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MAGNETIC ALIGNMENT OF THE HIGH POWER SYNCHRONOUS HYDRO-GENERATORS

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This paper analyzes the theoretical and practical aspects of the magnetic alignment in order to obtain an air gap evenly distributed to the high power synchronous hydro-generators. According to the studies realized on one real case, it was obtained that the electro-magnetic disturbing forces would be cancelled as a result, and the hydro-generator would operate in long duty to the designed parameters. In most of the cases, the geometrical axis of the synchronous hydro-generator does not coincide with the magnetic axis. Therefore, it is necessary to carry out magnetic alignment operates prior to the putting into operation of a hydro-generator in order to meet the performance imposed by the design.

1. Introduction

A safe operation of the hydro-generator depends on the accurate steadiness of the air gap in all modes of operation.

As the air gap represents the medium through which the entire mechanical energy from the rotor is passed over to the stator as electro-magnetic energy, it is highly important that the electro-magnetic energy density from the air gap is steady which would assume a steady air gap in all modes of operation.

Provided that the air gap is not steady, especially during the to throw load transients, this leads to a significant variation in the density of electro-magnetic energy inside the air gap which causes the appearance of certain disturbing forces of high values which act against the rotor-stator generator.

It was theoretically and experimentally proved that these forces might compromise the bearings or in an extreme situation might cause the damaging of the hydro-generator.

Worldwide, this aspect is carefully considered, advanced studies having been conducted in this regard together with the specialists from universities.

After detailed studies carried out at the Branch in Hateg with Hydro-Engineering SA company Reşiţa, the true cause of the event since 1986 which resulted in the complete damaging of the hydro-generator no. 1 from Hydro-electric power Râul Mare-Retezat was precisely the high degree of instability of the air gap which had led to the collision of the rotor into the stator.

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In the case when a smaller value of the air gap is adopted, smaller than the correct value, the radial vibrations from the bearings increase due to the centrifugal forces of mechanical and magnetic imbalance.

If assuming a bigger value, then the magnetomotor voltage increases unjustifiably in the air gap, it also increases the nominal excitation current and eventually the increase of shock value of the short-circuit tri-phase current and stabilized short-circuit tri-phase current due to the reduction of the longitudinal synchronous reactance x_d.

This was the case of the 216 MVA hydro-generators from the Hydro-electric power Porțile de Fier I, 2nd generation rehabilitated, where the correct value of the air gap needed to be [1], [5], [6], [10], [11]:

$$\delta = \frac{0{,}4\,A\tau}{x_d B_\delta} = \frac{0{,}4\;\;896\;\;53{,}1}{1{,}28\;\;0{,}812\;\;10^4} = 1{,}83[cm] = 18{,}3 \text{ mm}, \tag{1}$$

But it was assumed an increased value of $\delta = 22\ [mm]$.

In the relation (1), there were used A is the current layer [A/cm], τ − pole pitch [cm], B_δ − magnetic induction in the air gap [T], x_d [Ω].

The consequences of choosing an increased air gap are:

- Increase if the magnetic voltage of the air gap
- Additional loss in the excitation coiling
- Corresponding energy loss for the entire life span

Besides the inappropriate selection of the air gap, another important issue is represented by the irregularity of the air gap due to the deviations from the circular shape of the stator's inner diameter and rotor's outer diameter of the hydro-generator measured in the middle area of the rotor's poles. The entire energy produced by the electric generator goes through the air gap as electro-magnetic energy as a state characteristic of the electromagnetic field.

2. Theoretical remarks [5], [6], [9], [10], [11]

The electro-magnetic field is generally defined by four vector variables:

$\bar{E}, \bar{D}, \bar{H}, \bar{B}$, where $\bar{E}$ and $\bar{D}$ are variables which define the electric field ($\bar{E}$ represents the intensity of the electric field, and $\bar{D}$ is the electric induction), whereas $\bar{H}$ and $\bar{B}$ are quantities which define the status of the magnetic field (intensity and respectively the magnetic induction). The four vector variables define the magnetic status of the electromagnetic field from the air gap by means of the volume density of the electro-magnetic energy w_e [2]:

$$w_e = \frac{\bar{E}\,\bar{D}}{2} + \frac{\bar{H}\,\bar{B}}{2} \tag{2}$$

The total energy of the air gap W_e will be integral of the energy density over the volume v corresponding to the space from the air gap [2]

$$W_e = \frac{1}{2}\int_v \left(\overline{E} \cdot \overline{D} + \overline{H} \cdot \overline{B} \right) \cdot \mathrm{d}v \tag{3}$$

As the electric field in the air gap is insignificant, the energy W_e can be considered completely magnetic [3],

$$W_e = \frac{1}{2}\int_v \overline{H} \cdot \overline{B} \cdot \mathrm{d}v \tag{4}$$

During the operation of the generator with load, both the stator's magnetic core and the poles' magnetic core are magnetizing so that the magnetic forces of interaction occur in the air gap, between the two magnetized ferromagnetic parts.

