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Investigation on Self-Organization Processes in DC Generators by Synergetic Modeling

In this paper is suggested a new mathematical model, based on which it can be justified the self-excitation DC generators, either shunt or series excitation, by self-organization phenomena that appear to overcome threshold values (self-excitation in these generators is an avalanche process, a positive feedback, considered at first glance uncontrollable).

Keywords: DC generators, synergetic modeling, self-organization processes, self-excitation non-linear dynamics

1. Introduction

The electric machines, both DC and AC, are inventions of the 19th century. Of course, as a consequence of new materials and technologies, they experienced many changes during the 20th century. It is remarkable that, even nowadays, in the beginning of the 21st century, most electric machines of medium and high power are based on the electromagnetic principle. This identity of functional principle allowed an identity (first of all, conceptual) regarding modeling of electric machinery. It is worth to mention the different approachements [1], [2], [3], [4] and different authors [6], [7], [8], [9] to mathematical models of electric machinery in dynamic running.

The main feature of most mathematical models is the assumption that the ferromagnetic cores of the electric machines are linear/straight. In practice, this assumption although accepted for the macroscopic behavior of electric machines, often revealed that non-linearity of these cores has a relevant influence on what is going on inside these machines.

The latest research reveal that more and more specialists try to remodel the electric machinery considering more the non-linearity of the processes that take place in the component assemblies of electric machines [5], [10], [11], [12].

Consideration of non-linearity - similar to consideration of shape anisotropy, in the first part of the 20th century - leads to an increasement of mathematical model complexity and to highlighting of new properties, undetectable using the linear model, but seen in practice.

A remarkable and relevant case is the DC machine. In principle, it is the self-exciting phenomenon in DC branch and series excitation generators, a process that claims a positive reaction in the machine (a phenomenon that may take place and cannot be modeled as a linear process). It is only the non-linearity of the ferro-magnetic core that provides the conditions of its occurrence.

In this paper, the authors approach these problems based on a non-linear model, but synergetic, which - in the conditions of a positive feedback - provides, however, for a certain variation ratio of inner processes, the possibility to keep under control the macroscopic system (the electric machine).

2. Classical modeling of DC generator

The self-exciting takes usually place in idle running conditions and requires three conditions:

a) the main poles must be residually magnetized. Otherwise, they must be magnetized through temporary excitation from a DC power supply;

b) the excitation winding should be connected so as the emf E_{rem} produces an excitation current which increases the residual magnetic flux.

Thus, the connections of the excitation winding must be reverted or the sense of rotation reversed. The rotor circuit in series generator must be shut. In the mixed excitation differential generator, the series excitation is in short circuit during self-excitation.

c) excitation circuit resistance must not exceed a critical value R_{cr} .

Once in these conditions, in the rotor of thee generator (at rated speed) is going to be induced an emf by the main poles residual magnetism (Figure 2 and Figure 3). This emf results in an excitation current, field of which will overlap on the residual one. Next, a raise of emf, and again of current and excitation field, as the process of self -excitation takes place in avalanche until the emf reaches the value corresponding to the point M (Figure 3), where characteristic idle E_0 (I_E) crosses the excitation line.

The term “shunt” is synonymous with “parallel”. Since the field circuit is wired in parallel with the load, as far as the armature is concerned, the field circuit is just another load to be supplied with current (Figure 1).

a) Separately-excited Generator b) Self-excited Generator (Shunt Generator)

Figure 1. DC typical generators schematic diagrams. Comparison of generator connections

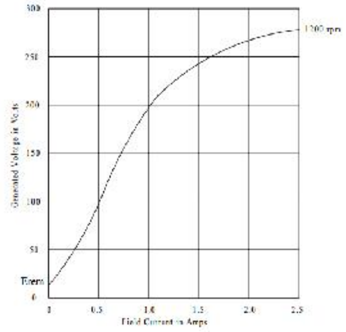


Figure 2. Magnetization Curve for a Typical DC Generator

There is interdependence between the field circuit and the armature circuit since the field current supplies the magnetic field which produces the armature induced voltage but at the same time the armature supplies current to the field current, a feedback situation.

