System Frequency Response Model Considering the Influence of Power System Stabilizers

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***Abstract*— Frequency stability analysis of large power systems are extremely time consuming, laborious and may even exceed the computational capacity of modern computers. Hence, simplified power system models have being developed in the literature. These models are usually called System Frequency Response (SFR). In SFR models, generators are represented by transfer functions, nonlinearities are generally neglected and the grid is not taken into account. Conventional SFR models only contemplate the mechanical behavior of speed governors, turbines and synchronous machines of generators. This is because, a common simplification is to consider that frequency and voltage can be controlled independently. However, it is demonstrated that there is an interaction between them, so frequency can be affected by the effect of power system stabilizers (PSSs) over excitation system controllers. In this work, a modified SFR model is proposed, considering the influence of generators excitation control on frequency. Simulation results show an improvement of the accuracy in the estimation of frequency response of the power system.**

***Index Terms*— system frequency response (SFR) model, power system stabilizers (PSS), frequency stability studies.**

I. Introduction

FREQUENCY stability of a power system is defined as the ability of the electrical power system to maintain the frequency in an allowable range around the nominal value, after a severe disturbance that causes an important imbalance between generation and demand plus loses. Following such disturbance, e.g. loss of generation, system frequency drops, touches a minimum and then reaches a new equilibrium point. During this process, there are four main indices that describe the dynamic performance of the power system frequency as seen in Fig. 1: rate of change of frequency (*df/dt*), frequency minimum point (f_{nadir}) or maximum deviation point (Δf_{nadir}), time to reach the nadir (t_{nadir}) and post disturbance steady state frequency (f_{ss}) or deviation (Δf_{ss}) [1]. In order to measure the Δf_{ss} more accurately, secondary frequency control actuation is not considered in this work.

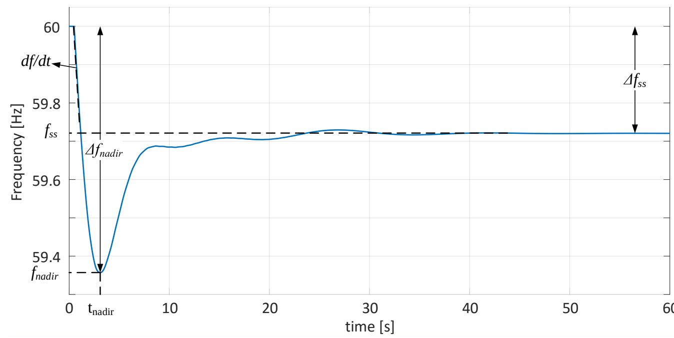

Fig. 1. Typical time domain system frequency response to a disturbance

Frequency stability studies can be extremely time consuming and require many computational resources. Hence, simplified power system models have being developed in the literature. In these models, known as system frequency response (SFR) models, speed governors, turbines and synchronous machines of generators are represented by transfer functions and grouped into a single busbar electrical system. Further, nonlinearities are generally neglected and secondary frequency control is not taken into account [2].

SFR models are used to estimate the essential characteristics of the time-domain evolution of the power system frequency after a disturbance. They are useful when a fast estimation of frequency response is needed, either through simulations or by closed-form expressions, i.e. by a single transfer function that represents the entire electrical system. For example, in [3] an analytical adaptive load shedding scheme is proposed, where the appropriate amount of load rejections is determined with the help of a developed extended SFR model. In [4], a SFR model incorporating an under-frequency load-shedding (*UFLS*) scheme is presented. The main motivation is to derive closed-form expressions of the load-frequency response that include the effect of the *UFLS* so that the system and UFLS performance indicators can be directly computed. In [5, 6], different SFR models are developed for frequency stability analysis, including the frequency response of wind turbines in SFR models. In [7], a sensitivity analysis of load-damping characteristic in power system frequency regulation is carried out using a typical SFR model. Finally, given that system frequency stability is being compromised by the penetration of variable renewable energies, SFR models are used to add frequency limits restrictions to security-constrained unit commitments [8-10].

However, conventional SFR models only take into account the

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mechanical behavior of generators, neglecting the electrical components. Behind this simplification, there is an implicit assumption that the active power-frequency ratio and the reactive power-voltage ratio are independent, so that the frequency and voltage can be controlled independently. This simplification can lead to unacceptable estimation errors, especially in presence of power system stabilizers (PSSs).

