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Transient Support to Frequency Control From Wind Turbine With Synchronous Generator and Full Converter

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***Abstract-* The aim of this paper is to describe two regulators for a wind turbine equipped with a synchronous generator and a full converter for the interconnection to the grid. The idea is to extract a temporary amount of power from the wind turbine in order to provide short-term frequency support. The wind turbine model presented is specifically designed to analyse effects of wind generation on the electric grid. The first proposed regulator works to decelerate the rotor and hence transferring part of its kinetic energy to the electric grid: this can be done with variable speed wind turbines because the presence of electronic converters decouples the rotational speed of the turbine rotor from the grid frequency. The second proposed regulator acts on the pitch angle of the blades. Normally wind generators work at maximum efficiency: in this case a reserve of power is obtained working at a degraded point in the aerodynamic characteristic and it can be injected into the grid by pitching the blade. The simulation for testing the behaviour of the two regulators is performed in Matlab-Simulink using the Phasor simulation mode of SimPowerSystems.**

Index Terms – Renewable Generation, Wind Power, Distributed Generation, Primary Frequency Control Support.

I. INTRODUCTION

The percentage of wind energy sources is growing worldwide and wind generators aggregated into wind farms will be required to contribute to ancillary services provision such as frequency regulation in order to ensure power system stability and reliability.

The aim of this paper is to present and discuss the efficacy of two proposed regulators applied to wind turbines in terms of transient support to frequency regulation.

Hence a model of a wind turbine equipped with synchronous generator has been developed in Matlab-Simulink and it is presented in section II.

Two filter topologies are discussed in section III: their role is to extract from the turbine a proportion of the produced electric power when the grid frequency goes below its nominal value; the first regulator manages the kinetic energy stored in the rotating masses while the second produces a de-loaded working condition acting on the pitch angle of the blades. This kind of regulation can also be useful for applications where wind turbines are used in isolated networks coupled with conventional generators. In this case the support can be useful to improve the performance of the power system.

Section IV describes the electric grid used in the simulation study. It is composed of a conventional plant with provision of active and reactive power control, a wind farm and the load.

Section V presents the simulation results. Simulations are performed inserting an additional load in the electric grid: to allow verification of the proposed regulator effectiveness, frequency transient response of the grid voltage is discussed both with the regulators switched on and switched off.

II. WIND TURBINE MODEL OVERVIEW

The wind turbine model is composed by a rotor with three blades directly coupled to a synchronous generator (without gearbox) with excited rotor. Electric power that comes from the generator is conditioned by an electronic converter that provides the correct features in terms of magnitude and phase of voltages and currents to be integrated with the electric grid. Fig 1. shows the elements of the system.

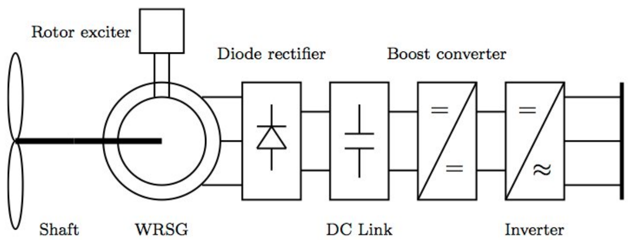

Fig 1. Elements of the full-converter wind turbine used in the study.

The model is developed in Matlab Simulink using the SimPowerSystems libraries and the simulations are performed in *Phasorial Mode*. This kind of simulation uses complex numbers to describe electrical quantities in AC circuits and hence does not allow representation of switching devices; therefore some components of the wind turbine have been studied in order to give an alternative description that was consistent with this type of simulation (which is faster than discrete or continuous modes, reducing the computational burden).

The following wind turbine components are described:

- Aerodynamic behaviour;
- Mechanical shaft;
- DC link;
- Boost converter;
- Inverter.

Control loops implemented in the turbine include:

- Maximum power point tracking (MPPT);
- Voltage across DC link;
- Gain of the boost converter;
- Blades pitch angle.