This interdependence is well expressed by the mathematical model of the shunt excitation generator, both in dynamic and steady-state running (see the equations 3 and 4). It must be mentioned, first of all, the self-excitation characteristic in figure 3, in the voltage equation:

$$U_E = I_E \cdot (R_E + R_A + R_C), \quad (1)$$

where R_E and R_C are the excitation winding resistances, respectively of field rheostat, and R_A is the resistance of the rotor winding.

In Figure 3, the slope "$tg\sim$" of the excitation line must be below a critical value:

$$tg\sim_{cr} = R_{cr}, \quad (2)$$

Thus, the point of intersection of the two characteristics is somewhere in N, on the first non-linear section of the idle characteristic, for low voltage, and the self-excitation does not take place.

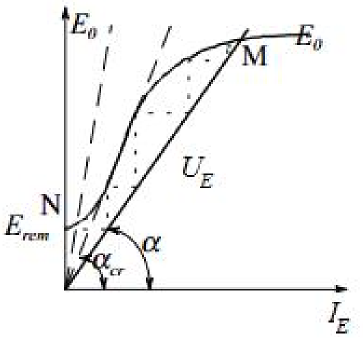


Figure 3. Self-excitation process in the DC generator

The mathematical model of the shunt excitation DC generator in dynamic running (Figure 1, b) is as follows (for ferromagnetic linear core):

$$u_A = (R_E + R_C)\cdot i_E + \frac{d\Phi_E}{dt}$$
$$\Phi_E = L_E \cdot i_E$$
$$u_A = -R_A \cdot i_A - L_A \cdot \frac{di_A}{dt} + \mu \cdot \Phi_{AE} \tag{3}$$
$$\Phi_{AE} = M_{AE} \cdot i_E$$
$$i_L = i_A - i_E$$
$$T = -p \cdot \Phi_{AE} \cdot i_A$$
$$u_A = R \cdot i_L + L \cdot \frac{di_L}{dt},$$

where:
- Φ_E - the flux created by the excitation winding;
- μ - the angular velocity at the shift (variable);
- M_{AE} - the coupling inductance in the excitation and rotor windings;
- Φ_{AE} - the interaction (bondage) flux between the excitation and rotor windings;
- i_L - the current intensity discharged through the load connected to the terminals of the rotor winding;
- R, L - the load parameters;
- p - the number of main pole pairs (of excitation);
- T - the electromagnetic couple expanded by the generator (load torque).

In steady-state running, the mathematical model (3) is:

$$U_A = (R_E + R_C)\cdot I_E$$
$$U_A = E - R_A \cdot I_A,\ \Delta U_p = 0$$

$$E = k \cdot \Phi \cdot \Omega\,,\ \ \Phi = \Phi_{AE} = ct\,,\ \ \Omega = ct \qquad (4)$$
$$I_L = I_A - I_E$$
$$T = -p \cdot \Phi \cdot I_A$$
$$U_A = R \cdot I_L\,.$$

where electric, magnetic and mechanic parameters designated with capital letters are, now, constants signifying, thus, steady-state operation.

3. Synergetic modeling of DC shunt excitation generator

The great problem of the electromagnetic systems for which is accepted the supposition of linear ferromagnetic cores is that of not allowing threshold phenomena that appeal forks in the processes taking place in the system. As a consequence of such forks, the system may have new features and behave better (a super-order) or, on the contrary, may be instable, that may lead to chaos. These behaviors may cannot be foreseen based on linear mathematical models. It is only non-linearity and accelerated variation - in certain periods of time - of electromagnetic system parameters that allow such behaviors with exceeding of limit values if the whole system, integrating microsystems, is driven out of the thermodynamic equilibrium. Such a behavior may also occur especially in the magnetization processes of non-linear magnetic cores.