The basic function of a PSS is to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signals. Commonly used inputs are shaft speed, terminal frequency, and power [11]. To provide damping, the stabilizer produce a component of electrical torque in phase with the rotor speed deviations [12]. In this sense, in [13] a novel method for adding virtual inertia in power systems, by controlling the frequency through Volt-Amperes reactive (VAr) modulation, is presented. The purpose is to assist speed governors' action during power imbalance events. This is achieved by tuning a PSS to adaptively adjust reference voltage of a synchronous condenser (SC). Results show that VAr modulation by SC has a considerable impact on frequency nadir. In [14], a design method for a multi-loop PSS structure is proposed. The tuning method arises from an architecture for multi-site power system control, using wide-area information provided by GPS based phasor measurement units. Simulation results clearly demonstrate the effectiveness of the PSSs on preventing transient instability after a fault. In [15], a fast-acting distributed load control for primary frequency regulation is proposed. The control is tested in the IEEE 68-bus electrical system for various scenarios, combining the load control with or without PSSs. Simulation results show that best performance is achieved when PSSs are used, limiting frequency deviation after a disturbance.

As seen in the brief review above, frequency response of electrical systems is influenced by PSSs. Since PSSs are widely used in electrical systems, novel simplified models are needed. However, it has not been possible to find works that develops SFR models with this in mind. Therefore, in order to consider the effect of PSSs on frequency response estimation, a modified SFR model is pr0oposed in this paper. Given that PSSs are connected to synchronous generators, this research focuses on them.

The paper is organized as follows. In Section II, two test systems are used to demonstrate, through simulation, the effect of PSSs over system frequency response. Then, these systems are used to validate the SFR models. Section III describes a conventional SFR model and its limitations are outlined. In Section IV, a modified SFR model is proposed. Later, performance of both SFR models is compared in Section V. Finally, Section VI presents the key conclusions and important findings of the research.

II. TEST SYSTEMS

The test systems used to demonstrate, through simulation, the effect of PSSs over frequency and to validate the subsequently proposed SFR model, are presented in the following subsections A and B:

A. *Kundur's System*

Fig. 2 shows a four-machine two-area power system, known as Kundur's system [12]. The main reason of selecting this simple electrical system is its wide availability: it has been fully modeled in MATLAB and is easy to access by other researchers. The test system consists of two fully symmetrical areas. It was specifically designed to study low frequency electromechanical oscillations in large interconnected power systems. Despite its small size, it mimics very closely the behavior of typical systems in actual operation. Each area is equipped with two identical round rotor generators rated 20 kV/900 MVA, so total system power is 3.6 GVA. The synchronous machines have identical parameters, except for inertias which are H = 6.5s in area 1 and H = 6.175s in area 2. Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciters with a 200 gain. Loads are represented as constant impedances, and modified with respect to the original values in order to achieve a stable scenario, originally unstable. Specifically, Load 1 modified from 967 MW, -87 MVAr to 773.6 MW, -69.6 MVAr and load 2 from 767 MW, -87 MVAr to 1236.9 MW, -60.9 MVAr. In this test system, three different PSSs or none, can be chosen. The available PSSs are Delta Pa PSS, Multi Band PSS (MBPSS) and Delta w PSS. Original test system is available at Simscape Power Systems™ examples. Performance analysis of each PSS can be found in the help section of the example [16].

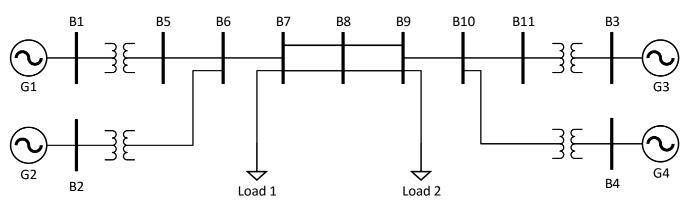

Fig. 2. Four-machine two-area system (Kundur)

To study primary frequency response, a sudden load increase is simulated in the detailed system model of Fig. 2, with MATLAB - Simulink. It is assumed that load 1 increases 5% of total system power, i.e. disturbance power ΔP_d = 180 MW, at t= 1s. The simulation is repeated for each one of the PSS types available in the power system example. System angular frequency deviations dw are plotted in Fig. 3. It can be noticed that frequency response is strongly influenced by PSSs, modifying the average df/dt, f_{nadir} and t_{nadir}. However, post disturbance steady state frequency can be considered unmodified. Each PSS influences system frequency response differently, depending on its input signals and settings. On the one hand, Delta Pa PSS uses the accelerating power as input, while Delta w PSS and MBPSS use dw. The difference between the latter is that Delta w PSS is tuned to a certain frequency, while MBPSS structure is based on multiple working frequency bands [17, 18].

Delta Pa PSS is included illustratively, as the system frequency response when using this PSS is not considered acceptable.

