plot comparing air-gap torque over time for identically parameterized GENROU and GENDCO models. A fault is applied at t = 2 s for 0.15 s.

The additional oscillatory component in the air-gap torque response of the `GENDCO` generator model can also be confirmed through linear eigenvalue analysis. Table 2 shows the pole pair and modal frequency obtained through linear analysis using the

Modelica_LinearSystems2 library in Dymola for a simple test system including the GENROU generator model. Table 3 shows the pole pairs and modal frequencies for the same test system when the generator model was changed to the GENDCO model. In comparing the two tables, it can be observed that as a result of the DC offset components, the GENDCO model contains an additional, higher frequency pole while retaining the same 0.814 Hz pole exhibited by the GENROU model.

While the GENDCO model and the inclusion of DC offset components is critical in obtaining the correct dynamic characterization of any sudden changes in the electromagnetic torque of the generator, it is important to note that DC offset approximation effects are only valid when analyzing the effects of symmetrical faults and imbalances. Consequently, the model should only be used for studies involving shaft torsional dynamics (Siemens 2015c).

Table 2. Pole and Modal Frequency of GENROU generator model

Eigenvalue	Frequency (Hz)
$-0.26835 \pm j5.1092$	0.8143

Table 3. Poles and Modal Frequencies of GENDCO generator model

Eigenvalue	Frequency (Hz)
$-0.2684 \pm j5.1087$	0.8142
$-0.021085 \pm j5605.7$	892.7985

4 Example of Subsynchronous Resonance Analysis

The interaction between the sub-synchronous oscillations created by the torsional shaft of a turbine-generator system and the rest of the electrical system can lead to equipment failure and damage due to torsional fatigue if improperly damped (Walker et al. 1975). As such, it is important to be able to analyze how the resonance resulting from these interactions can penetrate into the power system.

As a preliminary investigation into how the models developed in this paper can be applied to sub-synchronous resonance studies, a single-machine, infinite-bus (SMIB) test system was developed as shown in Figure 10.

The generator unit on the left hand side of the test system in Figure 10 models a turbine-generator consisting of a six-mass implementation of the torsional shaft model described in Section 2 and the GENDCO model described in

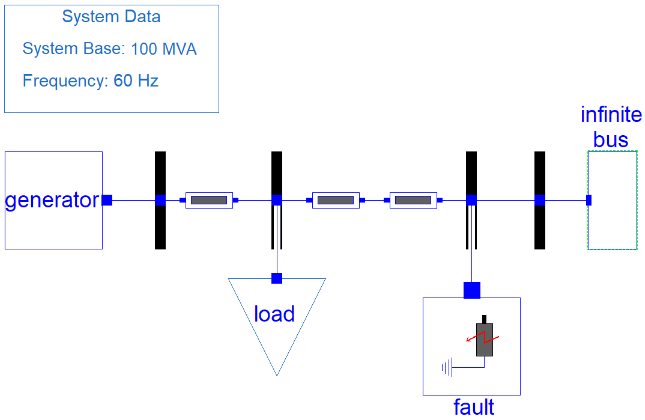

Figure 10. Single-machine, infinite-bus test system used to analyze the penetration of sub-synchronous oscillations throughout an electrical system.

Section 3. The GENCLS generator model at the far-right of the test system is parameterized as an infinite bus, representing the reminder of the power grid. A fault was configured to be applied to the system at $t = 2$ seconds and cleared at $t = 2.15$ seconds. The turbine-generator system and lines were parameterized using parameters from the IEEE first benchmark model for computer simulation of sub-synchronous resonance (Farmer 1977). With these parameters, the turbine-generator system is able to return to a stable state following a disturbance. Figure 11 shows the air-gap torque response of the GENDCO model in the test system when the torsional shaft model is included in the turbine-generator system and when it is omitted.

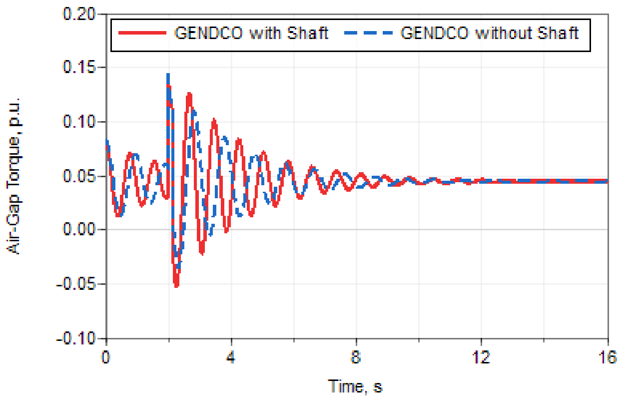

Figure 11. Plot of the air-gap torque of the test system turbine-generator model when the torsional shaft model is omitted and included.

The response of the two model variants of the system are similar, with a slight discrepancy in the frequency of the oscillations preceding and following the fault being the primary difference. To further illustrate this difference, Figure 12 shows a detailed view of the air-gap torque response of the test system after the turbine-generator system has returned to a steady state after the fault was cleared. The turbine-generator system with the shaft omitted exhibits an approximately 60 Hz oscillation, corre-

DOI 10.3384/ecp204541

sponding with the expected behavior due to the effect of the DC offset components. The turbine-generator system with the shaft included contains a sum of several other oscillations, representing the torsional modes of the shaft.

