Towards the New Low-Order System Frequency Response Model of Power Systems with High Penetration of Variable-Speed Wind Turbine Generators

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***Abstract*—In the recent years, frequency support from converter-connected wind power generation has been a hot topic in the field of power system dynamics and control. At the same time, the share of wind generation in the power systems worldwide has significantly risen. Therefore, it is necessary to discuss a new approach to low-order system frequency response (SFR) modelling of power systems. In this paper, a new low-order SFR model of a power system with high penetration of wind power generation is proposed by taking into account the different operating regimes of variable-speed wind turbine generators (VSWTGs). The results are compared to the nonlinear transient stability dynamic models to show that the low-order model adequately describes the nonlinear model. The proposed model can be used (e.g. by researchers, students or power system operators) to qualitatively simulate power system frequency behaviour for different operating scenarios.**

***Index Terms*—wind energy integration, power system dynamics, power system simulation, power system modelling, power generation control**

I. INTRODUCTION

To reduce the carbon footprint of the power & energy sector, many countries throughout the world introduced various measures encouraging the integration of renewable energy sources (RES). The most popular energy sources for renewable power generation are the photo-voltaic (PV) plants and the wind power plants (WPPs): in 2016, installed PV capacity was 291 GW and installed WPP capacity was 467 GW in the world [1] and will continue to rise. Variable-speed wind turbine generators (VSWTGs) fall under converter-connected generation and due to the intermittent and stochastic nature of wind they utilize variable-speed drives to maximize energy capture over a wide range of wind speeds. Consequently, they utilize frequency converters to ensure power generation at grid frequency. On the other hand, they effectively decouple the electrical frequency of the grid and the mechanical frequency of the rotor (DFIG) or completely decouple the generator from the grid (full converter wind generators), thus eliminating the inertial response of the WPPs, although there is a significant amount of kinetic energy stored in the wind turbine rotor due to its large mass [2], [3]. As this converter-connected renewable power generation replaces conventional units, the total grid inertia is reduced which negatively impacts the frequency stability of the power system: the grid becomes weaker and reduces the capability of the system to remain stable after the occurrence of faults or disturbances [4], [5]. Therefore, a significant amount of recent research has focused on utilizing the controllability of VSWTGs to provide an inertial response (so-called virtual or synthetic inertia) and/or primary frequency response which can be found in an excellent state-of-the-art overview [6]. Furthermore, even some system operators have started requiring active power support from WPPs [7].

As the share of VSWTGs and other converter-connected generation in the power systems worldwide is exponentially increasing, coupled with the introduction of virtual inertia and power electronics control for frequency support, the paradigm of what is a power system is changing. Low-order SFR models provide a simple platform for studying power system frequency changes by taking into account only the most significant system dynamics in the time scale of interest which is $\leq$ 30 s. Thus, it is necessary to step towards new low-order model of a power system by taking into account the impact of wind power generation on the system frequency behaviour. So far, not many works dealt with low-order modelling of VSWTGs for integration with existing SFR models [8], including our earlier works [3], [9]. However, different operating regimes of VSWTGs were not taken into account which have an impact on grid frequency behaviour.

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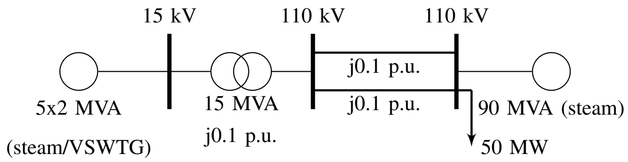

