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Wave-based Modeling and Control of Interconnected Synchronous Machines - Application on Mechanical Model

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Abstract: The motivation for this work is the control of flexible mechanical systems, specifically their position control without residual vibrations. The actuators are attempting to position the "important point" at the far end of the flexible system through wave based control to eliminate the vibrations at the end of the motion. The synchronous electric generator is modelled as flexible mechanical system. The wave-based control method is presented. The paper shows how to compute and use the "launch" and "reflected" waves for control. If appropriate strategy is used, the flexible system will be displaced to the required position with no residual vibrations. If the superposition principle is valid, various motions can be controlled simultaneously. The state feedback control is shown for comparison.

Keywords: wave-based control; flexible system; lumped mass model; mechanical waves; position control; modeling and control of power system; synchronous machine; mechanical models of synchronous machines and electronic oscillators; stability of the systems.

1. INTRODUCTION

The synchronous machine is one of the most important part of the power grid. To ensure the grid stability it is necessary to control the power sources connected in the grid together with electric appliances, which can cause instability as electric consumption demands change the conditions in the grids and power sources must adapt to such demands. In the past, the properties of Synchronous Machines were investigated on a mechanical model, because the theory of electrical machines was unknown (Griscom, 1926), (Bergvall, 1928), (Kron, 1952), (Blake, 1963), (List & Provazník, 1953), (Pavelka, 1965).

The control of synchronous machine is performed by the two approaches, the first control is a PD regulator applied to each state (state feedback control), which is well known type of regulation. The second control employs a wave-based approach (O'Connor, 2005), which uses part of so called wave model of the system to obtain the feedback to modify the input by the model response as input shaping (Beneš & Valášek, 2016). The wave based control approach modifies the system input without full model knowledge by measuring the position of the one (usually first) mass. The wave based approach is successfully applied to the different technical fields (O'Connor, 2007), (Valášek & Marek, 2008), (Valášek & Neusser, 2015), (Valášek, et al., 2016).

Based on the analysis of the electric model of the synchronous generator (Park, 1929), (Laible, 1952), (Singh, 2006) and (Machowski, et al., 1998) it can be shown that using mechanical model analogy (Pavelka, 1965) is justified. We agree that bond graph technique, which uses energy concepts, allows using analogous systems, but there exist other reasons for using mechanical models – see more in conclusions.

According to (Singh, 2006) and (Machowski, et al., 1998) the electrical air-gap power P_e can be simplified using eq. (1).

$$P_e = \frac{U_V U_r}{X}\sin(\varepsilon) \tag{1}$$

In the equation (1) there is variable U_v representing the terminal stator voltage, variable U_r represents internal (rotor) magnetic field, variable X is the machine and wire reactance and angle ε is torque (loading) angle. This simplified electrical behavior is further compared with mechanical model representation.

2. MECHANICAL MODELS OF SYNCHRONOUS MACHINES

Simple power system and its equivalent mechanical model is used. Heuristic mechanical approaches have been very successful. Load flow is equivalent of the mechanical torque. Voltage controller is equivalent of "the mass-rod system" (Weber, 1997).

Constant frequency (50 Hz) is maintained in the electricity network. All synchronous machines (generators, alternators) work synchronously with the same frequency. Alternators that work together must have the same voltage, or transformer must be connected with the appropriate gear between them.

Reducing the voltage of one of the alternators, the grid voltage is not reduced, since the voltage maintaining behaviour of other alternators. To the alternator begins to flow such a current that the rotating magnetic field make up the magnetic flux of the rotor so that the resulting flux is induced in the stator winding voltage. Changing the excitation current with unchanged voltage varries the current in the stator. This current can not perform any work because we did not increase mechanical power (mostly steam turbines). We say that it is a reactive current. If we measure the stator current I_s and the excitation current I_b and if we plot their dependence in the graph, we get a P_O curve in Fig. 1.