The knowledge of these magnetic forces which act on the two electromagnetic parts are of high importance because they can seriously influence the operation of the hydro-generator.

According to the theorem of the generalized forces, the forces f_x which occur in a magnetic field to a certain x direction, are given by the relation [2]:

$$f_x = -\left(\frac{\partial W_m}{\partial x} \right), \ \phi = ct \tag{5}$$

where: W_m is the magnetic energy; ϕ – magnetic flux.

From the relation (5) it can be noticed that the forces which occur in a certain direction in the air gap depend on the variation manner of the energy in the air gap.In this regard, there are two different cases:

- The volume density of the magnetic energy is constant in the air gap according to all axes;
- The volume density of the magnetic energy is not constant in the air gap according to different axes;

In the first case, the energy density being constant, it results that the magnetic induction B is constant in every direction in the air gap (Fig. 1).

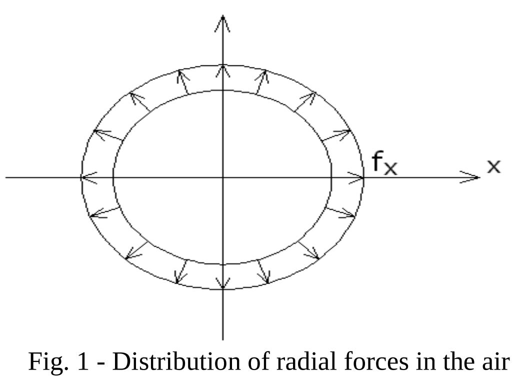

Fig. 1 - Distribution of radial forces in the air

In this case, the forces f_x which will occur according to a radial direction x, shall be:

$$f_x = -\left(\frac{\partial W_m}{\partial_x}\right)_{\phi=ct} = ct \tag{6}$$

In this ideal case, the force resulted in a radial direction over the mobile ferromagnetic parts shall be null. Thus, the magnetic parts of the generator rotor will centrically rotate from the stator's magnetic parts or in other words, it is magnetically centered to the stator.

It thus results, the necessary condition for an accurate magnetic alignment: the volume density of the magnetic energy is steady according to all axes, in this case, the resulting force according to the radial direction being null.

In the second case, when the volume density of the magnetic energy is not steady according to all axes, the forces occurring according to different radial directions will not be equal.

The force f_α after a radial direction x_α which realizes the angle α with the axis OX will depend on the angle α (Fig. 2), meaning:

$$f_\alpha = -\left(\frac{\partial W_m}{\partial x_\alpha}\right)\mathrm{d}x_\alpha \tag{7}$$

In this case, it is shown a resulting force F_r different from zero, meaning:

$$F_r = \int_{\alpha=0}^{2\pi} f_\alpha \cdot \mathrm{d}x_\alpha \neq 0 \tag{8}$$

In Fig. 2, it has been shown the resulting of the forces after an axis x. During the operation with load, the rotor shall undergo a radial resulting not zero force whose value depends on the irregularity of the volume density of the magnetic energy from the air gap space.

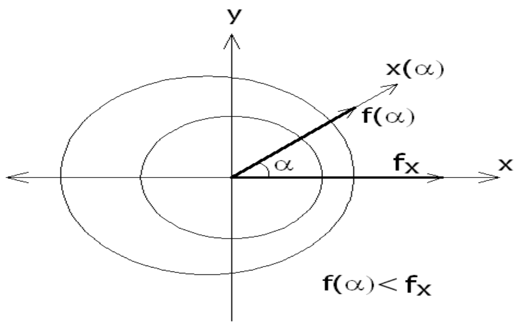

Fig. 2 - Resulting force on x direction

This force can produce vibrations which in time can be amplified because of the tendency of the air gap to strengthen the irregularity by modifying the clearances in the bearings. In this case, there appears a magnetic misalignment of the rotor from the stator. Sometimes, the magnetic misalignment exists even if geometrical deviations are controlled, because of the shape's irregularity of the stator and rotor. Out of this reason, it is imposed that any geometric alignment of a hydro-generator is accompanied by an inspection of the magnetic alignment.

