Aspects on Compact Electrical Drive Systems

NICOLAE JULA
Military Technical Academy
Bd. George Cosbuc no 81-83, Sector 5, Bucharest
ROMANIA
nicolae.jula@gmail.com

TUDOR URSU
SC Sistem Euroteh SRL
Str. Depozitului no. 2, Buzau
ROMANIA
tudor@sistemeuroteh.ro

Abstract: The paper presents some aspects on actual directions regarding electrical drive systems field. The necessity to developing compact drive systems and the present world economical situation determine the manufacturers to concept special integrate drive systems, where there are at least three fundamental requirements: minimal specific weight (kg/W), high reliability, low manufacturing costs. The analyzed integrated system includes: electrical servomotor, speed transducer, position transducer, electro-magnetical brake, mechanical gear, control and power electronic. Each from the above system components has original elements, as follows:
-a brushless servomotor having a fractional number of slots per magnetic pole
- a speed transducer, where the output is processed linear trough digital methods
-no conventional solutions to develop very compact brake systems, as well as mechanical gear
-vectorial analysis for the control system.

Key-Words: electrical servomotor, speed transducer, position transducer, mechanical gear, electrical drive systems

1. General Considerations

Our purpose for this paper is to present some aspects on actual directions regarding electrical drive systems field.

The necessity to do compact drive systems and actual world economical situation determine the manufacturers to concept special integrate drive systems, where it is found less three fundamental requirements: minimal specific weight (kg/W), high reliability and low manufacturing costs.

The analyzed integrated system includes: electrical servomotor, speed transducer, position transducer, electromagnetical brake, mechanical gear, control and power electronic.

Each from the above system components has original elements, as follows:

- a brushless servomotor having a factionary number of slots per magnetic pole;
- a speed transducer, where the output is linearized trough digital methods;
- no conventional solutions to do very compact brake systems, as well as mechanical gear;
- system control trough vectorial analysis.

The team that presents this paper had researched, had designed and had produced such kind of systems.

Even will be presented some results, obtained on certain systems, the aspects presented in this paper are general, only to explain the reasons to concept any component, as well as to concept any kind of system.

In our presentation, we take into consideration, as main propose, a practice goal, as well as flexible, but the attention is focused on the theoretical reasons (aspects) to demonstrate clearly what is new as concept.

The actual critical world economical situation determine to elaborate a new thinking, as general and particular concept, to be sure to succeed on a market, where actually is characterized by a high level of offer, but requests are decreasing. In these circumstances, the customers want products as performing as possible, enough cheap and to be delivered from stock. The above conditions demonstrate that, actually, a producer do not may work based on classic conceptual solutions, technologies and managerial methods, but he must change totally manner to think, to work and to elaborate solutions. A researcher must consider that any restrictive concept, that is not enough objective, does not permit to find an optimum solution, totally adequate to a certain complex situation. For this reason, taking into consideration any acknowledgements from a field, as well as from the connected fields, he has to push on the limits, but to be anytime inside of the objective reality.

A certain complex situation (for example, the actual critical world economical situation) determines, usually, some several restrictions. A researcher must find optimum solutions just in these conditions.

If we are referring to electrical drive systems, electric special machines represent main components. We can consider, surely, that the general theories developed till now offer a complete solution for any kind of question. But it is not sure if this solution can solve, totally, the problems that a certain complex situation determines. In this situation, maybe it is not necessary a general solution, to cover any limits (generally, very, very large). We have to analyze, very minutely, just necessary limits for: supply voltage, current in load conditions, rotation speed, electromagnetic or / and mechanical torque, ripple voltage or / and ripple torque etc.). But we have to analyze, also minutely, as much more important restrictions, the limits for total available space, where must be put certain energetical parameters, environmental conditions, total life time, dynamic operating conditions, price, quantities, delivery schedule, competition on the market etc.

In the above circumstances, it must concept no conventional solutions, but to be sure to obtain higher performances.

Let us to present, shortly, main and representative aspects for each component from a special electrical drive system.

a. Servomotors

In most part of applications, are using, in special electric drive systems, servomotors based on permanent magnets, high energy. These servomotors can be dc with brushes and dc without brushes. We can discuss about dc brush servomotors, but actually there is a tendency do not use them (because some known disadvantages). In this paper will be presented only aspects on brushless servomotors.