A. Aerodynamic behaviour

The model of the wind turbine rotor is realized using an interpolating function which represents the aerodynamic characteristic of the rotor blades[1]; this family of curves ties the aerodynamic efficiency (defined as the ratio between the power that comes from the wind kinetic energy and the mechanical power collected by the blades) to the tip speed ratio λ and to the pitch angle β of the blades. The aerodynamic efficiency C_p (power coefficient) multiplied by the power in the wind gives the mechanical power P_m applied to the rotor shaft according the following equation:

$$P_m = \frac{1}{2}\rho A V^3 C_p$$

where ρ is the air density (1.225 kg/m^3) and V is the wind speed in the free air stream.

The C_p- λ characteristic of the modelled wind turbine is shown in Fig. 2.

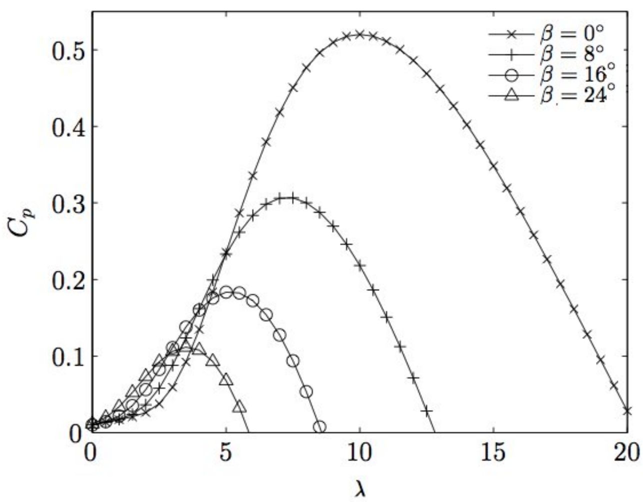

Fig 2. Aerodynamic (Cp- λ) characteristic of the wind turbine model.

B. Mechanical Shaft

The shaft is modelled as a two-mass model that takes into account the non infinity stiffness of the shaft and introduces a small amount of time to transfer the torque from one head of the shaft to the other one.

The dynamic equations that describe the two-mass model are given by:

$$\begin{cases} T_m - T_a = J_1 \dfrac{d\omega_1}{dt} \\ T_a - T_r = J_2 \dfrac{d\omega_2}{dt} \\ T_a = (\vartheta_1 - \vartheta_2)K + (\omega_1 - \omega_2)D \end{cases}$$

where J is the inertia, T_m and T_r are the mechanical and resistant torques, ω and θ are the angular speed and position of the shaft: subscripts refer to the quantities at the two ends of the shaft.

C. DC link and boost converter

As already noted, phasor simulation does not allow representation of switching devices such as diodes, FETs or IGBTs. Hence DC link, boost converter and inverter models[2] cannot be built using directly the blocks available in the SimPowerSystems libraries.

The diode bridge and the boost converter have been modelled in terms of power flow between the generator – supposed ideal – and the inverter.

The non linear charge law of a capacitor as a function of the injected power P_{in} and extracted power P_{out} is:

$$v(t) = \sqrt{\frac{2}{C}\int P_{in}(t) - P_{out}(t)dt}$$

Applying this equation to describe charging laws of the DC link and boost converter capacitors allows us to describe voltage variations in the electronic train conversion as a function of the power provided by the generator and the power drawn by the inverter.

It is worth noting that this solution does not provide the description for the reactive power exchanged between the generator and the diode bridge.

D. Inverter

The three phase inverter model could be built using three ideal voltage sources with vector control. In this case the frequency of the sources is defined by the user with the proper setting in the SimPowerSystem libraries.

This model is valid only if it is used in a grid where frequency is kept fixed. If the simulated electric grid is powered by conventional plants, frequency varies transiently according to loads' variation and to the regulation law of the active power: hence, in this case, inverter models must be equipped with a frequency follower and a phase regulator. In the analyzed case, the model of the three phase inverter, shown in Fig. 3, has been built using two controlled current sources instead of three voltage ones.

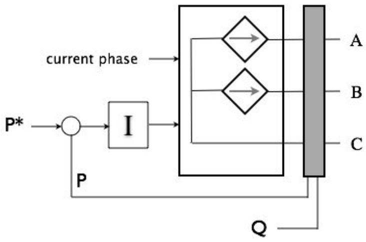

Fig. 3. Model of the inverter

Each current source in Fig. 3 is driven by a complex number that describes the current in terms of the modulus I_m and phase θ. Hence the injected currents can be written as:

$$I_A = I_m e^{j\vartheta}$$

$$I_B = I_m e^{j\vartheta} e^{j\frac{2}{3}\pi}$$

The third current I_C is imposed by Kirchhoff current law.