For the better alignment of the rotary generator inside the stator, after the completion of the shafts' alignment and geometric alignment, it is necessary to check the magnetic axis. The magnetic alignment is a new procedure in Romania which is scoped to ensure the perfect alignment of the generator rotor inside the hydro-generator stator thus the resulting of the radial electro-magnetic forces is the smallest possible. For example, it has been shown the experimental determination of the magnetic axis Hidrounit 2 Hydro-electric power Vădeni, the hydro-generator being actuated by a Kaplan turbine, *P*= 5,5 MW.

3. Experimental determination of the magnetic axis Hidrounit 2 Hydro-electric power Vădeni [6], [7], [8]

Hydro-electric power Vădeni is a hydro-electric power plant located on the Jiu River and consists of two hydro-generators with P= 5,5 MW actuated by Kaplan turbines.

In order to determine the magnetic axis of hydro-generator 2 at Hydro-electric power Vădeni, the excitation coiling had to be supplied with electric current impulses which had values of approximately 200A [4],

During the application of the electric impulse, both the relative deviations of the rotor from the stator by means of mechanical comparators and also the voltage induced by means of inductive transducers installed on the stator were checked. According to this procedure, the following operates were carried out.

3.1. Checking the magnetic axis after the geometric alignment

The inspection of the magnetic axis can be realized through the following means:

- By checking the relative deviation of the rotor from the stator in magnetic field (by geometric measurements of air gap);
- After the geometric alignment and with the clearance in the bearings to the minimal value, was continued with the experimental determining by measuring the air gap before the inspection of the magnetic axis; the measurements have indicated values of the air gap settled in 4 diameter opposite points, in position 1 of the rotor (fig. 3);
- By supplying the coiling with an electric impulse.

The air gap being that from point 1, the excitation coiling was supplied with an electric current impulse, checking thus the rotor's deviations:

- Radial deviations of the rotor
- δ1, δ2 at the level of the radial thrust bearing according to the axes X and Y;
- Vertical deviations of the rotor
- δ3 according to axis Z, on the (-X) side of the rotor;
- δ4 according to axis Z, on the (-Y) side of the rotor;

There have resulted the values of the deviations indicated in table 1:

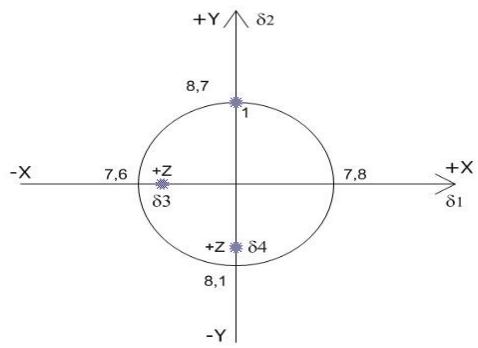

Fig. 3 - Air gap rotor-stator – position 1 rotor

Table 1

Values of generator deviations [mm]

δ1	δ2	δ3	δ4
-0,01	-0,01	0	+0,01

According to the analysis of the obtained values, it can be noticed:

- A radial magnetic force according to axis (-X, -Y);
- An axial magnetic force which has the tendency to lift the rotor, slightly tilted. The existence of a magnetic misalignment in this position of the rotor can be noticed. The deviation tendency according to axis (-X, -Y) due to the magnetic forces is settled by the irregularity of the air gap. Under these terms, the deviation of the rotor according to axes (+X, +Y) is imposed. In order to obtain accurate information on the position of the rotor's axis, the deviation values of the generator in motion in positions 2, 3 and 4 obtained by rotation from 90^0 and 90^0 by supplying the coiling with an electric impulse must be determined.

For position 4, the resulting values of the deviations indicated in table 2 are:

Table 2

Values of generator deviations in motion

δ1	δ2	δ3	δ4
-0.02	-0.01	-0.01	0

Out of the values resulted for the deviations, it can be noticed:

- a radial magnetic force according to axes (-X, -Y);
- an axial magnetic force which has the tendency to tilt the rotor;

It results a magnetic misalignment in this position of the rotor.

Under these terms, the rotor must be shifted to axes (+X, +Y).

In conclusion, a magnetic deviation of the rotor is noticed, its geometric re-alignment being imposed by shifting on axes (+X, +Y). The results obtained have been intuitively shown in Figs. 4 and 5 for the positions 1 and 2 of the rotor.