It is known the general theory of electric machines, three phase, in accordance with that we need minimum one slot per pole and phase. So, for a machine with two poles we need minimum 6 slots, only to do a winding, not to obtain high performances. To have medium performances, we need three slots per pole and phase, that is to say 18 slots for a machine with two poles. But in practice, the machines are designed with many poles, usually 6 poles or 8 poles. There are and special machines, having more than 40 poles. On this way, we need from 48 slots to 72 slots, or even 360 slots. If we are based only on classic theories and methods, sometimes it is impossible, or very difficult to design a special servomotor. Setting out from the above, to be on market and to be a competitive partner, a producer must search for and find no conventional solutions. The general idea for this action is to use any actual acknowledgements, but to create new theories and methods, that are viability in certain restrictive conditions for the main electric, energetic and mechanical parameters that the application imposes to the electric drive system, respectively to each component of system.

Our team has now many no conventional solutions for special brushless servomotors, from that some aspects will be presented more detailed below.

b. Transducers

Generally, an electric drive system uses two kinds of transducers (based on electric phenomena, as electromagnetical induction): speed transducers and position transducers.

b1. Speed transducers

As speed transducers, based on electromagnetical induction, are used the tachometers. The classic tachometers are much known and it is not our interest to present in these paper aspects regarding such machines. The problem is that in the last time, because very special conditions of space and parameters (relatively, very small space and the necessity to obtain high level of back e.m.f. constant), designer has to concept new, very special solutions. These solutions are based on permanent magnet high energy excitation (rare earth permanent magnets). A permanent magnet from AlNiCo should be the best (because its very high stability at temperature several excursion), but has, in the same time, an important disadvantage – the magnet has a high sensibility at a variable air gap, especially if a magnetized item has to be removed from initial magnetization circuit to be introduced inside of tachometer. In this situation, it is very difficult to stabilize the working point of the magnet and are necessary special and complex devices. On the other hand, a tachometer based on

AlNiCo has relatively big dimensions and is not adequate for special, small size, electric drive systems.

For the above reasons, in last time were developed and used transducers based on rare earth permanent magnets. From these types of magnets are used SmCo type, because its relatively low variation of magnetic energy with the temperature. Though, it is not permitted a very large excursion of temperature values. This matter is not so convenient in certain applications, where there is a special environmental and there is a high level of temperature (for example, 180^0C because of the motor heating) inside of drive system. In these conditions, it is better to use NdFeB type of magnets because its convenient mechanical properties. Using NdFeB magnets, a designer can do small size tachometer, versus back e.m.f. constant high level. In this situation it is necessary to use some special global solutions for linearization of the output of tachometer, so to reduce several times the influence of temperature on magnetic field value. Such kind of tachometers will be presented below.

b2. Position transducers

Most used transducers for position, full rotation, based on induction phenomena, are electric machines named resolvers. In the last time are used multispeed resolvers (8, or 16, or 32 speeds). For this reason, it is mandatory to develop new concepts as solution and technology for laminations and windings, to obtain very accurate resolvers, small size. In paper will be presented more detailed our solutions and results.

c. Electromagnetic Brakes

Any actual electrical drive system uses electromagnetic brakes. This brake has more many functions: to stop fast the rotation of system; to maintain a certain position of system; to ensure that a supplementary rotation is not possible when a bigger resistive load is operating etc. The problem is that the users need brakes having bigger brake torque in smaller volume. To solve this problem, it is mandatory to develop and to implement new solutions. A brake based on magnetic and electromagnetic phenomena is required. Our team has such kind of solutions and some aspects will be presented more detailed below.

d. Gear Boxes

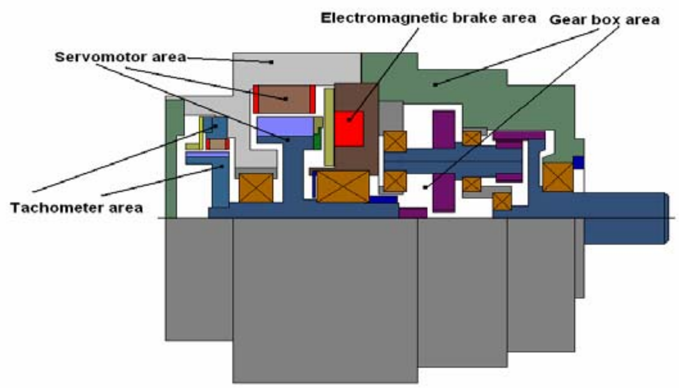
A complete electrical drive system must include a gear box. The requirements for certain electrical drive systems are very special relative to gear box parameters. We can present some of them: high torque versus small volume; very low backlash; high efficiency coefficient etc. In these circumstances must develop special solutions, where planetary concept is mandatory. Our tam had developed proper solutions, used successfully in electrical drive systems. Some aspects will be detailed in paper.