The modulus value I_m is obtained with the regulation loop shown in Fig. 3: the integral regulator, driven by the error between the produced active power and the reference power, acts on the module of the injected current in order to produce the correct value of active power.

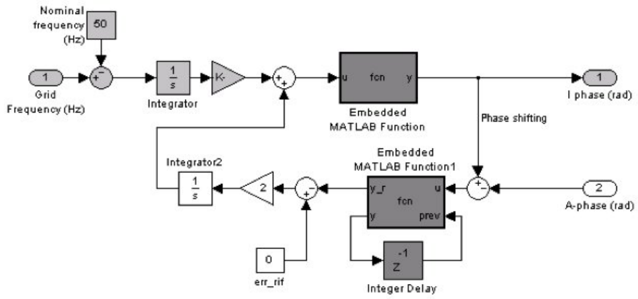

Fig. 4. Phase regulation loop.

The signal for the current phase θ is produced by the control diagram shown in Fig. 4. As said before, in phasor simulation the electric quantities are described with complex numbers: in such representation the frequency is implicit and hence, for example, a sinusoidal wave is fully described by a modulus and a phase value. In this domain it is still possible to represent a change in frequency by changing the value of the phase with respect to time. With reference to Fig. 4, the first integrator produces a line whose rate is the same as the rate of the voltage phase. The regulation loop after the first integrator aims at setting the phase displacement of current with respect to voltage. In this case the phase displacement (*err_rif*) is set to zero and hence voltage phases aligned with current phases are obtained. This is necessary because the wind farm is required to work, in our case, with a unitary power factor. It is possible to implement the regulation of the reactive power adding another loop to produce the signal *err_rif*.

The blocks filled with dark gray are aimed to convert the values of the angle in the [–π , +π] range.

E. Implemented controls

The efficiency of a wind turbine depends on the tip-speed ratio value, defined as the rotational speed of the rotor multiplied by the ratio between the blades radius and the wind speed (λ=ω R/V). To enable a wind turbine to work at maximum efficiency, it is necessary to implement a maximum power point tracking (MPPT) control that acts on the rotational speed of the wind mill, ω, which is the only controllable variable in the tip-speed ratio expression.

The control diagram for MPPT regulation is shown in Fig. 5: the produced electrical power P_e drives an MPPT block that generates a reference for the rotational speed.

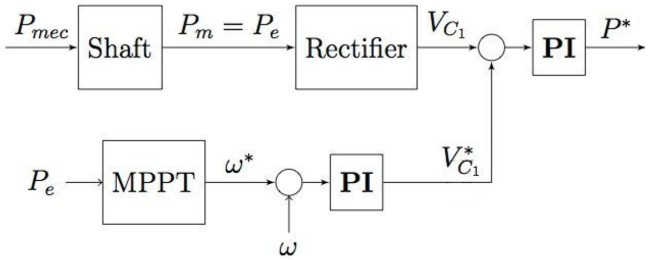

Fig. 5. MPPT Regulation control diagram.

The rotational speed error is the input to a *PI* regulator that generates a reference for the voltage across the DC link. The DC link voltage is finally regulated by controlling the power that the inverter injects into the grid.

The MPPT block is based on a lookup table (built offline) that ties the produced power with the rotational speed that is able to produce that power at the maximum efficiency: this relation is shown in Fig. 6.

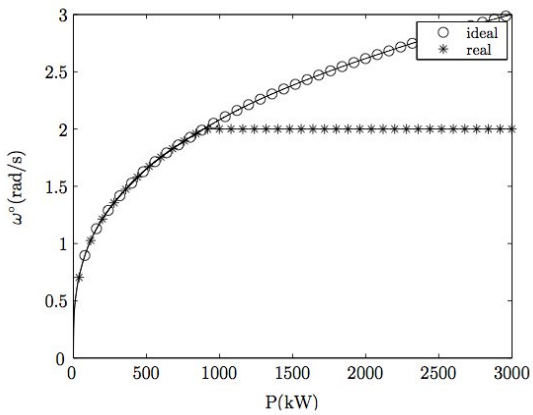

Fig. 6. MPPT curves. Real curve differs from the ideal one because the MPPT must operate as speed limiter after the turbine has reached the nominal rotational speed

The reason why the *real* curve in the graph becomes constant after a certain value of electric power is that the wind turbine cannot work over its nominal rotational speed: in fact to work at maximum efficiency, a wind turbine should increase its rotational speed while wind speed increases.