Fig. 1. Simulation system

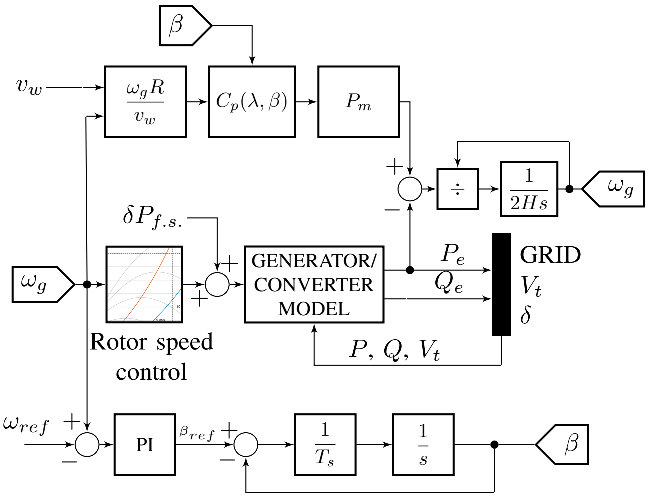

Fig. 2. Nonlinear wind turbine model

In this paper, the discussion on different operating regimes of VSWTGs is presented alongside with how those regimes are reflected on the SFR model of a power system through the low-order models of VSWTGs.

II. Modelling approach

A single machine infinite busbar system is modelled in PSS/E where a generator is connected to the infinite busbar through an impedance as shown by Fig. 1 to simulate impact of wind penetration in section III-A. The infinite busbar is modelled as a large steam reheat turbine-generator. Since system frequency response in the electromechanical time scale is observed, the same system is modelled in MATLAB-Simulink as a single machine SFR system dominated by steam reheat turbine (Fig. 4) to compare responses of nonlinear and linearized model. Mechanical and electrical parameters of VSWTGs can be found in [10]. System base is set to 100 MVA.

III. Towards the new low-order SFR model

In this section, an approach to new low-order SFR modelling of a power system with a significant penetration of wind power generation is presented by taking into account different operating modes of the VSWTG. The response of the low-order model of the VSWTG will be compared to the nonlinear model for fundamental frequency studies. This model relies on certain assumptions that are very well documented in [11]. The operating regimes of a VSWTG can be divided into four zones as shown in Fig. 3. The red line corresponds to the normal operating curve and the orange line corresponds to the deloaded curve that ensures a 10% power reserve. The generator power vs. rotor speed curves are easily implemented in the plant control (e.g. lookup tables, logic switches to switch between MPPT and deloaded mode, etc.). The different zones will be addressed in the following subsections.

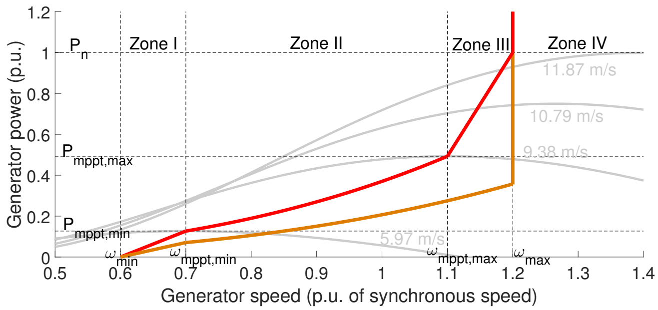

Fig. 3. Operating zones of a VSWTG

A. *Operation at low wind speeds—Zone I*

At low wind speeds, the generator power vs. rotor speed curve is defined by a line between minimal rotor speed at cut-in wind speed (ω_{min}) and the rotor speed where the maximum power point tracking (MPPT) or deloaded operation starts (where power varies with the cube of rotor speed, $\omega_{mppt,min}$). The rotor speed is kept at its minimum in this region (although in this case the rotor speed varies linearly with power to avoid power fluctuations near the minimal speed). It can be concluded that the VSWTGs will not provide any frequency support in this region because an extra power injection to the grid could ultimately lead to stalling of the turbine. In this case, the WPPs will provide active power to the grid, but are not sensitive to changes in grid frequency. The total grid inertia of a conventional power system can be calculated as:

$$H_{SYS} = \frac{\sum_i^n H_i S_{b,i}}{\sum_i^n S_{b,i}} = \frac{\sum_i^n H_i S_{b,i}}{S_{SYS}} \tag{1}$$