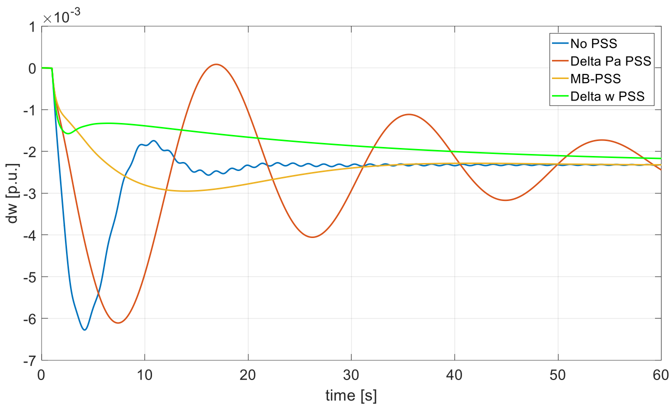

Fig. 3. Kundur's system frequency response for different PSS

B. *Western North American Power System*

In Western North American Power System (WNAPS), eight pairs of generators G1-G16, are connected to buses 17 through 24, Fig. 4. At each of these buses: one generator is base loaded with no speed governor, while the other uses a governor. All units are equipped with an automatic voltage regulator. Generators 1, 2, 6, 8, 9, 10, 14, and 16 (blue) are driven by hydro turbines, while generators 3-5, 7, 11-13 and 15 (red) are driven by faster acting steam turbines. All generators are equipped with PSS units. Loads, represented as constant impedances, are distributed in load buses 31 through 41. Transmission lines are modeled by a single pi section.

The power system is modeled in Simulink, where MBPSS, Delta w PSS, or no PSS, can be chosen [19]. Table I and Table II show information about generators and loads respectively.

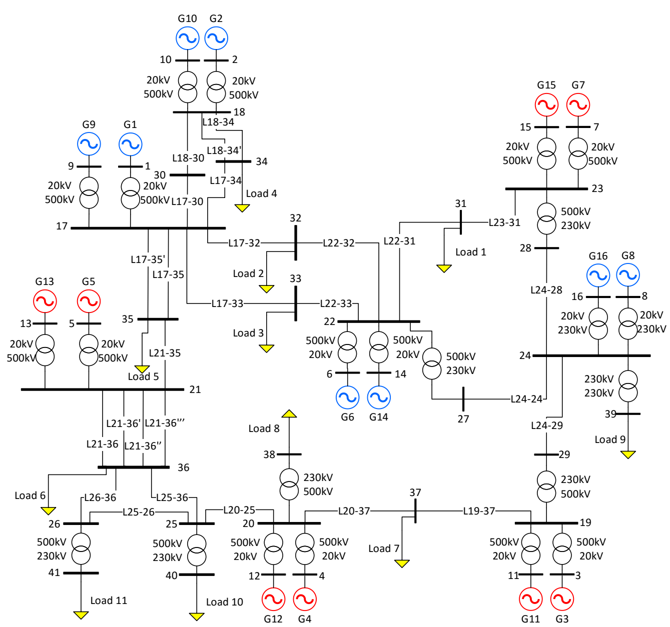

Fig. 4. Western North American Power System

TABLE I
WNAPS GENERATORS

Generator	Rated power [GVA]
G1, G9	2.75
G2, G4, G10, G12	7.00
G3, G6, G11, G14	8.00
G5, G13	4.75
G7, G15	2.60
G8, G16	4.00
Total system power	**88.20**

TABLE II
WNAPS LOADS

Load	P [GW]	Q [MVAr]
Load 1	6.20	-1051.40
Load 2	5.50	299.20
Load 3	3.78	664.58
Load 4	8.00	698.80
Load 5	4.50	-100.80
Load 6	2.00	1200.00
Load 7	7.00	2119.68
Load 8	3.00	1200.00
Load 9	3.08	169.40
Load 10	1.40	400.00
Load 11	5.40	1229.72
Total demand	**50.06**	**6829.17**

To study the effect of the different PSSs over frequency response, a sudden load increase of 5% of total system power is simulated at bus 41, i.e. ΔP_d = 4.41 GW, at t = 1s. Simulation results of the detailed power system are plotted in Fig. 5.

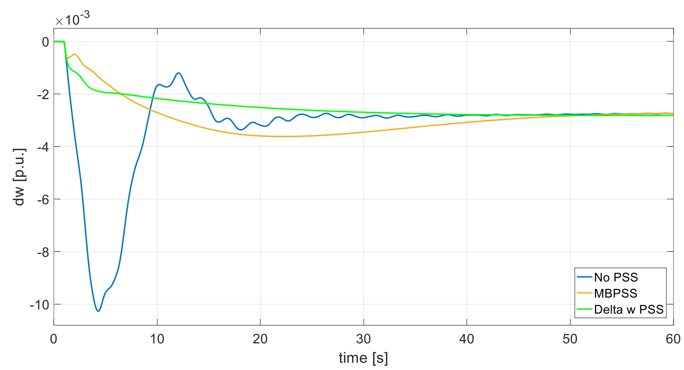

Fig. 5. WNAPS frequency response for different PSS

Once again, it can be seen that system frequency response is highly influenced by the PSSs.