e. Control and power electronics

Electronics (control and power) is an obligatory part of an actual electrical drive system. In practice, any type of drive system needs its electronics, to obtain maximum parameters (high torque versus small volume, as well as high accuracy). Even our team is not specialized in electronics, we had to develop some concepts of electronics, to be better adapted to the system needs. This matter permits to put inside any electronic control requirements for different components of system (for example, special transfer function of tachometer, to do a linear output).

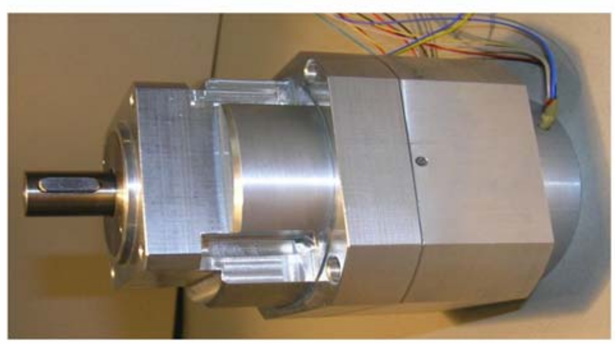
2. Main Aspects on an Actual Compact Electrical Drive System

In the above pictures (fig.1 and fig.2) is presented an example of an actual electrical drive system.



An example of compact electrical drive system

Fig.1



Picture of a compact electrical drive system

Fig.2

The above example is for a typical small size compact electrical drive system, where is required a high density of torque (Nm/kg, or Nm/cm^3). On the other hand, the parameters of other components are from high accuracy and energetical class. To do such system it must to have special solutions (concept and technology) for any component of system.

3. Main Aspects on Servomotors

Can be used any kind of performance electrical machines. Because some reasons, as: dimensions; solution to drive; kind of primary voltage; customer facilities etc. are used especially, as actual solution, brushless servomotors. Though, to meet the requirements of application systems, the classic solutions are not enough performance. To solve any requirements relative to high level of parameters, our team developed special solutions of brushless servomotors.

First of all, please find below a schema to explain operating principle of a servomotor controlled by Hall sensors.

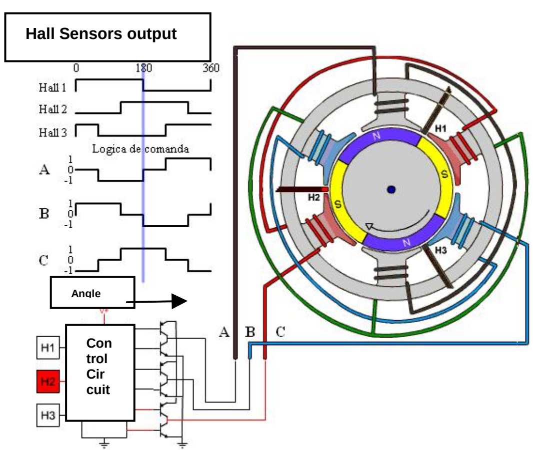


Fig.3 Schema to explain operating principle of a servomotor controlled by Hall sensors.

The example is for a two pole pair servomotor and is starting from the most simplified solution for a classical motor: 3 slots for 2 poles. This solution can be proper for certain applications, but not enough good when a very high density of torque (torque versus total weight or total volume) is required. In this situation, our team had developed a stronger solution, able to do a very high torque density: 3 slots for 4 poles. This solution is a basic solution. For certain application can be used a multiplication factory, from two to one hundred, depending of: density of torque; dimensions; accuracy etc.

You'll find below an example, where multiplication factory is 7 (21 slots and 28 poles). This example is referring to a mathematic model for numerical analysis of electromagnetic field.

The above situation and the following analysis are referring to A and B phases in serial connection and C phase out of voltage (one of the three situations during servomotor operating process).

