Development and Implementation of a Nordic Grid Model for Power System Small-Signal and Transient Stability Studies in a Free and Open Source Software

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***Abstract*—This article presents an implementation of a Nordic grid model in Power System Analysis Toolbox (PSAT) —a free and open-source software. A newly developed hydro turbine and hydro governor (HTG) model is implemented with this grid model and compared with the currently available PSAT turbine governor models. Small-signal and transient stability analyses of the system using the two models are carried out and compared to demonstrate the difference and necessity of accurate hydro turbine and governor model utilization. The paper ends with a validation of the linearized Nordic grid model generated by PSAT including the newly implemented HTG models. This validation is done through nonlinear time-domain simulation by applying both large and small disturbances.**

***Index Terms*—Power system modelling; nordic power system; hydro turbine modelling; hydro governor modelling; small-signal stability; inter-area oscillations**

I. INTRODUCTION

Responses of an electric power network after disturbances portray the dynamic behavior of the system. Understanding dynamic responses is crucial in evaluating the system's characteristics. Once these characteristics have been well-understood, the response of the system to disturbances may be anticipated, and unwanted behavior can be alleviated by the design and implementation of power system controls and protections.

Stability of a power system is dependent on the set of parameters describing the dynamic properties of each of its elements. Of particular importance are those parameters belonging to machines, e.g. generators, turbines, and/or governors. They play a major role in rotor angle stability which is classified into two types: small-signal stability and transient stability [1]. These two types of stability are widely and intensively employed for stability security assessment at network control centers and for planning purposes.

To correctly forecast dynamic responses and assess system stability, accurate modelling of power systems is highly important. The system model should be capable of representing the behavior of the real system as close as possible. Incorrect or incomplete modelling may lead to incorrect simulation results, which could in turn result in costly consequences in operation.

The Nordic electricity network has the characteristics of bearing heavy generation in the northern region while supplying large consumption in the southern region through weak transmission lines [2]. The northern region is largely supplied by hydro power and the southern region by thermal generation. Features of hydro generators are substantially different from those of thermal generators, and their respective modelling needs to be done appropriately.

Previous research on the Nordic grid system has been extensively carried out on proprietary simulation software such as PSS®E [3], PacDyn [4], and SIMPOW® [5]. Some sample studies include wide-area monitoring and control [6], [7], [8], wide-area damping control [9], [10], and linear analysis [11]. Some of these software are only capable of simulating one type of stability analysis and require different dynamic models; this is the case in [10] where PSS®E is used for transient stability simulations while PacDyn is used for small-signal stability analysis. The main disadvantage here is that the non-linear PSS®E model used for transient simulations may not necessarily correspond to the PacDyn linearized model used for the studies. As a result, controllers designed using PacDyn's linear model may not perform satisfactorily when simulated using the nonlinear PSS®E model. In addition, while these models developed for the analysis of the Nordic grid are useful, they have been implemented in proprietary software packages. High cost, license restrictions, and limited freedom of core software modifications are the hurdles of the type of proprietary software. On the other hand, to the authors' knowledge, none of the Free and Open Source Software (FOSS) alternatives has been utilized for the modelling of the Nordic grid. Hence, an attractive alternative would be to utilize a free and open source power system software that encompasses both transient and small-signal models.

Proprietary software are conceived by the general public to be well-tested, trustworthy, and computationally efficient. Note that this perception might not be necessarily true for all software [12]. More importantly, license agreements restrict the use of proprietary software by imposing different conditions; in other words, they are "closed" [13]. On the other hand, free and open source software allow users to change the source code, add new algorithms, and/or implement new

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components [1]. Unlike the proprietaries, FOSS give users the "freedom" and liberty which is the key difference between the two software. In addition, free software stands on an ethical pillar which aims to warrant intrinsic freedoms of computer users that are jeopardized by proprietary software [12], [14].

Power System Analysis Toolbox (PSAT) [15] is an educational open source software for power system analysis studies [16]. The toolbox covers fundamental and necessary routines for power system studies such as power flow, small-signal stability analysis, and time-domain simulation. PSAT is a suitable candidate as a power system analysis software which is capable of performing core stability analyses. There is, however, one limitation: hydro turbine and governors models were not available in the toolbox.

The aim of this paper is, therefore, to propose an improved model of the modified Nordic power system for power system stability analyses and studies. The improved model includes a newly developed hydro turbine and hydro governor model [17] which is capable of representing the actual dynamic behaviour of hydro units. Not only will this allow for a more accurate representation of the system's dynamic behavior but also allows for the analysis of small-signal and transient stability studies. Consequently, suitable controls can be properly designed to limit the negative impact of inter-area oscillations and other instabilities.