That is why, considering the non-linearity of the ferromagnetic cores [11], [12], a new model of the shunt excitation DC generator may be adopted so as to allow explaining of a positive feedback of the electromagnetic system, a feedback possible in the process of magnetization and self-excitation only through microscopic cooperation that is synergetically. Taking into account as reference the dynamic running of the generator, the equation that has to be changed is that of the excitation flux (to a different scale, that of bondage flux/mutual coupling) between the windings of the two armatures of the electric machine.

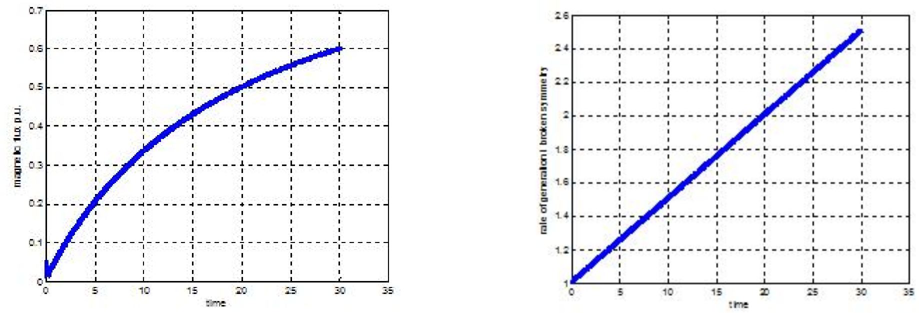
Consequently, in order to model the bondage $\Phi_E(\Phi_{AE}) = f(i_E)$ is suggested an equation, (5) - from population theory (thus accepting that the magnetization/demagnetization processes require birth/creation, respectively, death/breaking of symmetries between elementary magnetic couples in the Weiss domains of the ferromagnetic material).

By denoting ¨$_1$ the magnetic flux at the beginning of the period of time considered (ratio of flux value and a basical value representing the saturation flux for the core considered) and ¨$_2$ the value of magnetic flux at a certain time (after the beginning of the magnetization process), where the additional parameters of the flux were taken out, in order to make it less complicated, and r the ratio of creation/breaking of symmetries in the ferromagnetic system, the following equation may be written so as to reflect the magnetization process in time:

$$¨_2(t) = r \cdot ¨_1(t) \cdot (1 - ¨_1(t)) \quad (5)$$

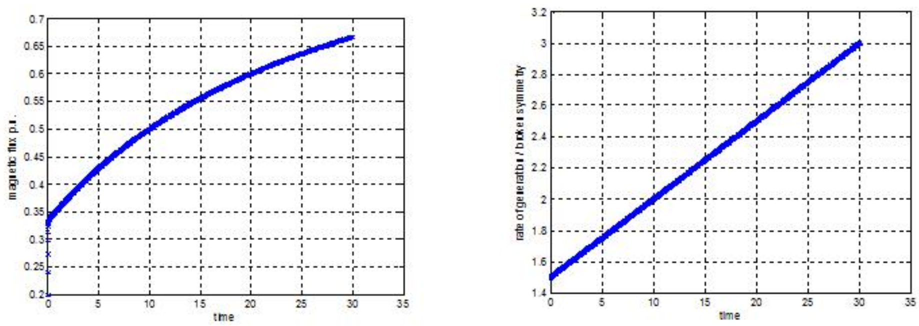
By analyzing the Figure 4 and 5 it can be seen that for values of the ratio of creation / breaking of symmetries " r " between 1 and 2.55, regardless the value of $¨_1$, the flux variation curve with time variation of excitation current (current representing a velocity variation of the load), is similar, to a different scale, with the magnetization curve (of Figure 2, for example).

Figure 6 shows the fork phenomenon, occurring when a critical value is exceeded (of the ratio of creation/breaking of symmetries) and changes in the magnetization process.