The servomotor can be considered as a certain number of complex electric and magnetic circuits (having resistive and inductive elements sitting in a magnetic field).

Using an adequate numerical analysis of electromagnetic field method can be computed any interested magnitudes (torque, back e.m.f., density flux, speed, magnetic potential etc.). By using of other mathematic methods, can be pre-determined some of these magnitudes, to be possible to do a proper model for numerical analysis of electromagnetic field method. The following example is to pre-determine back e.m.f. It is considered as referential one of windings, for that phase shift is considered zero degrees. The back e.m.f. diagram is as follows:

$$e(\alpha) = \frac{5}{\pi} \cdot \alpha \cdot E_{\max},$$

$$\text{for} \quad \alpha \in \left(0 \ ; \ \frac{\pi}{5}\right) \ + \ 2k\pi$$

$$e(\alpha) = E_{\max},$$

$$\text{for} \quad \alpha \in \left(\frac{\pi}{5} \ ; \ \frac{4\pi}{5}\right) \ + 2k\pi$$

$$e(\alpha) = \left[1 - \frac{5}{\pi} \cdot \left(\alpha - \frac{4\pi}{5}\right)\right] \cdot E_{\max},$$

$$\text{for} \quad \alpha \in \left(\frac{4\pi}{5} \ ; \ \frac{6\pi}{5}\right) \ + 2k\pi$$

$$e(\alpha) = -E_{\max},$$

$$\text{for} \quad \alpha \in \left(\frac{6\pi}{5} \ ; \ \frac{9\pi}{5}\right) \ + 2k\pi$$

$$e(\alpha) = \frac{5}{\pi} \cdot \left(\alpha - \frac{10\pi}{5}\right) \cdot E_{\max},$$

$$\text{for} \quad \alpha \in \left(\frac{9\pi}{5} \ ; \ 2\pi\right) \ + 2k\pi$$

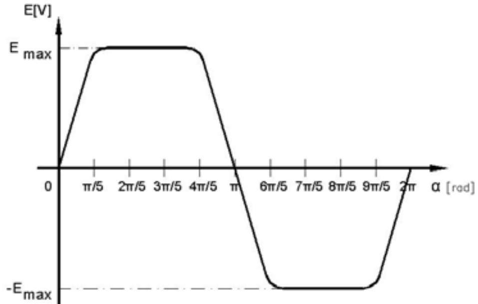


Fig.4 Back e.m.f. for one phase

Taking into consideration that phase shift between any two phases is 2π/3 electrical degrees, can be expressed the formula for the other two phase back e.m.f.

$e_1(\alpha) = e_1(\alpha)$ (as is shown above);

$$e_2(\alpha) = e_1\left(\alpha - \frac{2\pi}{3}\right);\ e_3(\alpha) = e_1\left(\alpha - \frac{4\pi}{3}\right)$$

The above relations are used to express operating electric circuit relations (simplified forms, used to pre-determinate parameters):

$$u_1 = R_1 \cdot i_1 + \frac{d}{dt}(l_1 \cdot i_1) - N_1 \frac{d}{dt}\varphi_{e1}$$

$$u_2 = R_2 \cdot i_2 + \frac{d}{dt}(l_2 \cdot i_2) - N_2 \frac{d}{dt}\varphi_{e2} \quad (1)$$

$$u_3 = R_3 \cdot i_3 + \frac{d}{dt}(l_3 \cdot i_3) - N_3 \frac{d}{dt}\varphi_{e3}$$

To characterize a dynamic operating regime, it has to be added and an equation of dynamic balance of torques:

$$J \cdot \frac{d\Omega}{dt} = m - m_f - m_s \quad (2)$$

$$\text{or: } \frac{d}{dt}\Omega = \frac{1}{J}\left(m - m_f - m_s\right) \quad (3)$$

Final results are obtained after will be used a numerical analysis of electromagnetic field method.