Hence, after the nominal rotational speed, the MPPT acts as a speed limiter.

The blades pitch angle is regulated to limit the produced power to its nominal value imposed by the inverter.

The gain of the boost converter is regulated to maintain a suitable voltage level at the input of the inverter in order to prevent an over modulation condition.

III. Regulators for transient support to frequency regulation

This section discusses the two proposed regulators aimed at providing transient support to frequency regulation: the first regulator manages the kinetic energy stored in the rotational masses, while the second one produces a de-loaded working point for the turbine by acting on the pitch angle of the blades.

A. *Kinetic energy regulator*

If a body with inertia J is subject to unequal mechanical and resistant torques, it starts to rotate according to the law:

$$J\frac{d\omega}{dt} = T_m - T_r$$

In terms of power, if the body increases its rotational speed, it means that not all the mechanical power from the shaft is collected. This power, that at first glance seems to be wasted, is given back when the body slows down and in the meanwhile it is stored in the kinetic energy of the rotating mass. Based on this idea it is possible to build a filter that, by slowing down the machine, extracts power from the kinetic energy and push it into the grid when the system frequency decreases[3],[4]. The operation is allowed because the electronic converter totally decouples the turbine from the grid and hence there is no correspondence between the rotational speed of the rotor and the grid frequency.

It is worth noting that during the slowing down phase, the working point of the turbine begins to move towards the left in its aerodynamic characteristic, causing a decrease in the aerodynamic efficiency and hence in the produced power.

The filter that detects the grid frequency drop and that acts to slow down the turbine takes the form shown in (1). The zero in the numerator ensures a null response in steady state (*T(s)* is a high-pass filter): this is because kinetic energy can support the grid only for a small period of time (without stalling the turbine).

$$T(s) = k\frac{s}{1 + 2\frac{\varepsilon}{\omega_n}s + \frac{s^2}{\omega_n^{\,2}}} \tag{1}$$

The gain k, damping ε and resonance frequency ω_n of the filter have been chosen by taking into account the behaviour of the grid frequency during the transients.

B. *Pitch angle regulator*

The aim of this regulation is to produce a de-loaded working condition acting on the pitch angle of the blades. This means that in normal conditions the wind farm production is below the optimal production and the reserve power can be used to support grid frequency regulation; in this case, unlike in the previous one when it was only temporarily stored in the kinetic energy, the reserve of power is persistent. This regulation is obtained by modifying the values stored in the MPPT table in order to produce a new series of working points for the turbine; a new table (built offline) ties each value of the produced power to the pitch angle allowing an efficiency 10% off the optimal one for that wind speed. This regulation uses the same filter as before to detect the drop in frequency and it releases the reserve power into the grid by acting on the pitch angle of the blades. Since in this case the power does not come from a limited reserve, it could be used to give a steady state contribution to frequency regulation [5]; however this usage has been investigated only for transient support.

IV. Electric Grid and simulation scenario

The electric grid implemented to perform the simulations is shown in
Fig. 7.