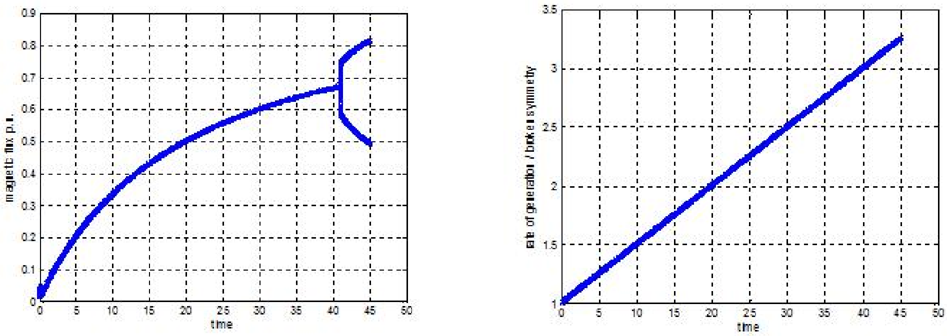
a) b)

Figure 4. Magnetic flux ratio (a) and ratio of creation/breaking of symmetries (b) with the time for an initial value of rated flux of $¨_{rem} = 0.05$ and an initial ratio of $r_i = 1.01$



a) b)

Figure 5. Magnetic flux ratio (a) and ratio of creation/breaking of symmetries (b) with the time for an initial value of rated flux of $¨_{rem} = 0.2$ and an initial ratio of $r_i = 1.5$



a) b)

Figure 6. Fork phenomenon occurence in the ferromagnetic system when a critical value of the ratio of creation/breaking of symmetries is exceeded:
a) magnetic flux variation for an initial value of $\Phi_{rem} = 0.05$;
b) ratio variation for an initial value of $r_i = 1.01$.

Considering the above, it is suggested a change of the mathematical model (3) using the equation (5), resulting a new mathematical model, with synergetic features (as to inner processes in the DC generator):

$$
\begin{aligned}
u_A &= (R_E + R_C)\cdot i_E + \frac{d\Phi}{dt} \\
\Phi_2(t) &= r(t)\cdot \Phi_1(t)\cdot (1 - \Phi_1(t)) \\
u_A &= -R_A \cdot i_A - L_A \cdot \frac{di_A}{dt} + \mu \cdot \Phi^l \\
i_L &= i_A - i_E \\
T &= -p \cdot \Phi^l \cdot i_A \\
u_A &= R \cdot i_L + L \cdot \frac{di_L}{dt},
\end{aligned}
\qquad (6)
$$

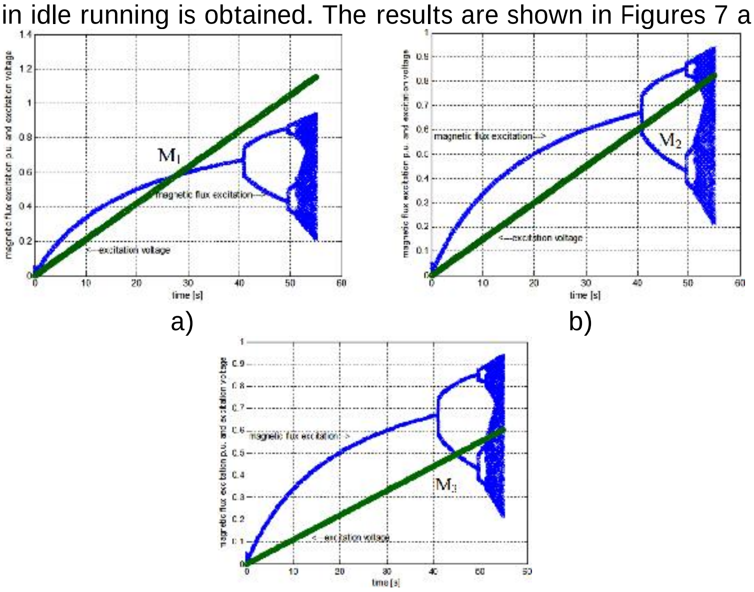
where Φ - intrinsic excitation flux and Φ^l - coupling flux, which practically have the same function shape with the time, but slightly different amplitudes.