With the previous test systems, the influence of PSSs over frequency response is verified. Then, the conventional SFR model is described and its limitations are shown.

III. CONVENTIONAL SFR MODEL

A conventional SFR model is shown in Fig. 6, where ΔPe [p.u.] is the electrical power variation (disturbance), ΔPm_i [p.u] the variation of the mechanical power output of turbine i, ΔPa [p.u] the accelerating power variation, H_{eq} [s] the equivalent system inertia constant, D [%] the load damping coefficient, dw [p.u.] the angular frequency deviation and k_i the portion of rated power of machine i with respect to the whole system.

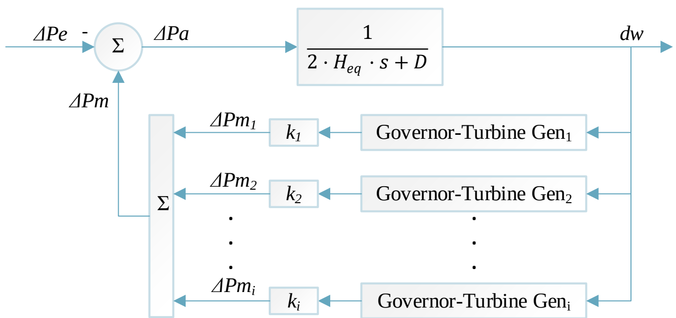

Fig. 6. Multi-machine conventional system frequency response model

From the point of view of a single generation unit, a low-order SFR model of a reheat steam turbine generator is shown in Fig. 7. It can be seen that the dynamic behavior of the model is mainly dominated by the largest time constants in the equations of the generating unit: high pressure turbine fraction F_H, reheat time constant T_R, droop coefficient R, inertia constant H and damping torque component Kd [1].

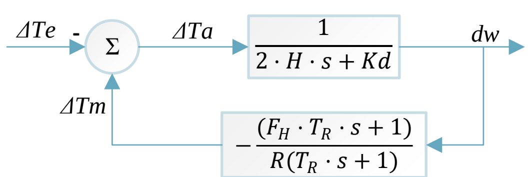

Fig. 7. Single-machine SFR model of a typical reheat steam turbine generator

In this case, electrical power, mechanical power and acceleration power variation are named in terms of electrical torque variation ΔTe [p.u.], mechanical torque variation ΔTm [p.u.] and accelerating torque variation ΔTa [p.u.] respectively. Although ΔTe is the input of the SFR model, it has to be clear that ΔTe is the electrical torque output of the synchronous machine. The same reasoning applies to ΔPe of Fig. 6.

Since large frequency deviations are caused by active power imbalances, and given that active power generated by conventional generators depends on mechanical power control, it makes perfect sense that conventional SFR models only consider speed governors, turbines and rotating masses inertia of power plants. However, neglecting the influence of PSSs can lead to an inaccurate model. To verify this, a conventional SFR model is built in.

Generators are modeled using system identification toolbox from MATLAB. System identification Toolbox provides functions for constructing mathematical models of dynamic systems from measured input-output data. It lets create and use models of dynamic systems not easily modeled from first principles or specifications. Time-domain and frequency-domain input-output data can be used to identify continuous-time and discrete-time transfer functions, process models, and state-space models. It uses identification techniques such as maximum likelihood, prediction-error minimization, and subspace system identification [20, 21]. In this work, nonlinear least-squares solver (lsqnonlin function) is used. The solver solves curve fitting problems of the form

$$min_x \left[f_1(x)^2 + f_2(x)^2 + \cdots + f_n(x)^2\right] \quad (1)$$

Starting from the detailed model of the electrical system under study, each generator is isolated and submitted to a step-type load perturbation ΔPd, as shown in Fig. 8. Load perturbation ΔPd [W] can be defined as:

$$\Delta P_d = A \,.\, \mu(t) \,.\, P_n \quad (2)$$

Where Pn [VA] is the rated power of the generator and A is the amplitude of the unitary step function $\mu(t)$; so the disturbing load power is $A.Pn$.

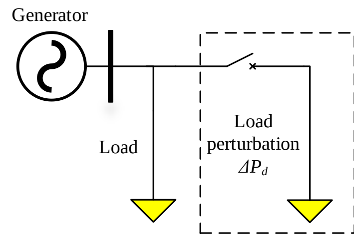

Fig. 8 Wiring diagram for generator modeling

To identify the transfer function of the speed governor-turbine, a disturbance of 5% (A = 0.05) of generator's rated power is simulated; and two signals are measured and stored: dw (input) and ΔTm (output). Then, these signals are processed by the System Identification Toolbox, yielding as a result a fourth order TF that represents its response. The TF can be expressed as:

$$TF(s) = \frac{b_4 s^4 + b_3 s^3 + b_2 s^2 + b_1 s + b_0}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \quad (3)$$

Where b_i and a_i are the constant coefficients calculated by the MATLAB tool.