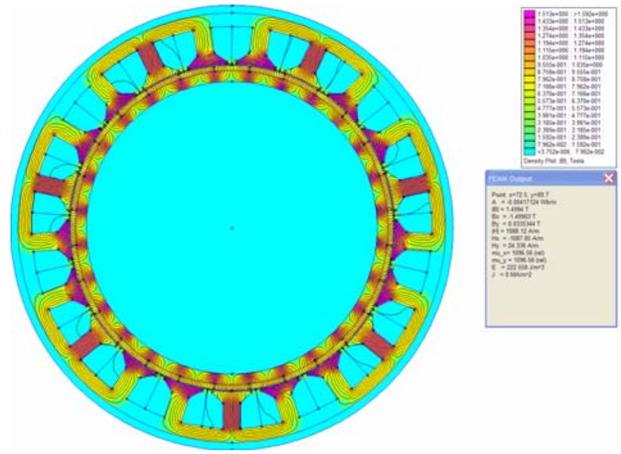


Fig.5 Result for 1A supply current

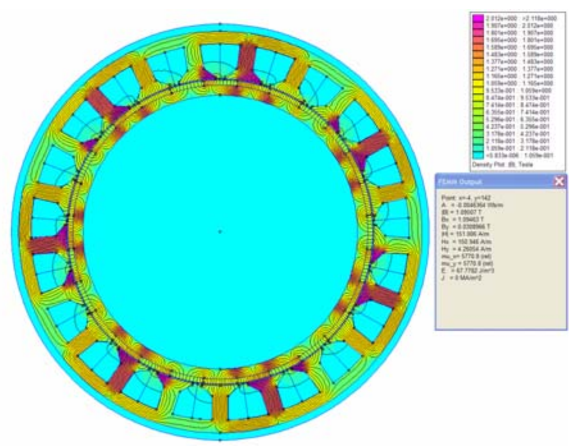


Fig.6 Result for 10A supply current

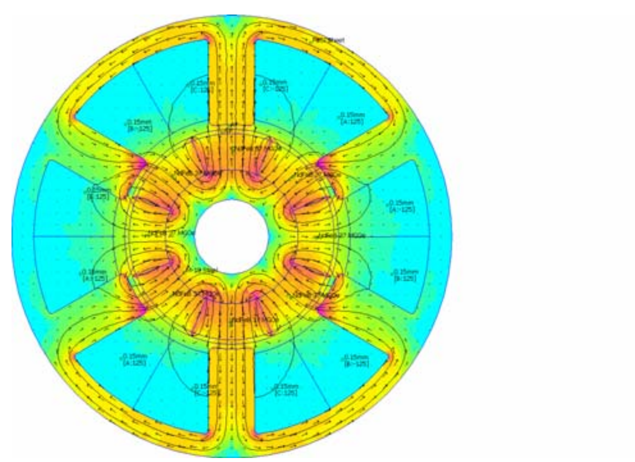


Fig.7 Radial model for an electric machine controlled with Hall sensors (6 slots, 8 poles) - configuration of excitation field

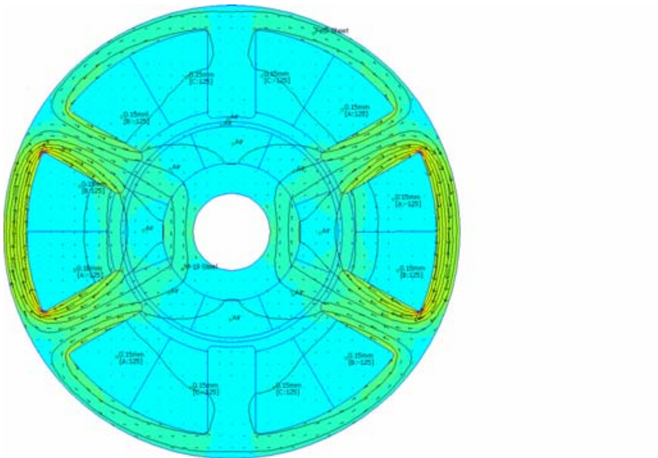


Fig.8 Radial model for an electric machine controlled with Hall sensors (6 slots, 8 poles) - configuration of reaction field