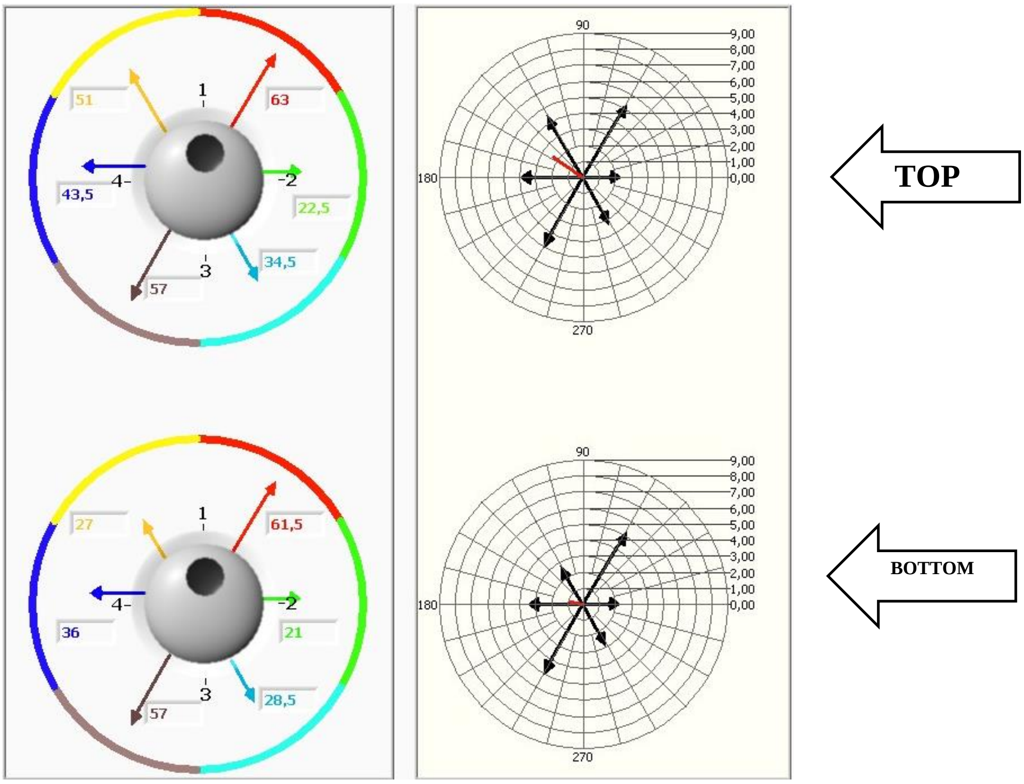

Fig. 4 – Forces in position 1 rotor.