where H_{SYS} and S_{SYS} are the total grid inertia constant and total system generation capacity connected to the grid, respectively. H_i and $S_{b,i}$ are the inertia constant and base apparent power of i^{th} conventional generator, respectively and n is the total number of conventional generators in the system. If an x number of conventional generators (corresponding to some percentage d of total kinetic energy connected to the grid) get displaced by an equal share of WPPs S_{WPP}, the grid inertia constant can be calculated as:

$$\begin{aligned} H_{SYS}^{'} &= \frac{\sum_i^{n-x} H_i S_{b,i}}{\sum_i^{n-x} S_{b,i} + S_{WPP}} && (2)\\ &= \frac{(1-d)\sum_i^n H_i S_{b,i}}{(1-d)S_{SYS} + S_{WPP}} && (3)\\ &= (1-d)H_{SYS}. && (4) \end{aligned}$$

Thus, it can be concluded that if a d_w percentage of conventional units (corresponding to d percentage of total kinetic

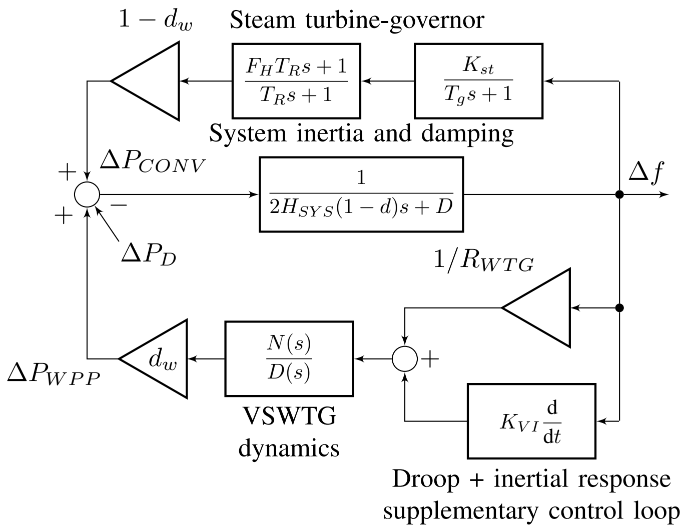

Fig. 4. Low-order SFR model of a power system with frequency support capable VSWTGs

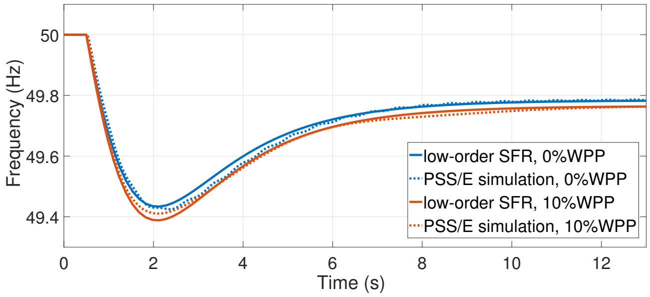

Fig. 5. Grid frequency behaviour for wind power operation in Zone I for a step increase in load

energy of the grid) is displaced by an equal amount of WPPS, the grid inertia constant is reduced by d percentage. Concurrently, the share of conventional generation is reduced by d_w percentage. A more general case is when the share of WPPs S_{WPP} is not equal to the amount displaced per (2). Since WPPs do not participate in frequency support in this region, the VSWTG transfer function from Fig. 4 is equal to 0. From the grid side, this is seen as reduced system inertia and spinning reserve. Simulation results are shown in Fig. 5, where blue lines correspond to no WPPs in the system, while orange lines correspond to a system where 10% of conventional units were displaced by an equal amount of WPPs. SFR model was compared to the simulation in PSS/E software package. In Fig. 4, ΔP_{CONV}, ΔP_{WPP}, ΔP_D and D are change in conventional units' power output, change in WPP power output, active power disturbance and system damping constant (all in p.u.), respectively.