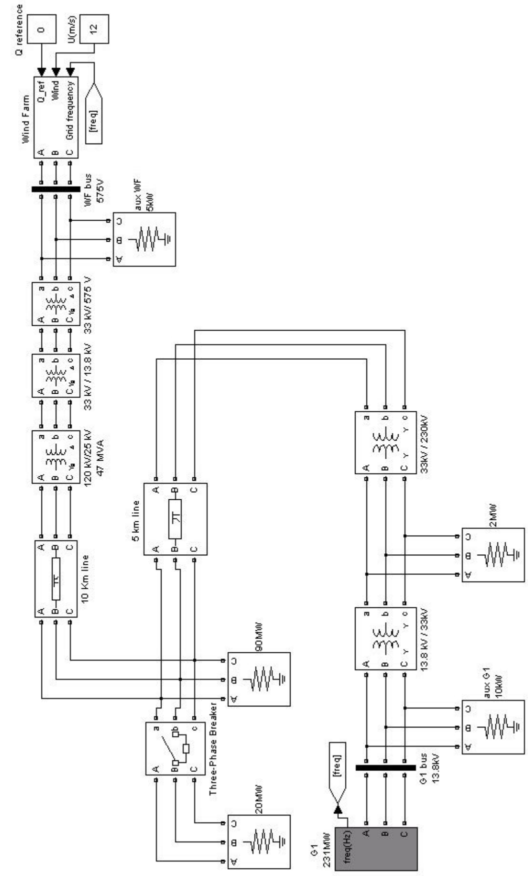

Fig. 7. Analyzed electrical network

It is composed by a 230MVA unit modelled as hydroelectric plant that acts as slack generator, providing the reactive power support and the primary frequency control. Wind generation is realized by the mean of a wind farm composed by twenty five 2.1 MW turbines.

The percentage of nominal wind power capacity with respect to electric power from conventional plant is 22%. Along the grid some loads are displaced for a total of 92MW. The rest of the grid is composed of transformers and transmission lines.

The wind farm is represented by an aggregated model. TABLE 1 reports the main details about the realized grid.

TABLE 1.
NETWORK MAIN DATA

Conventional capacity	231 MVA
Nominal wind Capacity	52.5 MW
Load at t=0	92 MW
Load at t=50	112 MW
Wind speed during simulation	12 m/s
Maximum aerodynamic efficiency	0.52
Droop for the power plant[6]	10%

V. SIMULATION RESULTS

The simulations are performed analyzing a transient that starts at 50s, after the insertion of an additional load in the grid. The action of the filters has been removed during the simulation at t=65s and t=85s because they create small oscillations in the produced power. The three-phase breaker, normally open, inserts an additional load of 20 MW when closed. Wind speed is assumed constant during the simulations.

Figures 8, 9, 10 and 11 show the reactions of the wind turbines and of the grid. Both figures 8 and 10 show a black line and a red one for the different behaviours when the filters discussed above are respectively switched on and turned off. Figure 8 shows the power produced by the wind farm: at t=50s the filter detects the drop in frequency and starts to slow down the turbines (Fig. 9); at the same time the pitch regulator tends to decrease the pitch angle of the blades and the efficiency grows by up to about 10% (Fig 9); these two events cause a 21% growth in the production of the wind farm in the early seconds after the start of the transient; the turbine, slowing down, changes its working point and the efficiency goes below the maximum: this causes a fast decrease in the produced power as visible in Fig 8 at t=60s. At about 65s the kinetic energy filter is turned off and the turbines start to reach the optimal rotational speed value as imposed by the MPPT.

The filter that acts on the pitch remains switched on until t=85s and hence continues to support the grid as shown in Fig. 11.

It is worth noting that the aerodynamic efficiency of the turbines - that is shown in Fig. 9 and expressed as the ratio between actual efficiency and the maximum one (0.52) - should be 0.9 at the beginning of the transient according to the considerations made in the paragraph about the pitch regulator: with a wind speed of 12m/s this does not really happen because the turbines already work in a below optimal condition to avoid overspeed.

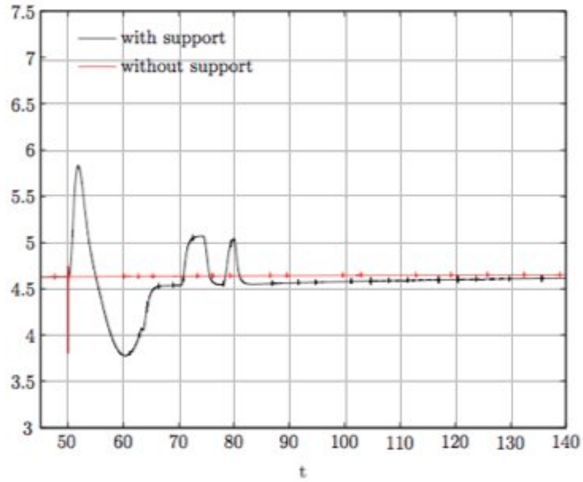

Fig 8. Active power injected in the grid by the wind farm.