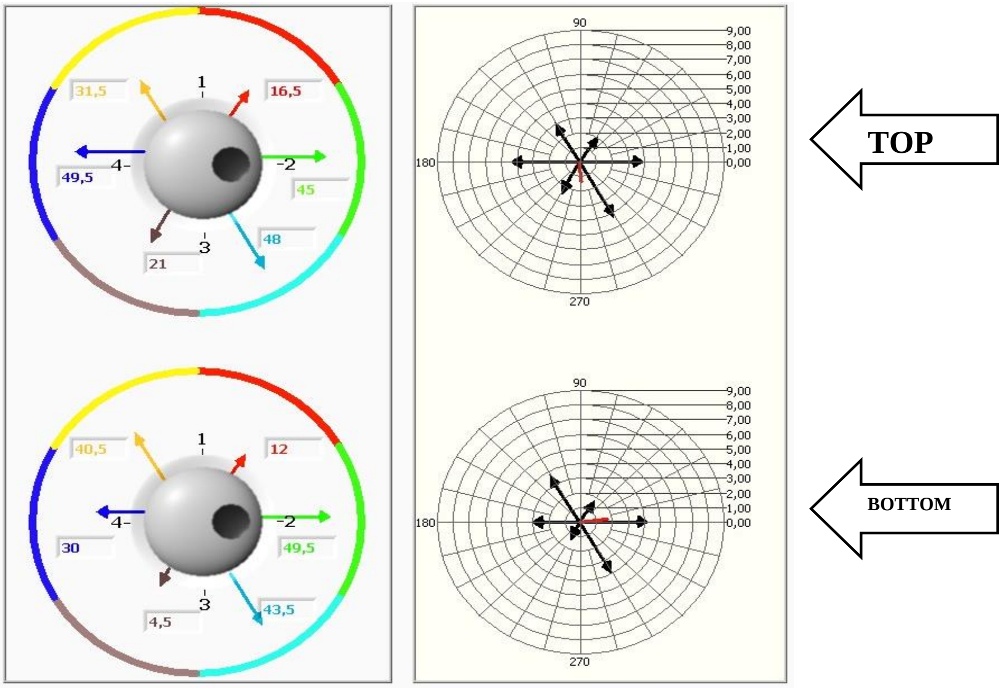

Fig. 5 – Forces in position 2 rotor

3.2 Checking the magnetic alignment by monitoring the electromotor voltage induced in the inductive transducers

The electromotor induced voltages are proportional with the value of the magnetic flux which covers the useful surface of the inductive transducers' circuits used. The magnetic flux shall be the result of the inducing magnetic fluxes produced by the pole windings of the rotor and of the response flows produced by the electric currents through the stator windings of the synchronous generator. The value of the magnetic flux depends on the magnetomotor voltage and on the magnetic resistance of the respective magnetic circuit.

As the equivalent resistance is highly dependent on the air gap resistance, the resistance of the magnetic core being insignificant, it can be assumed that the value of the magnetic flux is dependent on the value of the air gap. It results that the electro-motor voltages induced (fig. 4 and fig. 5) depend both on the value of the air gap and on the value of the forces of attraction between the rotor and the stator at the level of the air gap, in different positions of the rotor.

3.3. Magnetic re-alignment

As a magnetic imbalance was noticed, it was continued with shifting the rotor by 0,1 mm on the air gap direction minimum and with the rechecking of the magnetic alignment.

3.3.1. Generator rotor stability check by supplying the coiling with an electric current impulse

After the modification of the air gap, the excitation coiling was supplied with an electric current impulse, checking thus the rotor's deviations:

- Radial deviations of the rotor (in mm)

-δ1, δ2 at the level of the thrust bearing according to axes X and Y;

- Vertical deviations of the rotor (in mm)

-δ3 at the top level of the rotor according to vertical axis Z;

-δ4 according to axis Z, on the (-Y) side of the rotor;

It results values of the deviations indicated in table 3: for analysis in position 1 of the rotor.

Table 3.

Deviation values of the rotor

δ1	δ2	δ3	δ4
0	0	0	0

An accurate magnetic alignment can be noticed:

- The radial magnetic forces are null;
- The axial magnetic forces are null;
- The rotor remains fixed

This position of the rotor is the accurate one for the operation with load of the generator, even though, from the perspective of the air gap it appears as if misaligned geometrically.

3.3.2. Checking the magnetic re-alignment by monitoring the electromotor voltage induced in the inductive transducers

The main advantage of using the inductive transducers installed in the stator is represented by the fact that the permanent alignment of the rotor is possible only by monitoring the electromotor voltages supplied by the respective transducers. In this case, a variable magnetic flux can be used, which might be obtained by means of an alternating electric current through the pole windings of the rotor. The values of the air gap shall be proportional with the values of the electromotor voltage induced in the coils located in front of the measuring points. In the present case, direct current impulses were used with values of up to 250A, monitoring electromotor voltage induced during the connection of the electric current.