II. KTH-NORDIC32 SYSTEM

A. Background

The system analyzed in this study is a conceptualization of the Swedish power system and its neighbors circa 1995. It is based on a system data set proposed by T. Van Cutsem [18], which is a variant of the CIGRE "*Nordic 32A*" test network developed by K.Walve [19]. Due to some adjustment to the system model and its parameters, the system in this study is called KTH-NORDIC32.

B. System Characteristics

The KTH-NORDIC32 system is depicted in Fig. 1. The overall topology is longitudinal; two large regions are connected through considerably weak transmission lines. The first region is formed by the North and the Equivalent areas located in the upper part, while the second region is formed by the Central and the South areas located in the bottom part. The system has 52 buses, 52 transmission lines, 28 transformers and 20 generators, 12 of which are hydro generators located in the North and the Equivalent areas, whereas the rest are thermal generators located in the Central and the South areas. There is more generation in the upper areas while more loads congregate in the bottom areas, resulting in a heavy power transfer from the northern area to the southern area through weak tie-lines.

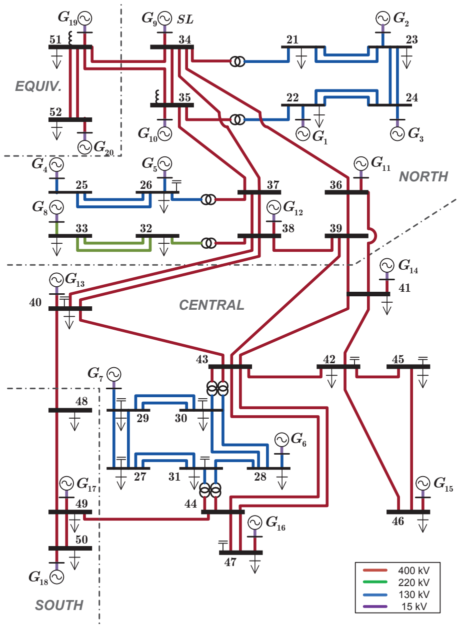

Fig. 1. KTH-NORDIC32 Test System

C. Dynamic Modelling

Dynamic models of synchronous generators, exciters, turbines, and governors for the improved Nordic power system are implemented in PSAT. All models used are documented in the PSAT Manual. Parameter data for the machines, exciters, and turbine and governors are referred to [18], [19] and provided in Appendix B.

1) Generator Models: Two synchronous machine models are used in the system: three-rotor windings for the salient-pole machines of hydro power plants and four-rotor windings for the round-rotor machines of thermal plants. According to Fig. 1, thermal generators are denoted by G_6, G_7 and G_{13} to G_{18} whereas hydro generators are denoted by G_1 to G_5, G_8 to G_{12}, G_{19} and G_{20}. These two types of generators are described by five and six state variables, respectively: δ, ω, e'_q, e''_q, e''_d, and with an additional state e'_d for the six-state-variables machine. All generators have no mechanical damping and saturation effects are neglected.

2) Automatic Voltage Regulator and Over Excitation Limiter Models: The same model of AVR, as shown in Fig. 2, is used for all generators but with different parameters. The field voltage v_f is subject to an anti-windup limiter.

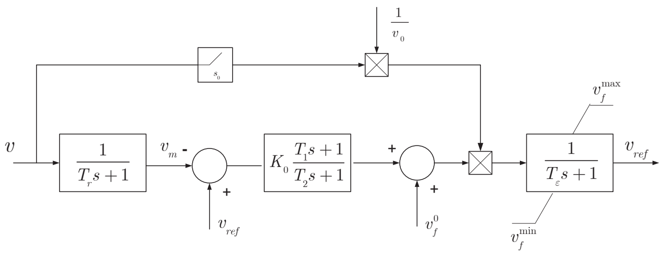

Fig. 2. Exciter Model

The model of over excitation limiters (OEL) used in the system is shown in Fig. 3. A default value of 10 s is used

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[1] Free and open source software is usually distributed on-line "cost free". The word "free" in this context is focused not in cost but rather in respecting the software users' freedoms outlined in [12].

for the integrator time constant T_0, while the maximum field current was adjusted according to each field voltage value so that the machine capacity is accurately represented.