4. Results and discussions

In accordance with the model (6) it was performed a case study, for a DC generator, with the following parameters: $p = 2$, $R_E = 75\Omega$, $R_A = 0.5\Omega$, $L_A = 10mH$. For idle running, when $i_L = 0$, the fourth equation of (6) is: $i_E = i_A$. Consequently, the system (6) changes into (7):

$$u_A = \left(R_E + R_C\right) \cdot i_E + \frac{d¨}{dt}$$
$$¨_2(t) = r\left(t\right) \cdot ¨_1(t) \cdot \left(1 - ¨_1(t)\right)$$
$$u_A = -R_A \cdot i_E - L_A \cdot \frac{di_E}{dt} + \mu \cdot ¨^{\,l} \qquad (7)$$
$$i_E = i_A$$
$$T = -p \cdot ¨^{\,l} \cdot i_E$$

To make it less complicated, it is considered a linear variation of the ratio of creation/breaking of symmetries in the ferromagnetic system as follows: $r\left(t\right) = a \cdot t$, where $a = tg\sim$ is the slope of the variation line (Figures 4.b, 5.b, 6.b), and choosing for R_C a value below this slope, the magnetization function of the generator in idle running is obtained. The results are shown in Figures 7 a, b, c.



a) b) c)

Figure 7. Self-excitation of shunt excitation DC generator in the case of magnetization synergetic model:
a) finding of the point of intersection (with the excitation line) in the increasing part of magnetization flux (the classic case) - the point M_1;
b) finding of the intersection point after forking occurence in a linear area of variation of the magnetization flux - the point M_2;
c) finding of the intersection point after forking occurence in a non-linear area of variation of the magnetization flux - the point M_3.

The intersection between the characteristic idle (magnetization characteristic) - $\ddot{} = f(i_E)$ - and the line of excitation circuit - $u_E = f(i_E)$ - as the excitation current is a function of time, it may get to the points M_1, M_2 și M_3 (according to Fig. 7 a, b and c), as a function of the resistance value R_C. Such points of intersection may be precisely defined only on certain parts of the curve of variation of the magnetic excitation flux, as shown in the figures above. An inadequate value of R_C might make impossible the intersection, since the variation of excitation flux is chaotic. In this case, the self-excitation process does not occur and the DC generator cannot operate.

5. Conclusions

Some conclusions can be drawn as a consequence of the analysis performed in the paper:

- self-excitation of DC generators - either shunt or series excitation - may occur only if there is residual magnetism (a pre-magnetization of the ferromagnetic cores);

- subsequent magnetization of the ferromagnetic cores (in idle running) requires complex non-linear processes, and as a function of variation velocity (ratio) of breaking of symmetries (or creation of new symmetries) non-univoc (actually, chaotic);

- considering a linear increasement with the time of the excitation current - based on a non-linear time variation of the magnetic flux - the self-excitation of the shunt excitation DC generator and, in the end, the delivery of voltage to the terminals ($u_A = u_E$) are possible only if there is no flux limitation after reaching a first stage equilibrium of the winding - core electromagnetic system (current flowing in the winding, flux carried by the core);

- such an equilibrium may occur only if time variation of flux creates ordered islands (self-organization phenomena) when magnetic couples line up with constant speed, but below a limit, to the direction of outer magnetic field;

- each time the intrinsic order is broken (chaos), the equilibrium state is no more possible, but the potential of the system is there and voltage may occur to the terminals;

- the macroscopically equilibrium in the winding-core system is also driven by the value of the whole resistance of excitation circuit. This resistance, too, has a limit (critical) value, that once exceeded does not allow occurrence of intrinsic equilibrium state in the electromagnetic system, and voltage delivery becomes improbable, even impossible.

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