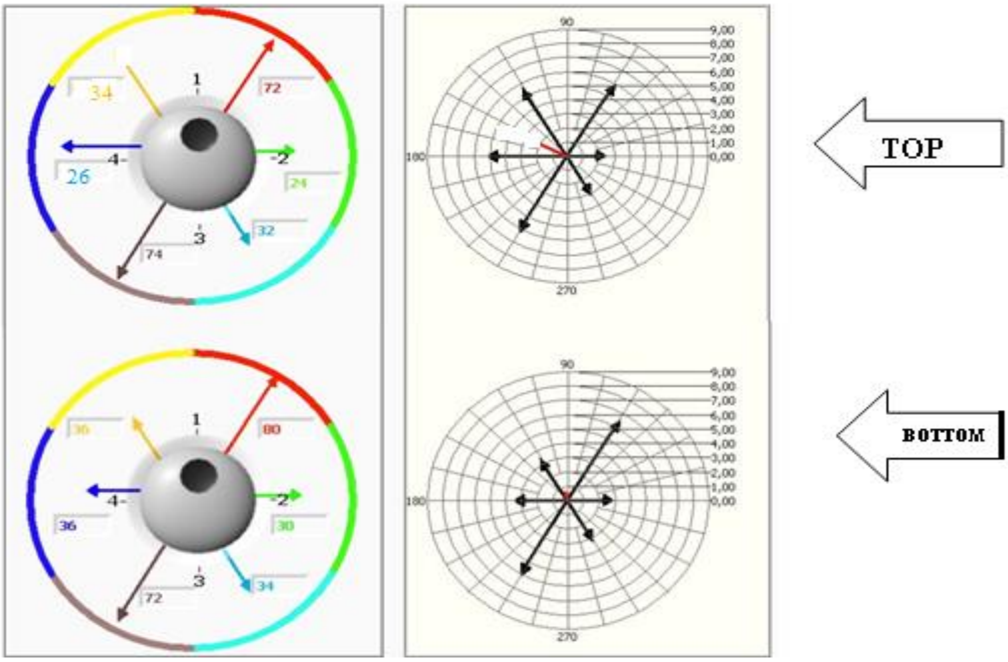

Fig. 6 – Forces in position 1 rotor; the resulting force on radial direction which actuates on the rotor during one complete revolution is practically null after re-alignment

In Figs. 6 and 7, the results of the magnetic forces which actuated on the top and bottom side in 2 different positions of rotor laying deviated at 90^0 have been shown. In the diagrams submitted it can be remarked a deviation of the resulting forces in different quadrants during one complete revolution. In this case, it results that the dynamics of the rotor's movement will no longer be influenced by the disturbing forces caused by irregularities of the rotor, the geometric axis of revolution overlapping the magnetic axis of the rotor-stator generator.

The conclusion is that, subsequently to the procedures made for the magnetic re-alignment, the rotor's alignment from the stator at hydro-generator 2 is accurate and the works for its putting into operation can be continued.

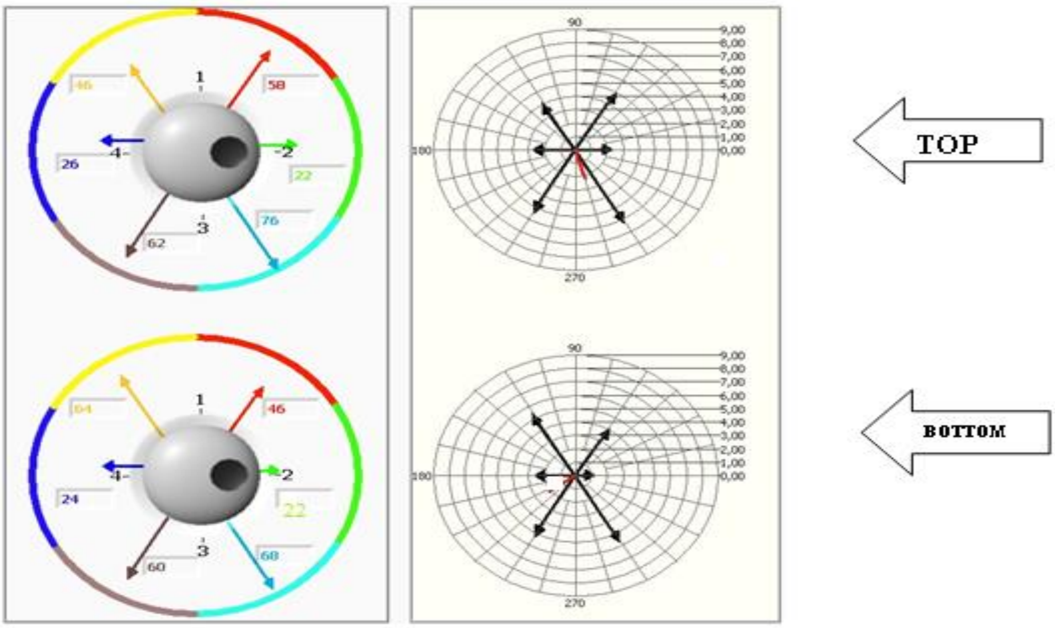

Fig. 7 – Forces in position 2 rotor

4. Conclusions

Due to the irregularities of the rotor and stator of the hydro-generator, resulted from the deviations from machining and erection operates, after the completion of the shafts' line (removal of deviations from perpendicularity and verticality), irrespective of the best alignment of the rotor from the stator of the hydro-generator, the geometric axis of the generator in motion does not coincide with the magnetic axis of the installation. After the magnetic alignment and thorough installation, the hydro-generator will operate at the designed parameters with a low level of vibrations and low temperatures on the bearings. That is why, the assertion is that, after each maintenance operate: for level 2(LN 2), for level 3(LN3) and for level 4(LN4) to the hydro-assemblies, this procedure of magnetic alignment should be applied.

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