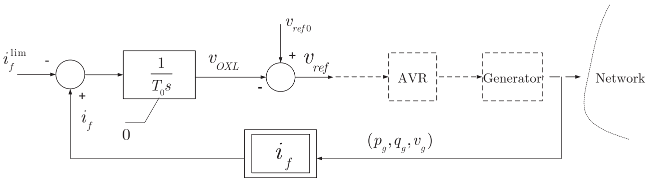


Fig. 3. Over Excitation Limiter Model

3) Turbine and Governor Models: In PSAT there are two models of turbine and governors; namely Model 1 and Model 2: the former being a thermal generator model while the latter a simplified model. As such, the system's hydro generator is temporarily represented by Model 2 while that of the thermal is represented by Model 1. Block diagrams of turbine and governor models for Model 1 and Model 2 are depicted in Fig. 4 and 5, respectively.

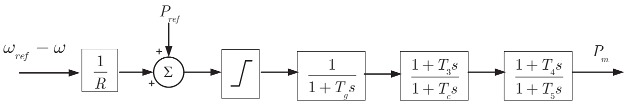


Fig. 4. Turbine Governor Model used for thermal generators: Model 1

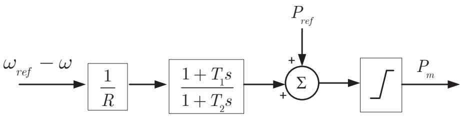


Fig. 5. Turbine Governor Model used for hydro generators: Model 2

III. Hydro Turbine and Governor Implementation

As of 2010, hydro power plants contributed nearly to 50% of the electricity production in Sweden [20]. As such, modelling dynamic characteristics of hydro generators, particularly in this Nordic system model, is of significance. The reason is that features of hydro generators are substantially different from those of thermal generators. Using only available turbine and governor models in PSAT (Model 1 and 2) to represent the hydro machines is inaccurate. This and the following sections will illustrate this modelling issue.

One important characteristics of hydro generators which distinguishes it from the others is the "water hammer effect" [21], [22]. That is, when the water gate opens in response to a load increase, the water pressure at the gate initially reduces due to a sudden increase in the volume of water, but, after a moment, it will increase afterwards (and vice versa for a load decrease).

A. Hydro Turbine and Governor Modelling

Li, W. *et al.* recently developed hydro turbine and governor (HTG) models in PSAT [23]. The block diagram of one of the models, Model 3, is shown in Fig. 6. The block consists of a typical hydro turbine governor and a linearized hydro turbine model where the corresponding elements are depicted in the figure. The linearized turbine is the classical hydro turbine model in power system stability analysis, corresponding to ideal turbine and inelastic penstock with water inertial effect considered.

Hydro turbines and their governors are normally combined together for representation. However, in some cases, the output of the turbine is the derivative of gate position (ΔG) while the input to the turbine is the gate position G. As such, a gate position reference, G_{ref}, is required between ΔG and G. Note that the number of state variables introduced by this model is equal to the total number of integrators.

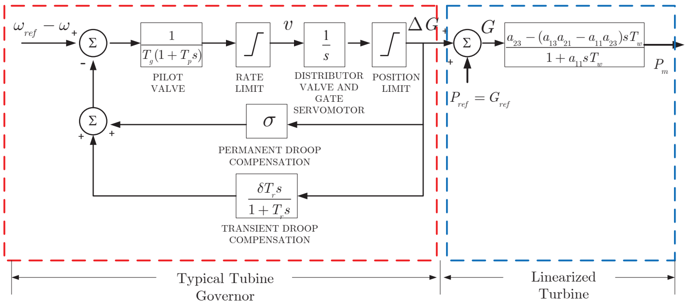


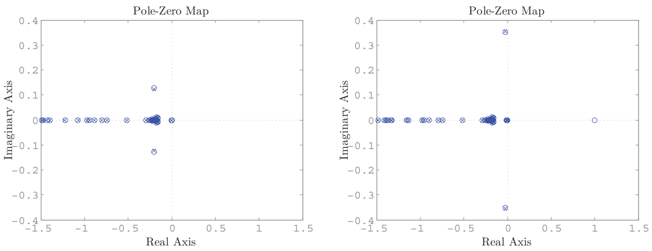
Fig. 6. Turbine and Governor Model used for hydro generators: Model 3

B. Hydro Turbine and Governor Simulation

To illustrate the real behavior of HTGs, pole-zero maps of the turbine and governor of G_1 using Model 2 and Model 3 are shown in Fig. 7a and 7b, respectively. In addition, responses of the mechanical power P_{m20} to a 10% load change at Bus 52 ,where the hydro generator G_{20} is connected, using Model 2 and Model 3 as HTG are compared in Fig. 8. Note that the load change is applied at t = 2 s and simulated for 20 s.