B. Operation at medium wind speeds—Zones II and III

In this region, the rotor speed is high enough to permit frequency support. This region is divided into two zones because usually the generator power cannot naturally change according to the optimal power curve (Zone II in Fig. 3) all the way to the nominal wind speed without violating the upper rotor speed limit which is usually around 1.2 p.u. of synchronous speed. Thus, a linear law is introduced for Zone III to reduce the power fluctuations around the maximum speed. If the VSWTG needs to be deloaded to ensure a constant power reserve, the gradient of optimal generator power-speed curve (red curve in Zone II in Fig. 3) can be reduced so the generator operates at a higher speed with lower power (orange curve in Fig. 3). If the desired deloading by over-speed cannot be reached solely by generator control because the maximum speed limit would be violated, pitch angle control must be coordinated with rotor speed control keep the speed at maximum while achieving desired deloading. Generator can be temporarily overloaded without the need for deloading to give an inertial response because the rotor speed will return to the initial after a steady state is reached, but cannot be used to provide a constant power increase because the rotor speed will decrease permanently, and with that the generator power. A large enough disturbance could lead to the stalling of the turbine.

In this case, the VSWTG will operate according to the deloaded curve to ensure a power reserve for primary frequency support alongside with the inertial response. Pitch angle is kept at 0° to maximize aerodynamic efficiency. The only associated differential equation is the swing equation (5),

$$\frac{\mathrm{d}\omega_g}{\mathrm{d}t} = \frac{P_m - P_e}{2H_{WTG}\omega_g} \tag{5}$$

where ω_g is the generator speed, H_{WTG} is the inertia constant of the VSWTG, P_m and P_e are the mechanical and electrical power, respectively (all in p.u.). P_m and P_e are calculated according to (6) and (7),

$$P_m = \frac{0.5\rho R^2 \pi v_w^3 C_P(\lambda,0)}{S_{WTG,r}} \tag{6}$$

$$P_e = k_{del}\omega_g^3 + \delta P_{f.s.} \tag{7}$$

where: ρ is the air density in kg/m^3, R is the rotor radius in m, v_w is the wind speed in m/s, $C_P(\lambda,0)$ is the dimensionless aerodynamic coefficient with λ being the tip-speed ratio, $S_{WTG,r}$ is the rated generator apparent power in MVA, k_{del} is the coefficient of the deloaded power curve in p.u. and $\delta P_{f.s.}$ is the change of power set-point from the supplementary frequency response control circuit.

By setting the state variable $x = \omega_g$, input variable $u = \delta P_{f.s.}$, and output variable $y = P_e$, the state-space model can be written. After applying the Taylor expansion around initial operating point, the low-order SFR model for medium wind speeds is obtained. At this point, wind speed v_w will be considered constant during frequency support because the rotor acts as a buffer with a fairly large time constant compared to the time it takes the generator to reach a new set-point [11].

The low-order SFR model in Zone II is described by (8), where H is the VSWTG inertia constant (H_{WTG}), ω_0 is the initial generator speed, $a_1 = \frac{\partial}{\partial \omega_g}\frac{P_m}{\omega_g}|_{\omega_0}$. It is important to note

TABLE I
SIMULATION PARAMETERS

Wind power plant	H_{WT} [s]	$1/R_{WT}$	K_{VI}
	3	20	$1.85H_{WT}$
Conventional unit	T_R [s]	$F_H T_R$ [s]	R
	8	2.4	0.05
System	H_{SYS} [s]	D	d_w
	3.75	1	0.2