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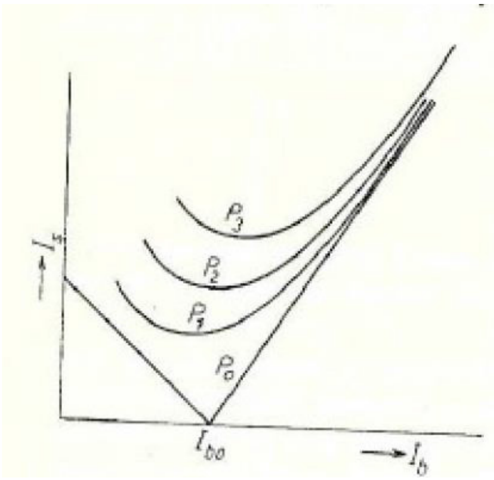

Fig. 1: "V-curves", I_s stator current, I_b excitation current

The graph shows that from limit of excitation current I_{b0} the stator current I_S increases when increasing, and also when decreasing the excitation current I_b. The curve on Fig. 1 is called "V-curve".

Now imagine that we will try to turn the alternator rotor faster. The other grid alternators will not allow us to do so. They will only allow the rotor to attain a certain angle ε against the resulting magnetic field $\boldsymbol{\Phi}_V$. At the same time electrical alternating current begins to flow through the stator windings such that it creates a magnetic field $\boldsymbol{\Phi}_S$, which will complement the rotor magnetic field $\boldsymbol{\Phi}_r$.

$$\boldsymbol{\Phi}_V = \boldsymbol{\Phi}_S + \boldsymbol{\Phi}_r \quad (2)$$

Greater the applied mechanical power is, the greater the angle ε and the larger is the actual active power that machine supplies to the electric network. In this case if we additionaly change the excitation current I_b, we get for different applied powers the shaft curves in Fig. 1. From these curves, we can easily determine the necessary excitation current for the desired active and apparent power of the machine.

2.1 Mechanical models

Alternator function could be clearly explained on the mechanical model analogy in Fig. 2 (Pavelka, 1965). This device consists of two shafts having a common axis.

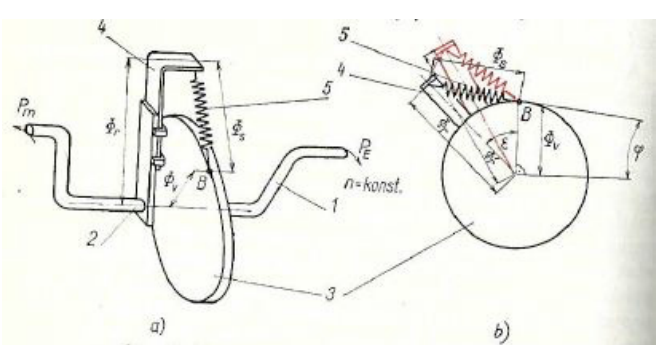

Fig. 2: Mechanical model of a synchronous machine

The parts of the mechanical model of synchronous machine are explained in the Table 1.

Table 1. Mechanical model variables explanation

stator current, current stator windings	I_S
excitation current	I_b
limit excitation current	I_{b0}
resulting / required magnetic field, (the terminal voltage of the alternator size of the diameter of the disk 3)	Φ_V
magnetic field (spring length 5)	Φ_S
rotor magnetic field, (DC excitation current to the rotor, length of arm 4)	Φ_r
the load / loading angle (the mutual angle between the arm 4 relative to the point B on the disk 3)	ε
Power	P
driving mechanical power (input)	P_m
actual active power supplied to the grid	P_E

The disk 3 is mounted on the shaft 1, the shaft 2 is mounted arm 5. Disk length Φ_r can be changed. Arm 4 and the disk 3 are interconnected by a spring 5.

Disk diameter corresponds to Φ_V magnetic flux and hence to the voltage at the terminals of the alternator. Direction of this flux can be imagined as the conneting line between the point *B*, where the spring is attached and the center of the disk. Length of the Arm 4 represents the magnetic flux Φ_r, length of the spring 5 represents the magnetic flux Φ_S.

If we try to rotate the shaft 2 faster than the shaft 1 rotates, it begins to stretch the spring 5, the arm 4 starts to swing relatively to the point B increasing their mutual angle, which represents the load angle ε.

It is obvious that the larger Φ_r is (i.e. direct current excitation of the rotor), the smaller load angle ε is for transferring the same torque from one shaft to another. Described context can be summarized in the Table 2:

Table 2: Description of the model

	Synchronous machine operating independently	Synchronous machine operating in the network.
Enlarging excitation current	increases the voltage at the terminals	changing reactive current according to the "V-curves"
Reducing the excitation current	reduces the voltage at the terminals	
Enlarging performance driving machine	increases rotor speed and frequency	increases the output of active power
Reducing performance driving machine	decreases rotor speed and frequency	decreasing output of active power