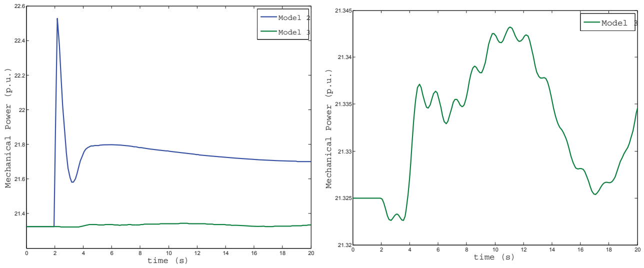
In Fig. 7b, it can be seen that there exists one zero in the right-half plane while a drop in P_{m20} before rising to meet the load increase can be noticed in Fig. 8b. This feature is a characteristic of *nonminimum phase systems*, which, for hydro generator, corresponds to its dominant characteristics: the water hammer effect. On the contrary, Model 2 in Fig. 7a or 8a (the blue line) fails to capture this effect, and thus, is not suitable as a representative model of HTGs.

The parameters of the hydro turbine and governor used in Model 3 are provided in Appendix B.



(a) Model 2 (b) Model 3

Fig. 7. Pole-Zero maps for turbine and governor models of G_1.



(a) Model 2 vs. Model 3 (b) Model 3 (enlargement)

Fig. 8. Response of the mechanical power P_{m20} to a 10% load change at Bus G_{52}.

IV. Results and Analyses

This section illustrates the main differences between the system behaviors in two cases: the use of Model 2 and Model 3 as HTGs in the KTH-NORDIC32 test system, and affirms why accurate modelling of hydro turbine and governor is necessary. As previously discussed, Model 2 is unsuitable and is used here for comparison purpose only. Note that Model 1 is used to represent thermal generators in both cases.

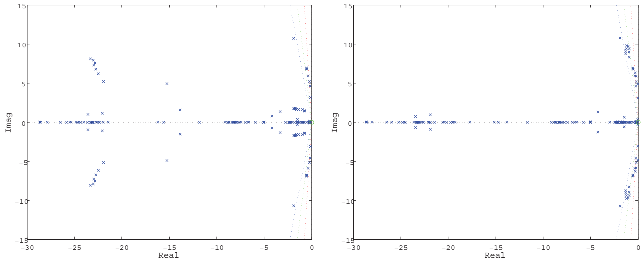
A. Small-Signal Stability Analysis

Small-signal stability is defined as the ability of a power system to maintain its synchronism after being subjected to a small disturbance [1]. Small-signal stability analysis reveals important relationships among state variables of a system and gives an insight into the electromechanical dynamics of the network.

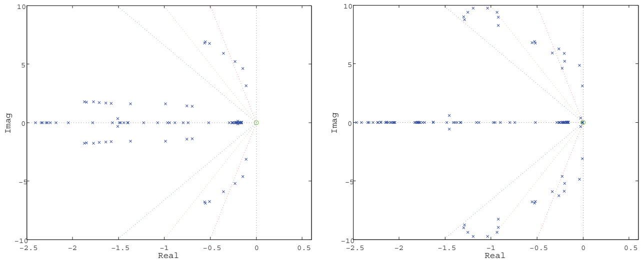
Eigenanalysis, a well-established linear-algebra analysis method [24], is employed to determine the small-signal dynamic behavior of the study system. Applying the technique to the linearized model of the KTH-NORDIC32 system, small-signal stability is studied by analyzing four properties: eigenvalues, frequency of oscillation, damping ratios and eigenvectors (or mode shapes). Stability of a system depends on the sign of the real part of eigenvalues; if there exists any positive real part, that system is unstable. The frequency of oscillation is derived from the imaginary part of eigenvalues while the damping ratio is derived from the real part. Damping ratios indicate "how" stable a system is; the higher the (positive) value of a damping ratio, the more stable the system is for a given oscillation. For instance, a low (but positive) damping ratio implies that, although the system is stable, the system is more prone to instability than other systems having higher damping ratios.