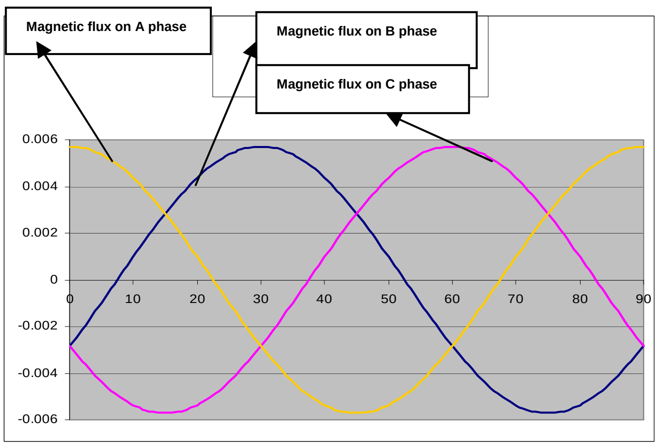


Fig.9 Diagram of magnetic flux on A, B and C phases

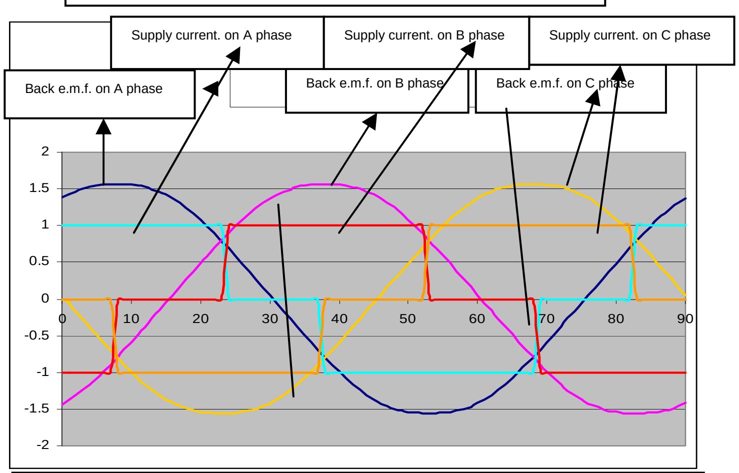


Fig.10 Diagram of back e.m.f. and supply current on A, B and C phases

In the following diagrams are shown some experimental results obtained on one of the servomotors that our team developed and produced.

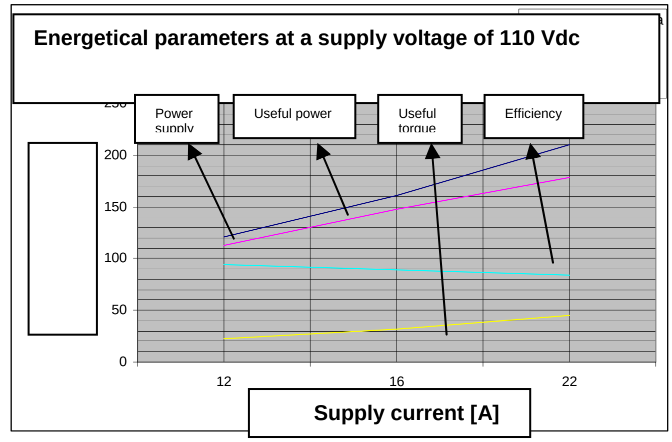


Fig.11 Diagram of energetical parameters at a supply voltage of 110

4. Main Aspects on Tachometers

Actually, are used two types of tachometers: dc brush tachometer; dc brushless tachometer (two phases and three phases).

Because dc brush tachometer is more usual, will be presented below this type. About a classical dc brush tachometer there are many papers and books, where is find a complete theory. The problem is to do a tachometer very accurate, having a high back e.m.f. constant, but relatively enough cheap. To solve this problem, two poles tachometers are the best. Also, using rare earth permanent magnets from NdFeB seems to be a proper solution. From electromagnetical point of view, the problem may be solved enough simple, therefore a good solution should necessity many solutions to be checked. But, there is a big problem: back e.m.f. constant is direct proportional with rotation speed, but with magnetic density flux, too. Unfortunately, magnetic density flux has not a constant value in any conditions. For example, the value of this parameter has a large variation with temperature excursion. To reduce in a convenient manner this influence on tachometer output, it is mandatory to use a special method to do a linearization of the output.

Before to do some considerations on the special transfer function, please find a short presentation of a tachometer having only two poles. To take a decision to do a tachometer with two poles is a problem of technology, to reduce total costs (for lamination, for winding, for bar commutator etc.). Generally, is mandatory to use an annular magnet winding, to obtain a convenient value of dc resistance. To arrange the technology for such winding is a complex action, but the costs of investment are compensating by exceptional results. In the next figures will be found the model of a tachometer with two poles, as well as the results of computation, using a method of numerical analysis of electromagnetic field.