The TF order is chosen to achieve a fit to estimation data above 95%. Then, these TFs are arranged as shown in Fig. 6 to build the multi machine SFR model.

Despite the used test power systems do not consider renewable generation, this modeling procedure can be extended to any generation technology. However, only those generators whose output power varies as a function of frequency, e.g., a photovoltaic system with frequency regulation control, are included in the SFR model. Then, the k_i coefficients are calculated considering the intervening generators. Lastly, asynchronous generators inertia, e.g., of a wind induction generator, or emulated inertia, have to be considered in the calculation of the equivalent inertia constant.

System equivalent inertia constant Heq is calculated as:

$$H_{eq} = \frac{\sum H_i . S_i}{\sum S_i} \quad (4)$$

Where H_i [s] and S_i [VA] are the inertia constant and the apparent power of each conventional generator respectively.

Finally, load damping coefficient D [MW/Hz] is calculated as:

$$D = \frac{-\Delta P_d}{\Delta f_{ss}} - \frac{1}{R_{eq}} \quad (5)$$

$$D\% = \frac{D \cdot f_n}{P_L} \quad (6)$$

Where ΔP_d [MW] is the disturbance power, Δf_{ss} [Hz] is obtained by simulation of detailed power system model as indicated in Fig. 1, R_{eq} [Hz/MW] the equivalent droop coefficient, f_n the nominal frequency and P_L [MW] the total post disturbance load [12].

Frequency response of the detailed systems models with no PSS, MBPSS and Delta Pa PSS connected, plus the frequency response estimation by the conventional SFR model are shown in Fig. 9 and Fig. 10 for Kundur's system and WNAPS respectively.

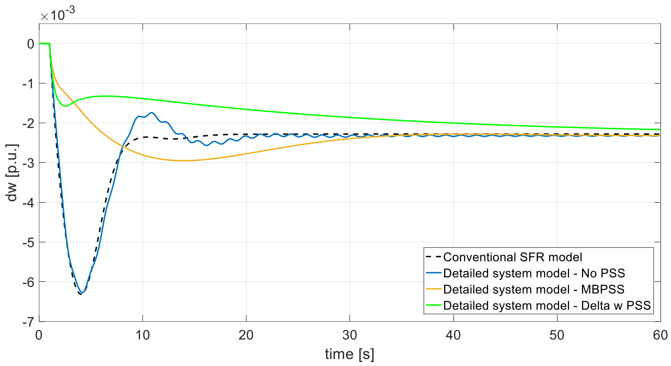

Fig. 9. Frequency response estimation by conventional SFR model - Kundur's system

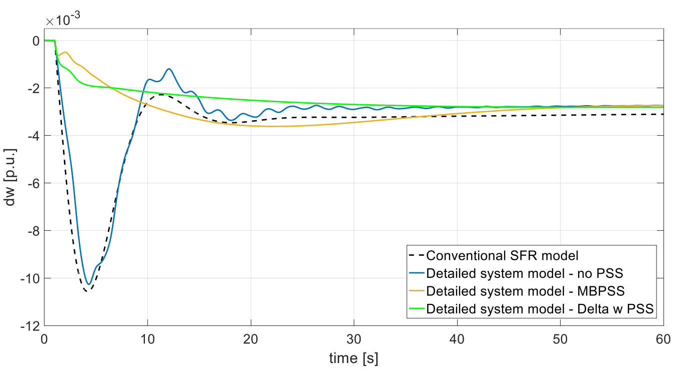

Fig. 10. Frequency response estimation by conventional SFR model – WNAPS

On the other hand, Table III and Table IV show the absolute and relative errors of indices estimation for Kundur's system and WNAPS respectively. In this case, errors are calculated between the conventional SFR model response and each of the responses of the detailed systems as:

$$Abs.error = estimated\ value - reference\ value \quad (7)$$

$$Rel.error = \frac{Abs.error}{|reference\ value|} x100 \quad (8)$$

Where estimated value is the one obtained from the SFR model and reference value from the detailed system model.

It is important to clarify that Δf_{nadir} and Δf_{ss} are calculated based on frequency deviations in Hz, since SFR models estimate the deviation of it from the steady state value. Also, df/dt is the average value of the frequency derivative during the first 500ms after the perturbation, as recommended in [22]. Moreover, Δf_{ss} is measured when frequency reaches a steady state. Finally, since system frequency response with Delta w PSS has not a typical response shape, t_{nadir} and Δf_{nadir} estimation errors are not calculated.

Mean squared error (MSE) of estimation is calculated as:

$$\text{MSE} = \frac{1}{n}\sum_{i=1}^{n}(Abs.error_i)^2 \quad (9)$$

Where n is the number of samples and $Abs.\ error_i$ the absolute error between the ith samples. MSE are shown in Table V for each case of both electrical systems.