Eigenvalues of the KTH-NORDIC32 system implementing Model 2 and Model 3 are illustrated in Fig. 9a and 9b, as well as their corresponding local enlargement depicted in Fig. 9c- 9d, respectively. Comparing Fig. 9c to Fig. 9d, it can be observed that there are more eigenvalues having lower damping ratios in the system with Model 3 than that with Model 2. The system has 223 states with Model 2 and 259 states with Model 3; the number corresponds to the same number of eigenvalues. The system is stable for both cases.

Small-signal stability issues are mainly associated with insufficient generator damping. Of particular interest are those having low frequency of oscillations. These types of oscillations, namely low-frequency inter-area oscillations (LFIO), occur in large power systems interconnected by weak transmission lines [25] that transfer heavy power flows. The system of study, KTH-NORDIC32, has the characteristics of bearing heavy power flow from the northern region supplying the load in the southern region through loosely connected transmission lines. Consequently, the system exhibits lightly damped low frequency inter-area oscillations. Table I provides the two lowest damping modes, their corresponding frequencies and damping ratios, and the most associated state variables for both cases. As shown in the table, the damping ratios obtained from the two models bear a significant difference. This discrepancy is due to the incorrect modelling of the HTGs using Model 2, for which damping ratios are larger than when using Model 3 for HTG representation. This model error might influence the design of damping controllers to be less effective; this precisely illustrates why HTG modelling is important.



(a) Model 2 (b) Model 3



(c) Model 2 (local enlargement) (d) Model 3 (local enlargement)

Fig. 9. Eigenvalues of the KTH-NORDIC32 system.

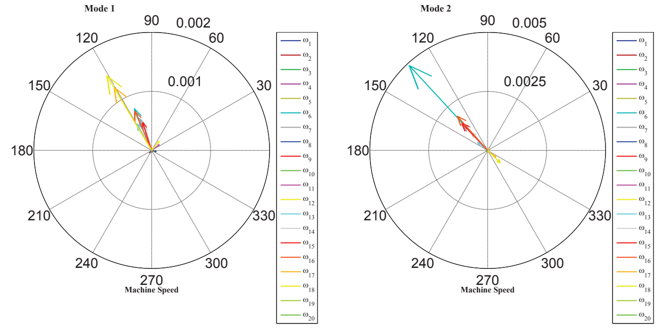
Mode shapes, or the right eigenvectors, give an insight into the relative activity of state variables in each mode. Within a mode, the larger the magnitude of the mode shape element, the more observable that state variable is. In this study, mode shapes of the generator speed, ω_i, is used for analysis as shown in Fig. 10 and 11 for the test system employing Model 2 and Model 3 as HTGs, respectively. It can be observed that ω_{18} is the most observable in Mode 1 whereas ω_6 is the most observable in Mode 2 of both models. These observations will later be useful in input signal selection for damping control design.

B. Transient Stability Analysis

Transient stability is defined as the ability of a power system to maintain its synchronism after being subjected to a severe (or large) disturbance [1]. One of the most commonly used means to assess the transient stability of a power system is

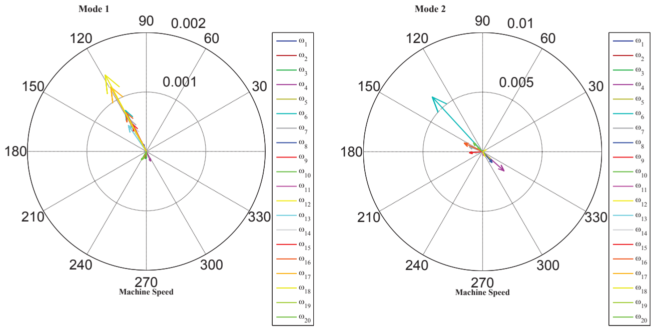
TABLE I
LINEAR ANALYSIS RESULTS OF THE TWO LOWEST DAMPING MODES IN KTH-NORDIC32

Model	Eigenvalues	Frequency (Hz)	Damping ratio	Most associated states
System with Model 2	$-0.11043\pm j3.1331$	0.49866	0.035223	ω_{18}, δ_{18}
	$-0.14637\pm j4.6004$	0.73218	0.031801	ω_{6}, δ_{6}
System with Model 3	$-0.0061875\pm j3.1015$	0.49362	0.0019950	ω_{18}, δ_{18}
	$-0.039918\pm j4.8658$	0.77442	0.0082036	ω_{20}, δ_{20}



(a) Mode 1: 0.49866 Hz (b) Mode 2: 0.73218 Hz

Fig. 10. Mode shapes of the KTH-NORDIC32 system implementing Model 2.

