Sliding mode control for aeronautical electrical generators

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Abstract

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Alberto Cavallo

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Sliding mode control for aeronautical electrical generators

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Abstract
A novel strategy for control of aeronautical electrical generator via sliding manifold selection is proposed. An electric generator used for aeronautical application is composed by a cascade of different machines, including a main generator and an exciter. Usual control strategies adopt standard regulators for obtaining a rectified output voltage regulated to the nominal DC bus voltage. The regulation is obtained by acting on a DC/DC converter that imposes the field voltage of the exciter. In this paper, the field voltage is fed to the generator windings by using a buck converter operated by a sliding mode control, resulting into a stable, robust (against disturbances) action and faster convergence to the desired reference. Although the controlled apparatus is strongly nonlinear, rigorous global stability proofs are given and detailed simulation results are provided. Future applications include the possibility to dynamically change the set point, taking advantage of sliding regulators increased performance, specifically when energy management objectives are considered.

Introduction
In the frame of More Electric Aircraft [1], a great emphasis is given about the generation stage, referring to the possibility of providing new “greener” generators, e.g. by removing the overload capacity [2] for obtaining weight savings, and consequently fuel consumption reduction. In addition to increased density power and reduced weight of structures, new improvements about the generation stage for more electrical aircrafts can involve also the control stage, that can be optimized for a variety of scopes. In this paper, first the structure of the aeronautical generator is discussed and a model in dq coordinates is presented. Then, the focus is on the DC/DC converter providing the field voltage to the exciter, that will be the equipment in charge of control aspects. Specifically, the following chain of equipment is considered: AC three-phase generator, motor (prime mover), exciter (for driving the generator field windings), GCU, for the control of the field voltage, along with its electric supply, namely a permanent magnet generator, as shown in Fig. 1, resulting into a realistic description of an aircraft generator for medium/large aircraft. The voltage produced by the generator is distributed to the loads on an AC bus. Moreover, if a rectifier or an ATRU are used, the AC bus can be the basic element for the definition of a derived DC bus. The control strategy, based on a sliding manifold control approach, is devoted to keeping the generator voltage at a prescribed level. Note that the prescribed level, although constant over small
time horizons, may vary in the long run, thus the AC bus voltage is required to track slowly varying references. The motivations for a change of voltage output set-point are different. For example, consider the following scenarios: 1) A three-phase resistive load is directly connected to the generator output, and a power regulation is desired (for resistive load power regulation is equivalent to voltage regulation). 2) An uncontrolled AC/DC rectifier is used, e.g. an ATRU, providing a DC bus voltage that needs to be regulated. 3) A sudden change of the rotor speed happens, then the overall rectified voltage variation shall be compensated for. All the above cases can be faced by changing the field voltage of the exciter machine (and of the generator). Finally, detailed SABER simulation results are provided in order to show the effectiveness of the proposed approach, and further application of the proposed control strategy for energy management are discussed. Electrical system model The Figure 1 depicts a typical three-stage brushless synchronous machine used as AC generator. The generator is a three-stage brushless synchronous machine composed of the main alternator, the excitation stage, and the permanent magnet generator (PMG) [3]. The three elementary alternators are connected in cascade. The output of the PMG supplies the excitation to the exciter, where the output of the exciter is connected to the input of a rotating rectifier bridge. The DC current delivered by the rectifier bridge energizes the rotor of the main generator. A model for an aeronautical AC electrical generator, neglecting the PMG and modelling the exciter machine as a controlled voltage source for simplicity, is hereafter reported: where: Fig. 1: Structure of a typical aeronautical generator Parameters and variables are: \( \tau \) = electrical rotor speed (i.e. \( \text{p} \) times the rotor angular speed, where \( \text{p} \) is the number of polar pairs of the machine); \( V \) = armature d- and q-axis voltage; \( \bar{V} \) = armature d- and q-axis current; \( V_{\text{F}} \) = field winding voltage and current; \( V = d- \) and q-axis damper winding current; \( \bar{V} = d- \) and q-axis damper winding resistance; \( \bar{V} \) = armature phase leakage inductance; \( \bar{V} \) = d- and q-axis coupling inductance; \( \bar{V} \) = field-winding resistance; \( \bar{V} \) = field-winding leakage inductance; \( \bar{V} \) = d- and q-axis damper winding leakage inductance. The output voltage of the generator is usually connected to an AC/DC rectifier, that needs to be taken into account for the following sliding mode control application. The selected rectifier for this application is a three-phase bridge full bridge, with an output capacitance filter, reported in Fig. 2. Fig. 2: Generator output diode bridge rectifier The rectifier bridge introduces nonlinearities to the system, due to the presence of the diodes, and different