TABLE III
ESTIMATION ERRORS OF CONVENTIONAL SFR MODEL – KUNDUR'S SYSTEM

	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
AE	-0.0065Hz	-0.1094s	-0.0249Hz/s	0.0015Hz
RE	-1.73%	-3.45%	-12.39%	1.07%
MBPSS				
AE	-0.2053Hz	-9.9167s	-0.1270Hz/s	0.0015Hz
RE	-116.05%	-76.48%	-128.36%	1.07%
Delta w PSS				
AE	-	-	-0.0892Hz/s	0.0015Hz
RE	-	-	-65.22%	1.07%

AE: absolute error, RE: relative error

TABLE IV
ESTIMATION ERRORS OF CONVENTIONAL SFR MODEL - WNAPS

	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
AE	-0.0192Hz	-0.1167s	-0.1114Hz/s	-0.0222Hz
RE	-3.13%	-3.54%	-50.38%	-13.39%
MBPSS				
AE	-0.4169Hz	-18.117s	-0.2616Hz/s	-0.0196Hz
RE	-192.36%	-85.05%	-368.02%	-11.61%
Delta w PSS				
AE	-	-	-0.2161Hz/s	-0.0197Hz
RE	-	-	-185.33%	-11.71%

AE: absolute error, RE: relative error

TABLE V
MSE OF ESTIMATION OF CONVENTIONAL SFR MODEL

Power System	No PSS	MBPSS	Delta w PSS
Kundur's system	8.93×10^{-5}	4×10^{-3}	5.5×10^{-3}
WNAPS	1.7×10^{-3}	2×10^{-2}	1.8×10^{-2}

As expected, the conventional SFR model can make a good estimation when no PSS is connected to the generators. However, if any type of PSS is connected, the conventional SFR model is not able to estimate system frequency response accurately. This is because speed governor-turbine model and inertia constant are not related to PSS and/or excitation system, so conventional SFR model do not contain any information about the latter. To address this issue, a modified SFR model is proposed, in order to consider the effect of PSSs on frequency response estimation.

IV. PROPOSED SFR MODEL

Analyzing the conventional SFR model from Fig. 6, it can be noticed that the only input signal is *ΔPe*. A sudden load increase can be represented as a step input signal *μ(t)* in the SFR model. However, this is (closely) valid when no PSSs are present in the power system.

From the point of view of a single generation unit, a load change is reflected instantaneously as a change in the electrical torque output of the generator *ΔTe*. This causes a mismatch between the mechanical torque and the electrical torque which in turn results in speed variations. As detailed before, in order to provide damping, a component of the electrical torque is controlled by the PSS and the exciter. So, the input signal of the SFR model can no longer be represented by a step signal as seen in Fig. 11.

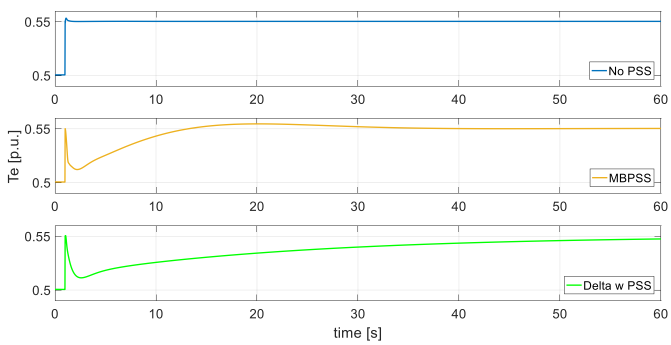

Fig. 11. Electrical torque output of isolated generator G1 (5% load increase)

With this in mind, the proposed SFR model for a single generating unit is shown in Fig. 12.

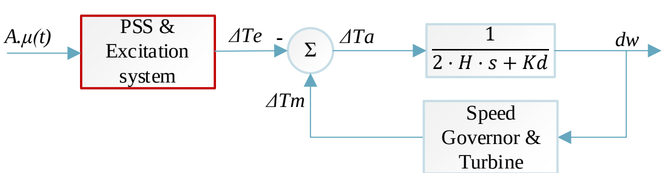

Fig. 12. Proposed SFR model

As seen, a new transfer function (red block) is added to the model. This new block estimates the electrical torque variation *ΔTe* from a step signal input. To obtain the TFs, same previous procedure is executed. Signals *A.μ(t)* (input) and *ΔTe* (output) are used to estimate the TF of the PSS - excitation system block, while *dw* and *ΔTm* are used to estimate the speed governor – turbine TF. To achieve acceptable estimation accuracy, a fourth order TF is used in both the new block and in speed governor-turbine TF, as in (3).

Multi machine proposed SFR model is shown in Fig. 13. In this model, constants k_i are the same as in the conventional SFR model, i.e. portion of rated power of machine *i* with respect to the whole system.