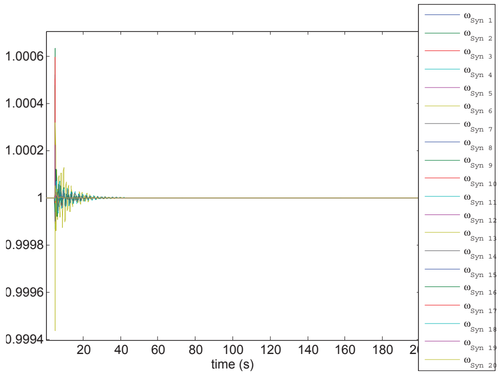


(a) Mode 1: 0.49362 Hz (b) Mode 2: 0.77442 Hz

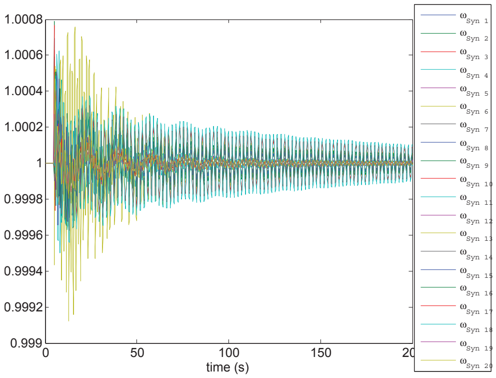
Fig. 11. Mode shapes of the KTH-NORDIC32 system implementing Model 3.

to apply a fault at a node and observe the corresponding responses. To allow for a proper comparison of the performance of the two models of turbine and governor, the fault should be applied at a bus in such way that the nonlinear behavior of the model can be evaluated. As such, a three-phase fault is applied at Bus 1011 at $t = 5$ s and removed after 20 ms in this study. The generator speed responses of the two models, Model 2 and Model 3, are displayed in Fig. 12a and 12b, respectively. Note that during approximately the first 10 s of the simulation, the responses of the system using Model 3 exhibit the nonlinear characteristics of the model.

Comparing the two simulations, the two responses behave considerably different; those of Model 2 converge to steady state while those of Model 3 show larger damped oscillations. This is due to the system's damping related to the inter-area swings [26], [27], [28]. Note that with this disturbance, both Mode 1 and Mode 2, discussed in the previous section, are excited.



(a) Model 2 Implementation.



(b) Model 3 Implementation.

Fig. 12. KTH-NORDIC32 system responses to a fault.

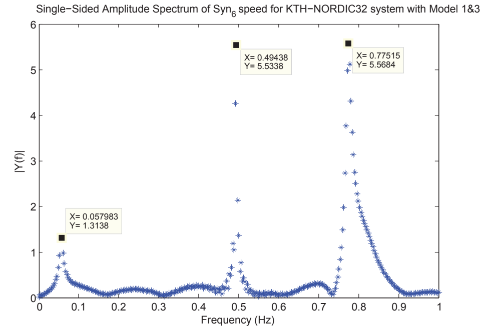
V. LINEAR MODEL VALIDATION THROUGH NONLINEAR TIME-DOMAIN SIMULATION

Power systems are nonlinear in nature as such their behavior is difficult to analyze. To simplify analysis of electromechanical oscillations (which are the primary concern), linearization techniques can be applied to the nonlinear system as shown in Section IV-A. To verify how well the linearized model represents the behavior of the nonlinear model under the linear-operating region where the model has been linearized, the linear models can be validated by: 1) verifying the linear properties from time-domain responses due to small perturbations and/or 2) tracking the response to control input changes. As such, the following three studies are conducted on the linearized model of the KTH-NORDIC32 system. In the studies below, Model 1 is implemented as thermal turbine and governors and Model 3 as hydro turbine and governors.

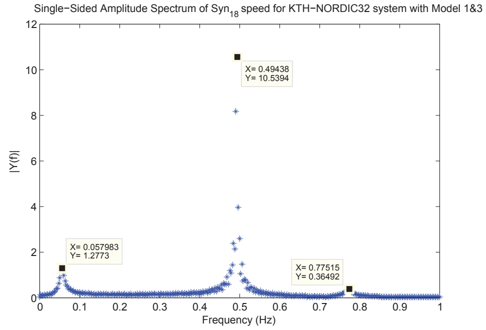
A. *Fault Occurrence*

To capture the general behavior of the KTH-NORDIC32 system, one approach is to apply a three-phase fault at a bus as a perturbation and study the dynamic response from a time-domain simulation. A similar fault is applied to the same bus with the same duration as in the previous section on transient stability analysis. The fast Fourier transform (FFT) is employed to identify the prominent frequency components in the frequency domain. Based on the small-signal studies in Section IV, the state variables ω_6 and ω_{18} are of our interests and their corresponding FFTs are depicted in Fig. 13a and 13b, respectively.