loads can be connected to the DC bus voltage. However, on the AC side of the converter the voltage is mainly distorted by the voltage drop in the diodes during commutation (see also [4]), thus an harmonic analysis of the voltage waveforms on the AC side show that the first harmonic is largely representative of the voltage shape. Dually, since the focus is on the AC generator, the action of the diode bridge rectifier connected to the PMG is simplified by considering a constant voltage DC source \( V_{\text{dc}} \) connected to the input of the DC/DC converter. Sliding mode control Sliding manifold and related sliding mode approaches have been used for years in control applications. There are many reasons for the successful application of these strategies, but the main is their ability to deal with the control of MIMO and nonlinear plants with strong robustness properties, with respect to unmodeled dynamics and exogenous unknown disturbances. Basically, the idea behind sliding mode is very simple: it is sufficient to formulate control objectives and performances in terms of a suitable “sliding manifold” \( \Sigma \) defined by the solution of a (set of) equation(s) \( \sigma=0 \) so that if the the system state time evolution is forced to belong to the manifold, the required performances are automatically met. Obviously, in practical implementation of sliding control the state of the system must be driven to the sliding manifold, and kept on it (i.e., a stable “reaching phase” must be guaranteed) and the motion on the manifold must be confined to bounded subsets (i.e., stability of the motion on the manifold must holds). Specifically, the so-called “equivalent control” is obtained by derivation (see [5]) or successive derivation (see [6]) of the sliding function \( \sigma \). The equivalent control is what is really needed to satisfy design specs, but cannot be directly implemented, since it would require a perfect knowledge of the system (i.e., perfect modelling and zero uncertainties on the parameters), that is clearly unrealistic. Thus, a high-gain or a switching implementation of the control law is designed so that a control action whose average coincides with the equivalent control is obtained. Control of the generator in sliding mode In order to control the generator, one of the suitable strategies [7] available in literature is to control the quadratic sum of \( V_d \) and \( V_q \) components, here called \( V_s \), in order to specify a voltage \( V_{\text{dc}} \) on the electrical bus created by rectifying the generator three-phase voltages, and proportional to the set point \( V_{\text{ref}} \). The reference schematic for a Wound Rotor Starter Generator (WRSG) is given in Fig. 3. Fig. 3: Sliding control for a generator The above strategy defines a DC field voltage \( V_{\text{F}} \) for the rotor windings of the generator. In the aeronautical electrical generator of our interest, the field voltage \( V_{\text{F}} \) has to be supplied by the exciter through the usage of a DC/DC converter, connected to the PMG reported in Fig. 1. Thus, in turn the exciter has to be controlled. A DC/DC converter connected to the voltage network can be adopted for the purpose, by using a PWM strategy. However, in this paper a simpler and more robust Buck converter, as already included in most of the aeronautical electrical generators, is adopted for the same purpose. Moreover, the control strategy is such that the regulation is straightforward, with a direct application of the gate signals for the DC/DC converter switches, without using a PWM modulation. The reference control schematic is reported in Fig 4. The output voltages of the generator, charged with a generic load (here not represented) are transformed using the Clarke transformation. Then the \( d \) and \( q \) component are compared, after a simple combination, with a suitable \( V_{\text{ref}} \). The error, multiplied by \( V_d \) as per above Fig. 3, is processed by a saturation block and a \( k_1 \) gain, that shall be lower than the value of the voltage source \( E \) [8]. The saturation-gain blocks are used to obtain in real time an approximation of the equivalent control for \( V_{\text{F}} \). The resulting error is processed by a PID (resulting from a 2nd order sliding strategy, as will be formally shown in the paper) and a \( k_2 \) high-value gain, necessary in order to obtain the sliding motion [9]. The Heaviside function is finally used in order to obtain a binary value, converted into a suitable command signal for direct control of the switches pair of the DC/DC converter. Fig. 4: Sliding control for an aeronautical generator Simulation results The proposed sliding mode control for aeronautical generators has been tested in SABER simulation environment. The generator model has been implemented by following the \( d \)q \) equation set presented in the correspondent paragraph. About the converter, it has been modeled using the topology shown in the previous paragraph, referring to ideal switches and electrical components (i.e. without losses). A pure resistive load is
connected to the DC bus, absorbing 3kW at a nominal voltage of 270V. The results obtained using the above control law are shown in Fig. 6, where in blue it is reported the output of the diode bridge (i.e., the DC bus voltage) and the control reference is plotted in red. As it is evident, the sliding regulator is able to control the voltage precisely at the desired value. The set points are 280V, 250V and 270V respectively at the initial time, at t=0.3 s and at t=0.6 s. Fig. 6: DC bus regulated voltage and reference Moreover, at t=0.9 s, an additional load is inserted and acts as a disturbance on the regulation system. As evident by analyzing Fig. 7, the load connection effect is immediately compensated by the sliding control. Fig. 7: DC bus regulated voltage and reference (zoom)


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