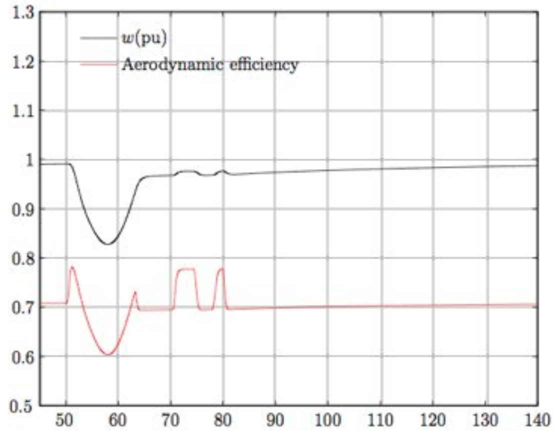

Fig 9. Rotational speed of the mill and the aerodynamic efficiency expressed as the ratio between actual efficiency and maximum efficiency for the turbine (0.52).

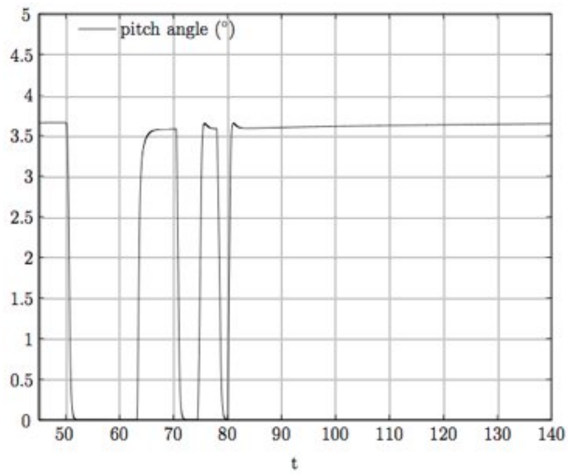

Fig. 10. Pitch angle of the blades.

Fig. 11 shows the graph of the grid frequency. When the wind farm provides support to frequency regulation the transient appears better than the one without support: the duration of the transient is shorter and the first drop is reduced by 35%. This can be justified with the intervention of the integral regulator implemented in the power plant: in fact the wind farm contribution prevents the rapid decrease of the frequency and so it helps the integral action to gain intensity. Results could be even better if the integral part of the regulation was stronger.

It is worth noting that the largest contribution to the reduction of the first frequency drop comes from the kinetic energy controller.

The steady-state frequency value is not 50Hz because the power plant implements only the primary frequency controller and so the speed droop regulator introduces a displacement from the nominal frequency equal to $\Delta f = R\Delta P$ (R is the droop of the power plant).

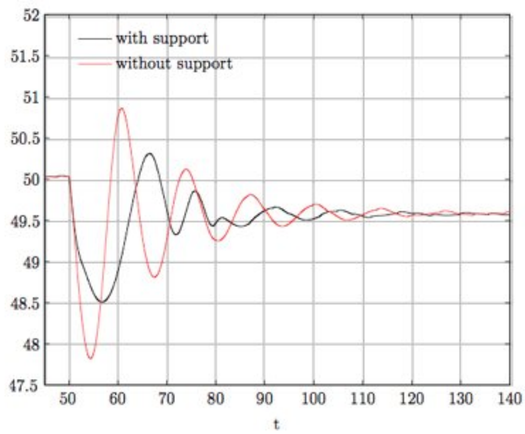

Fig 11. Voltage frequency behaviours during the transient.

The maximum contribution in terms of power from the kinetic energy of the turbine starts when the turbines reach their nominal rotational speed: after this point, any increment in the wind speed does not contribute anymore to the kinetic energy because the speed is limited: this consideration does not apply to the pitch controller.

VI. CONCLUSIONS

The paper reports the description of a model for a wind turbine equipped with synchronous generator and electronic converters. A model is built in Matlab Simulink and SimPowerSystems libraries using phasor simulation; this kind of simulation does not allow switching device representations but it is faster than the discrete or continuous one and so can be useful to perform long simulations in order to analyze the impact of wind energy in the electric grid.

The paper discusses two forms of regulation aimed to support the grid during the transient of primary frequency control.

Performed simulations show that such filters can improve the frequency behaviour during the transient period.

It is worth noting that the implementation of the proposed regulator is all done in software, i.e. there are no additional hardware requirements.

Further developments comprise a better definition of the filter aimed at detection of the frequency droop (i.e. adaptive filter) and a deeper analysis of the interaction between the kinetic energy regulator and the pitch one.

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