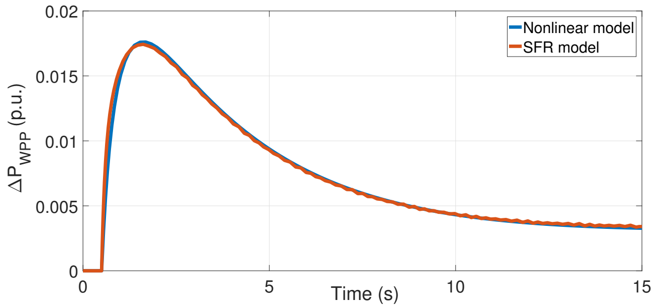

Fig. 6. Change in VSWTG output power for wind power operation in Zone II for a step increase in load

that unlike the synchronous inertia constant, the virtual inertia constant does not have any physical meaning but is merely the gain of the regulator. It can be set to twice the VSWTG inertia constant, but authors in [12] argue that it should be set to less than twice the inertia constant to reduce the chances of turbine stalling. The low-order model has been compared to the nonlinear model for a 5% load increase in a system with 20% WPP penetration where steam reheat turbines dominate (Fig. 4). Simulation parameters are shown in Table I. The simulation results are shown in Fig. 6.

$$\frac{N(s)}{D(s)} = \frac{2H\omega_0 s - (k_{del}\omega_0^2 + a_1\omega_0)}{2H\omega_0 s - \omega_0(a_1 - 2k_{del}\omega_0)} \tag{8}$$

It can be seen that the SFR model adequately describes the dynamics of the nonlinear model. The time constants of VSWTG depend on the VSWTG inertia constant and on the initial conditions: generator speed and the gradient of the deloading curve. It is clear that the response of the VSWTG will depend on the initial conditions. However, a more detailed analysis of the impact of the parameters and initial conditions on plant response is beyond the scope of this paper.

C. Operation at high wind speeds—Zone IV

During the above-nominal wind speeds, the rotor speed is held at its upper limit and the turbine blades are pitched to keep the aerodynamic power at its nominal value. However, deloading can be achieved by the pitch angle controller. Electric torque is held constant and the electric power varies linearly with the generator rotor speed. Frequency support can be achieved in the same way as described in the preceding subsection: by changing the generator power reference. When a frequency drop occurs, the pitch angle will be increased to inject extra active power to the grid while keeping the generator rotor speed at its maximum. However, some overspeed during the pitching action is possible, but simulations show that with careful tuning of the controls it is not significant and does not possess any danger to power electronics.

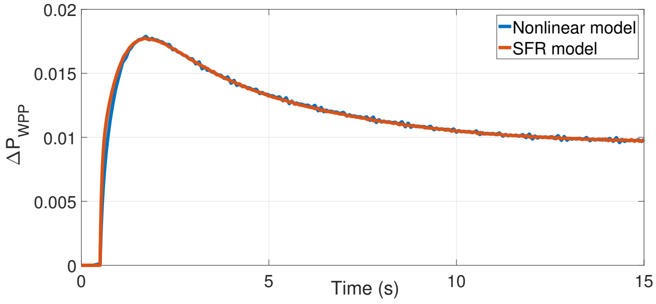

Fig. 7. Change in VSWTG output power for wind power operation in Zone IV for a step increase in load

A standard pitch angle controller that can be found in literature has been used, as shown in Fig. 2. The differential equations and state variables associated with this operating regime are described by (5), (9), (10).

$$\frac{\mathrm{d}\beta_I}{\mathrm{d}t} = \omega_g - \omega_{max} \tag{9}$$

$$\frac{\mathrm{d}\beta}{\mathrm{d}t} = \frac{1}{T_{servo}}\{K_p(\omega_g - \omega_{max}) + (K_i\beta_I - \beta)\} \tag{10}$$

where β_I is the output of the integral part of the PI controller in degrees, ω_{max} is the maximum rotor speed limit set to 1.2 p.u., β is the pitch angle in degrees, T_{servo} is the time constant of pitch actuator usually ranging around 0.3 s, K_p and K_i are proportional and integral gain of the PI controller.