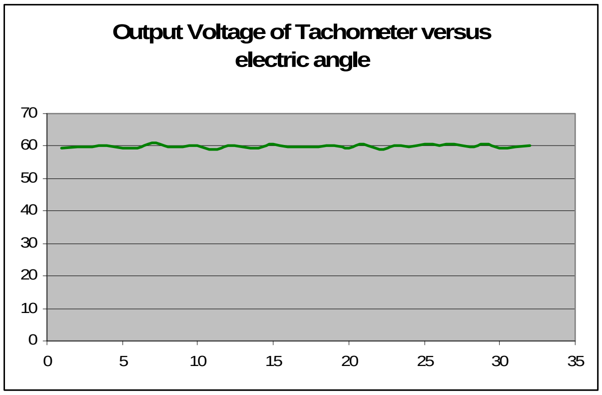


Fig.12 Diagram of output voltage of tachometer versus electric angle

If we analyze output voltage, we find that ideal accuracy is better than 1%. But, we discuss about real conditions of operating (temperature excursion), when density of magnetic flux is not constant. For this reason, it must to use an electronic correction, using a special transfer function.

The ideal output voltage of a tachometer can be expressed as follows: **$Y = K_t \cdot B \cdot n$,** and this answer should be direct proportional with rotation speed, **n.** But this situation will happened only in the conditions that **K_t** and **B** are simultaneously constant. **K_t** is a constant parameter per definition (is depending only of construction of tachometer). Unfortunately, density of magnetic flux magnitude, **B**, is strongly depending of temperature excursion. To reduce in a convenient range the influence of **B** hazard variation, must be introduced a new function, to correct this hazard influence. So, we have to introduce a **Z** function, as follows: **Z = Kt x B x (a – b x B) x n,** or in a more convenient expression: **Z = Y x (a – b x B).** In this expression, function Y is obtained naturally, but whole **Z** function will be obtained on an electronic way, by using a complex schema to elaborate of natural output **Y**. The electronic circuit of this schema will be integrated perfectly in the driver structure, as a regulation loop. We have to choose convenient values for **a** and **b** coefficients, to meet the proposed desiderata. As **Z** function is depending not only of **Y** function and **a**, **b** constants, but of hazarded variation of **B**, in a first vision should be necessary a transducer for this magnitude. To use such transducer is not a technological and efficient solution. In these circumstances, we have to proceed as follows:

- depending of tachometer construction and level of voltage output, we have to establish an optimum value for the expression: **Ke = [Kt x B x (a – b x B)];**
- will be applied **Z** output from the issue of the electronic circuit to the entrance of an very accurate potentiometer, from that will be selected a faction **n x Kt / b;**
- this output will be applied to another circuit, that will do a function **Y / (n x Kt / b) = b x B**; we can see that it is obtained a new function, that, even is depending of **B**, **B** value is not direct involved; this is first step to reduce the influence of **B** variation;
- will be used an addition circuit, where are introduced the previous value, as well as **a** coefficient, obtaining a new expression: **(a – b x B);**
- the previous output will be applied to a multiplication circuit, where, together with natural output Y of tachometer, is obtained final expression **Z = Y x (a – b x B)**.

5. Main Aspects on Electromagnetic Brakes and Gear Boxes

The actual compact drive systems need special brakes, having high density of brake force (force versus weight or volume). To meet this requirement, the system must be designed in an integrate construction – any components of system to be put in the same housing. For that, the electromagnetic brake has a special design, to entry exactly in the available space from integrated system. Our design is based on permanent magnets high energy and lamellar mechanical spring. This design ensures a high density of force and a better control of small air gap, as well as of movement.

Usually, a planetary gear box is used. Though, planetary gear, in certain circumstances, develops noises over admissible level. To avoid this disadvantage, we had developed a special solution, where all components of gear have not direct contact with outer parts of housing. Also, our gear boxes permit a high reduction ratio and a high torque versus total weight or volume.

6. Conclusion

In the paper are detailed certain aspects on compact drive systems based on electrical machines. The exposition was focused on special solutions to find a best answer to actual world economical situation: to ensure that the drive system will achieve high level parameters versus relatively low cost and optimum efficiency of company. We consider that it was possible to demonstrate that every time there are objective solutions to do an adaptation of concepts and production to real circumstances.

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