As shown in the figures, there are two primary frequency components: 0.49438 and 0.77515 Hz, as well as an inconspicuous frequency at 0.057983 Hz. The two primary frequencies belong to system electromechanical oscillations, which correspond to the two lowest damping inter-area oscillations, while the other smaller frequency is caused by turbine/governor dynamics. These results are in accordance with those of the small-signal studies (see Table I) where 0.49-Hz mode is dominated by the dynamics of G_{18} and 0.77-Hz mode by that of G_6. It is thus demonstrated here that the responses of the nonlinear time-domain simulation do capture the same dominant modes as the linear analysis does.



(a) FFT on ω_6



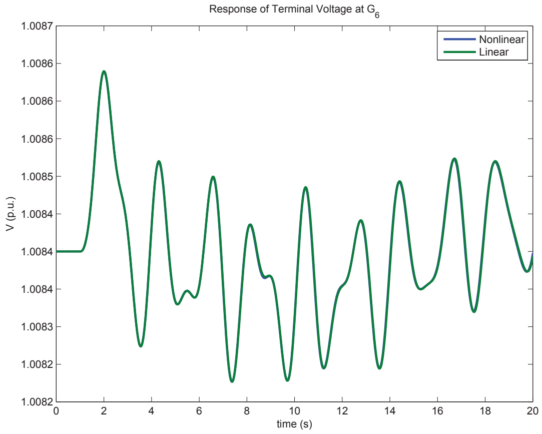
(b) FFT on ω_{18}

Fig. 13. FFT on rotor speed signals of the linearized KTH-NORDIC32 system.

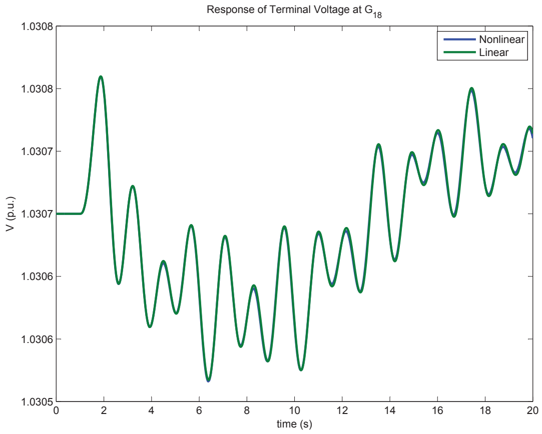
B. Disturbance at AVR's Reference Voltage

To assess the effects of controllers, such as power system stabilizers (PSS), on the system behavior, a perturbation is applied at the AVR's reference voltage (V_{ref}) since the PSS output modifies the AVR's reference voltage. The perturbation here is a 2% step change in V_{ref} of the AVR at G_2 at $t = 1$s and is simulated for 20 s. Two parallel simulations are conducted: a time-domain simulation to investigate the nonlinear model response and a time response of the linearized system. Both responses are analyzed and compared to validate the consistency of the system model. Note that over excitation limiters are removed to avoid changes in the AVR's reference voltage.

The comparison between nonlinear and linear simulations at generator terminal voltages V_6 and V_{18} are depicted in Fig. 14a and 14b, respectively. As seen from the figures, the results of both methods are consistent with each other. Although not shown here, using the FFT technique, the dominant frequencies in V_6 and V_{18} responses are approximately 0.49, 0.79 and 0.06 Hz which correspond to system oscillations and turbine/governor dynamics, respectively. Both results capture the dominant mode of concern and are coherent with each other.



(a) Terminal Voltage Responses at G_6.



(b) Terminal Voltage Responses at G_{18}.

Fig. 14. Responses after applying a perturbation at the voltage reference of G_2.

C. Disturbance at Governor's Reference Speed

To assess the effects of turbine and governors on the system behavior, a perturbation is applied at the governor's speed reference (ω_{ref}). The perturbation is a 0.05-Hz step change in ω_{ref} of G_2 at $t = 1$s and is simulated for 20 s. Similar to the previous section, a time-domain simulation is compared with a time response of the linearized system. As shown in

Fig. 15, both linear and nonlinear responses of the mechanical power at G_{18} are in accordance with each other.