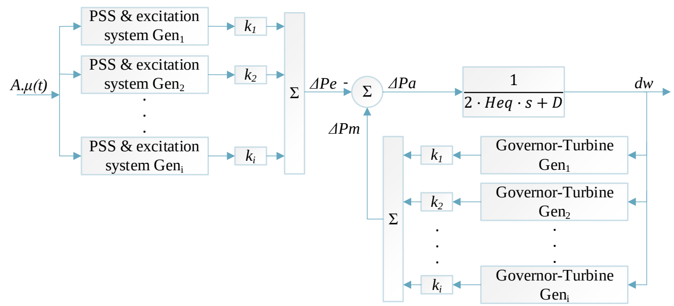

Fig. 13. Multi machine proposed SFR model

Once again, a sudden load 1 increase of 5% of total system power is simulated in the detailed system models and in the proposed SFR models. The different frequency responses and the estimation results from the proposed SFR model, are plotted in Fig. 14 and Fig. 15 for Kundur's system and WNAPS respectively. It can be seen that the proposed SFR model estimates frequency responses with good accuracy for all cases.

Table VI and Table VII show the indices estimation errors of the proposed SFR model. In this case, calculated between each of the detailed system model responses and its respective estimated response by the proposed SFR model.

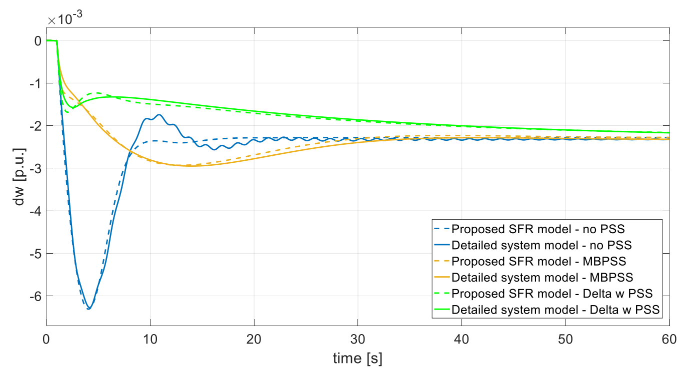

Fig. 14. Kundur's system frequency response estimation with proposed SFR model

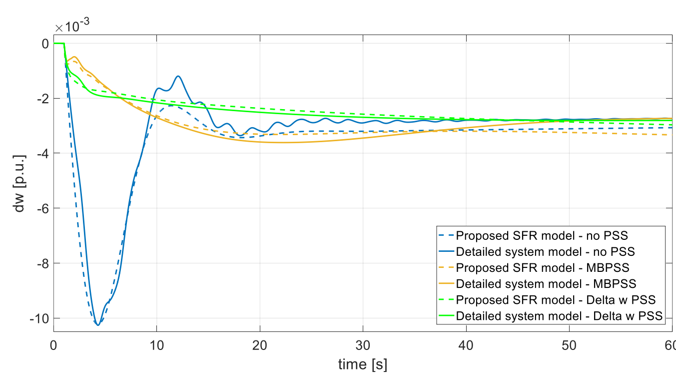

Fig. 15. WNAPS frequency response estimation with proposed SFR model

TABLE VI
ESTIMATION ERRORS OF PROPOSED SFR MODEL – KUNDUR'S SYSTEM

	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
AE	-0.0029Hz	-0.1205s	-0.0284Hz/s	0.0025Hz
RE	-0.78%	-3.8%	-14.12%	-1.83%
MBPSS				
AE	0.0010Hz	-1.0167s	-0.0377Hz/s	0.0029Hz
RE	0.58%	-7.84%	-38.10%	2.09%
Delta w PSS				
AE	-	-	-0.0305Hz/s	0.0027Hz
RE	-	-	-22.30%	1.91%

AE: absolut error, RE: relative error

TABLE VII
ESTIMATION ERRORS OF PROPOSED SFR MODEL - WNAPS

	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
AE	9.35×10^{-4}Hz	-0.0083s	-0.1023Hz/s	-0.0203Hz
RE	0.15%	-0.25%	-46.26%	-12.25%
MBPSS				
AE	0.0176Hz	-0.2667s	-0.0209Hz/s	-0.0265Hz
RE	8.14%	-1.25%	-29.34%	-15.69%
Delta w PSS				
AE	-	-	-0.0180Hz/s	-0.0101Hz
RE	-	-	-15.41%	-6.02%

AE: absolut error, RE: relative error

Finally, MSE of estimation of proposed SFR model are shown in Table VIII.