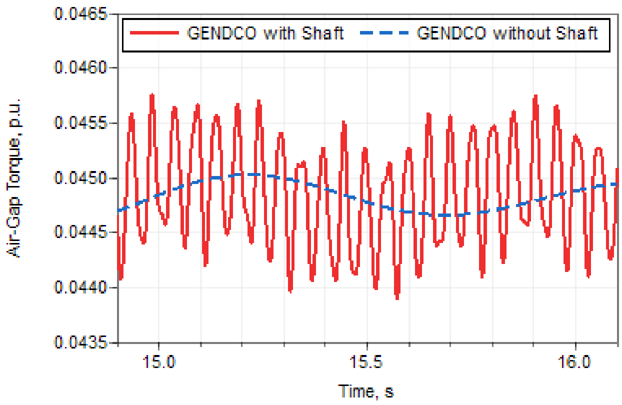

Figure 12. Detailed view of the steady-state portion of the air-gap torque response of the test system following a fault when the torsional shaft is included and omitted from the turbine-generator system.

The time constant controlling the decay of the DC offset torque components roughly corresponds to the network resistance-to-reactance ratio as seen by the generator (Siemens 2015c). As such, if this ratio is excessively large, the effects of sub-synchronous resonance may cause the system to become unstable. Figure 13 compares the bus voltage at the location of the fault in the test system for the line parameters used in the IEEE first benchmark model (Farmer 1977) and for arbitrary line parameters that greatly increased the ratio of resistance-to-reactance seen by the generator. The bus voltage response is similar for the two sets of line parameters before and during the fault, however, following the fault, if the resistance-to-reactance ratio is excessively large, the oscillations following the fault will persist as shown by the unstable case in Figure 13.

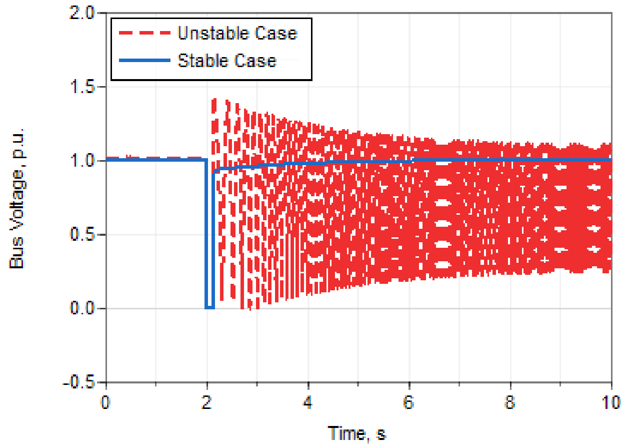

Figure 13. Plot of the bus voltage at the location the fault was applied to when the test system was parameterized with two different sets of transmission line parameters.

5 Conclusions and Future Work

The scalable, multi-mass torsional shaft model and the GENDCO synchronous machine model with DC offset torque components developed in this paper enable a flexible method for performing shaft torsional studies using Modelica. The torsional shaft model enables the ability to model the mechanical dynamics of any number of boilers, turbine pressure stages, and governor simultaneously. Two methods for coupling the shaft model to the rest of the turbine-generator system were explored. While modifying the OpenIPSL base machine class of the generator model to accept a mechanical torque input was shown to be more computationally efficient, an interface to convert the mechanical torque from the shaft to mechanical power input to the generator model would require less pervasive changes to the library to maintain. When coupled with the torsional shaft model, the GENDCO generator model with DC offset torque components enables modeling sudden changes in the electromagenetic torque of the generator more accurately for studies involving shaft torsional dynamics. By employing these models in an SMIB power system model, the effects of sub-synchronous oscillations can be observed. Consequently, adequate line parameters and lenient operating conditions for the modeled system can be determined to limit the impact of sub-synchronous resonance.

Future work includes validating the behavior of the GENDCO model developed in this paper. There is currently no openly accessible PSS®E dynamic model parameter data for an existing GENDCO unit. However, if this data was obtained, software-to-software validation could easily be performed to confirm that the Modelica implementation of the model behaves identically to the equivalent model in PSS®E. Additionally, while the IEEE first benchmark model for the computer simulation of sub-synchronous resonance was used to parameterize the test system developed in Section 4, implementing the first and second benchmark models in Modelica to further explore the effects of sub-synchronous resonance on an electrical system remains the subject of future work (Farmer 1977; Farmer 1995). Finally, the torsional shaft model developed in this paper assumes negligible damping throughout the shaft. The damping of torsional oscillations is generally very small, but difficult to predict without performing field tests on a specific shaft (Kundur 1994). By obtaining PSS®E dynamic data for an existing SHAF25 unit, the viscous damping of each mass with respect to the rotor and the damping between each mass could be accurately modeled in the equivalent Modelica implementation. Upon the completion of these tasks, the integration of the torsional shaft model and GENDCO model into OpenIPSL will be pursued.

Acknowledgements

This work was supported in part by Dominion Energy, the National Science Foundation Award No. 2231677, and the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing Office, Award No. DE-EE0009139.

The authors would like to thank Dr. Leonardo Lima of Kestrel Power and Mr. James Feltes of Siemens PTI for their modeling guidance.

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