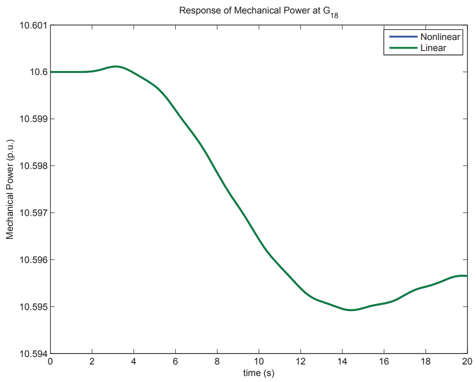


Fig. 15. Mechanical Power outputat G_{18}.

VI. Conclusion and Future Work

This paper presents the Nordic grid model of which the novelty being its implementation in a free and open source software; namely, Power System Analysis Toolbox (PSAT). The model takes into account detailed modelling of the dynamics which play an important role in the assessment of the system's behavior. Of particular significance is the implementation of the recently developed hydro turbine and governor (HTG) model in PSAT with the Nordic test system since more than half of the grid's generators are hydro power plants. This HTG model is capable of representing the true characteristics of hydro generators: the water hammer effect which translates into nonminimum phase characteristics. To demonstrate the importance of accurate modelling, stability analyses (small-signal and transient) of the Nordic grid model utilizing the HTG are compared with the test system employing the existing turbine governor models in PSAT. The discrepancies between the two models emphasize such necessity. Finally, the validation of the linearized Nordic grid model by nonlinear time-domain simulations is carried out. The results give confidence in the linear models generated with the inclusion of the new HTG model for its use in controller design, in particular, for inter-area oscillation damping which, was illustrated in the small-signal analysis section.

Acknowledgment

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Appendix A
Author's Note

Data of the KTH-NORDIC32 system can be obtained by signing an agreement with the authors. Contacts can be made via the provided e-mail addresses.

Appendix B
Data

TABLE II
Generator model parameters

Parameter	Thermal	Hydro
x_d [p.u.]	2.2	1.1
x'_d [p.u.]	0.3	0.25
x''_d [p.u.]	0.2	0.2
T'_{d0} [p.u.]	7	5
T''_{d0} [p.u.]	0.05	0.05
x_q [p.u.]	2	0.7
x'_q [p.u.]	0.4	0
x''_q [p.u.]	0.2	0.2
T'_{q0} [p.u.]	1.5	0
T''_{q0} [p.u.]	0.05	0.1
$2H$ [kWs/kVA]	12	6

TABLE III
Exciter model parameters

Parameter	Thermal	Hydro
K_0 [p.u.]	120	50
T_2 [s]	50	20
T_1 [s]	5	4
T_e [s]	0.1	0.1
T_r [s]	0.001	0.001
v_f^{max} [p.u.]	5	4
v_f^{min} [p.u.]	0	0
v_f^0 [p.u.]	0	0

TABLE IV
Over excitation limiter model parameters

Parameter	Value
T_0 [p.u.]	10
i_f^{lim} [p.u.]	3.0-22.0
v_{OXL}^{max} [p.u.]	1.1

TABLE V
Turbine governor system model parameters: Model 1

Parameter	Value
R [p.u.]	0.04
T_g [s]	5
T_c [s]	0.2
T_3 [s]	5
T_4 [s]	0.01
T_5 [s]	6
P_{max} [p.u.]	0.95
P_{min} [p.u.]	0, -0.5 for G_{13}

TABLE VI
Turbine governor system model parameters: Model 2

Parameter	Value
R [p.u.]	0.04, 0.08 (for G_{19}, G_{20})
T_1 [s]	3
T_2 [s]	0.5
P_{max} [p.u.]	1
P_{min} [p.u.]	0

TABLE VII
TURBINE GOVERNOR SYSTEM MODEL PARAMETERS: MODEL 3

Parameter	Value
T_g [s]	0.2
T_p [s]	0.04
T_r [s]	5
T_w [s]	1
σ [p.u.]	0.04
δ [p.u.]	0.3
a_{11} [p.u.]	0.5
a_{13} [p.u.]	1
a_{21} [p.u.]	1.5
a_{23} [p.u.]	1
G_{max} (Maximum gate opening) [p.u.]	1
G_{min} (Minimum gate opening) [p.u.]	0

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