TABLE VIII
MSE OF ESTIMATION OF PROPOSED SFR MODEL

Power System	No PSS	MBPSS	Delta w PSS
Kundur's system	9.1×10^{-5}	1.87×10^{-5}	1.14×10^{-5}
WNAPS	1.3×10^{-3}	3.1×10^{-4}	4.46×10^{-5}

V. ANALYSIS OF RESULTS

Before drawing conclusions, analysis of relative errors in estimating indices should be done carefully. Specifically, for Δf_{nadir} and Δf_{ss} since they are calculated from frequency deviation dw, instead of f_n+dw. Because of that, relative errors of Δf_{ss} are in the order of 10-15% but absolute errors of these indices do not surpass 30 mHz.

In order to compare the performance of the proposed SFR model with the conventional, relative errors of estimation of Table III and Table VI are shown in Table IX for Kundur's system. While relative errors of estimation of Table IV and Table VII are compared in Table X for WNAPS.

TABLE IX
RELATIVE ERRORS OF ESTIMATION OF KUNDUR'S SYSTEM - COMPARISON

Model	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
Conv	-1.73%	-3.45%	-12.39%	1.07%
Prop	-0.78%	-3.8%	-14.12%	-1.83%
MBPSS				
Conv	-116.05%	-76.48%	-128.36%	1.07%
Prop	0.58%	-7.84%	-38.10%	2.09%
Delta w PSS				
Conv	-	-	-65.22%	1.07%
Prop	-	-	-22.30%	1.91%

Conv: conventional SFR model, Prop: proposed SFR model

TABLE X
RELATIVE ERRORS OF ESTIMATION OF WNAPS - COMPARISON

Model	Δf_{nadir}	t_{nadir}	df/dt	Δf_{ss}
No PSS				
Conv	-3.13%	-3.54%	-50.38%	-13.39%
Prop	0.15%	-0.25%	-46.26%	-12.25%
MBPSS				
Conv	-192.36%	-85.05%	-368.02%	-11.61%
Prop	8.14%	-1.25%	-29.34%	-15.69%
Delta w PSS				
Conv	-	-	-185.33%	-11.71%
Prop	-	-	-15.41%	-6.02%

Conv: conventional SFR model, Prop: proposed SFR model

As observed, when no PSS is present, performance of conventional and proposed SFR models is similar. However, conventional SFR model fails in estimating the frequency response when PSSs exist in the power system. On the other hand, the proposed SFR model improves estimation accuracy by estimating the damping component of electrical torque produced by the PSSs. Improvement in estimation accuracy is noticeably seen in the estimation of f_{nadir} and t_{nadir}.

Regarding *df/dt*, none of the models can make a good estimation of *df/dt*. Although SFR model makes a good overall estimation of the first swing of frequency for all cases, *df/dt* needs to be measured in the first 150-500ms as indicated in [22, 23].

Finally, Table XI and Table XII compare the MSE of estimation of conventional and proposed SFR models, for Kundur's system and WNAPS respectively. Once again, it can be seen that performance of both models are similar when no PSS exist in the power system. However, in presence of PSSs, the proposed SFR outperforms the conventional one, reducing the MSE of estimation significatively.

TABLE XI
COMPARISON OF MSE OF ESTIMATION - KUNDUR'S SYSTEM

Model	No PSS	MBPSS	Delta w PSS
Conventional	8.93×10^{-5}	4×10^{-3}	5.5×10^{-3}
Proposed	9.1×10^{-5}	1.87×10^{-5}	1.14×10^{-5}

TABLE XII
COMPARISON OF MSE OF ESTIMATION - WNAPS

Model	No PSS	MBPSS	Delta w PSS
Conventional	$1.7\text{x}10^{-3}$	$2\text{x}10^{-2}$	$1.8\text{x}10^{-2}$
Proposed	$1.3\ \text{x}10^{-3}$	$3.1\text{x}10^{-4}$	$4.46\text{x}10^{-5}$

VI. CONCLUSION

Conventional SFR models are commonly used to estimate the essential characteristics of the power system frequency response after a disturbance. However, these models only consider the mechanical parameters of generators, neglecting the electrical ones. In this work, it is shown through bibliography and simulation, that generators' excitation system control and power system stabilizers affect the system frequency response. So, in such cases, conventional SFR models are not able to estimate the frequency response accurately.

Since PSS are widely used in electrical system, novel simplified models are needed. Therefore, an extended SFR model is proposed. It improves estimation accuracy by estimating the damping component of electrical torque produced by the PSSs. This is accomplished by a new transfer function block added at the input of the conventional SFR model. In this way, closed-form expressions of system frequency response can still be obtained, i.e. a single transfer function that represents the entire electrical system.

Results show a noticeable improvement in frequency response estimation accuracy, especially when PSSs are connected to generators. The proposed SFR model can make a good overall estimation of frequency response, i.e. of Δf_{nadir}, t_{nadir} and Δf_{ss}. However, it is found that estimating the rate of change of frequency is not a trivial task, so more research needs to be done in this area.

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VIII. BIOGRAPHIES

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