Generator electrical power is described by (11),

$$P_e = T_{e,0}\omega_g + \delta P_{f.s.} \tag{11}$$

where $T_{e,0}$ is the constant electrical torque set-point. After linearizing the system described by (5), (6) and (9)–(11), a third-order transfer function is obtained that relates the change in VSWTG output power to the change in generator power set-point. The low-order SFR model is defined by (12)–(15),

$$N(s) = 2HT_s s^3 + (2H - a_{11}T_s - \frac{T_{e,0}}{\omega_0}T_s)s^2 - \tag{12}$$

$$- (a_{11} + a_{13}K_p + \frac{T_{e,0}}{\omega_0})s - a_{13}K_i \tag{13}$$

$$D(s) = 2HT_s s^3 + (2H - a_{11}T_s)s^2 - \tag{14}$$

$$- (a_{11} + a_{13}K_p)s - a_{13}K_i \tag{15}$$

where $a_{11} = \frac{\partial}{\partial\omega_g}\frac{P_m}{\omega_g}|_{\omega_0,\beta_0}$, $a_{13} = \frac{\partial}{\partial\beta}\frac{P_m}{\omega_g}|_{\omega_0,\beta_0}$. For brevity, H_{WT} and T_{servo} were written as H and T_s, respectively. The simulation results are shown in Fig. 7. Parameters of the simulation stayed the same as in Table I. It can be seen that the low-order SFR model adequately describes the nonlinear model behaviour in the high wind speed region. If we compare this transfer function to the one that describes the behaviour in medium wind speed region (Subsection III-B), we can see that the time constants in this region, and thus the response, mostly depend on the pitch controller parameters T_{servo}, K_p, K_i, but the actual quantification of their impact is beyond the scope of this paper.

IV. DISCUSSION ON THE LOW-ORDER SFR MODELLING OF VSWTS

Conventionally, synchronous generating units operate in a narrow speed range and their operating speed does not change much during normal operation so their power-frequency dynamics mainly depend on the type of the turbine and turbine governor action because the primary energy medium is of deterministic nature. On the other hand, the wind cannot be controlled (only predicted with a certain amount of probability depending on the time horizon of prediction). Therefore, VSWTGs operate over a wide range of speeds (usually -40% to $+30\%$ of synchronous speed [11]) to maximize energy capture. This means that the stored kinetic energy and the deloading possibilities both depend on the current wind conditions. This dependency on initial wind conditions means that the developed low-order SFR models are valid for only the initial wind speed. A large change in operating point intuitively means the linear approximation is then rendered invalid. However, the analysis of impact of the initial conditions on frequency response is beyond the scope of this paper, but there exists headway for potential future work. If the wind speed is considered as a perturbation variable as opposed to holding it constant like in this paper, then the low-order SFR model becomes a multiple-input single-output (MISO) system.

On another note, the low-order SFR models presented in this paper assume that the change of power set-point is independent of the generator rotor speed. However, other forms of inertial response and primary frequency response exist that take into account measured rotor speed or different rotor speed control [6] which would then change the set of equations describing the VSWTG. Future work includes an additional case that was not considered in this paper: when there is combined pitch and rotor speed control in medium wind speeds when the deloading cannot be reached solely by increasing the rotor speed. However, the nature of the response shouldn't be very different as the simulations in this paper show that the responses when only rotor speed or only pitch angle is employed are virtually identical, which can also be seen in [12].

V. CONCLUSION

In this paper, low-order SFR models of VSWTGs for integration with existing power system SFR models have been developed. The models were developed for three characteristic scenarios: low wind speed when the VSWTGs don't participate in the frequency support; medium wind speeds when the deloading and frequency support are achieved by rotor speed control only; and high wind speeds when the deloading and frequency support are achieved by pitch angle control. During low wind speeds it has been assumed that the VSWTGs do not contribute to frequency support and they effectively only lower the inertia of the system. In medium and high wind speeds, VSWTG can provide frequency support by injecting the extra active power to the grid.

The SFR models were presented in their symbolic form to show which parameters determine the most significant time constants of the VSWTG. It has been shown that the low-order SFR model adequately describes the nonlinear model for small disturbances. However, the stochastic nature of wind was not taken into account, thus the presented models are valid for constant wind speed only. Potential future work includes: analysis of the characteristic parameters on the nature of frequency response, impact of stochastic wind speed as an input to the model and error analysis of low-order models.

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