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ELECTRICAL STABILIZATION OF THE AZIMUTHAL MODE IN LARGE INDUCTION PUMPS

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Introduction. Whereas the small cylindrical induction pumps operate stably, in the large sodium pumps of this type an azimuthal instability is observed [1] which is electrical in nature.

If in some pump channel portion the sodium flow velocity is somewhat lower than the mean value, the current induced there is stronger, and consequently, the external magnetic field is partially screened. In small pumps the screening is weak and due to the current increase, an electromagnetic force (being a product of the field and the current) appears which tends to equalize the flow. In the large pumps the screening predominates over the current increase, with the force decreasing with diminishing sodium flow velocity. The velocity perturbation continues to grow as long as the flow is not divided into two zones. One of them operates as a pump, while the other represents a bypass, through which the sodium wastefully flows back.

The pumps in the hundreds kW range can be designed for stable operation using the proper design and frequency optimization [2]. Attempts have been made to stabilize the pump operation by increasing the pump's hydraulic resistance, as well as by distorting the magnetic field profile [3].

The larger pumps require new stabilization methods. In the present report a nontraditional inductor coil design is described, in which the coils compensate the field screening and thus prevent the azimuthal instability.

Equivalent Circuits. To a first approximation, the two flow zones can ne considered as a joining of two elementary pumps. For sodium flow both pumps operate in parallel. In a traditional coil design, their coupling is equivalent to a series electrical connection of both pumps, since each power coil conductor encompasses both zones and the same current I is supplied to both pumps. The operating regime is characterized by the p(Q) curves of the elementary pumps. For small pumps the combined p(Q) curve is always a descending one, and the elementary pumps operate at the same point. In the case of large pumps, due to the field screening, the $p(Q) \mid_{I = \text{const}}$ curves turn out to be non-monotonic (Fig. 1a). Over the BD characteristic segment both pumps cannot work simultaneously. Even if an attempt is made to match their operating regimes at the point C, and then allow them to operate naturally, the regime of one of them shifts to the point A, while that of the other moves to E [1].

The connection of the coils, as proposed below, is equivalent to a parallel electrical connection of the elementary pumps (Fig. 1 b), hooked up to a source of a specified voltage V. If the coil cross-section is sufficiently large, the screening of the magnetic field is compensated by a reduced induction and, consequently, the $p(Q) \mid_{V = \text{const}}$ curves drop off monotonically, and the flow becomes uniform and stable.

The proposed coils are more complicated than the conventional ones, the current path is longer and the power losses are greater. Nevertheless, it is possible to use two coils in a pump — a traditional one as the excitation coil and one of the type proposed herein as the stabilizing coil (Fig. 1c). When the flow velocities are equal, there is no current flow in the short-circuited stabilizing circuit because in both branches of this closed circuit EMFs are induced which are of equal magnitude but of opposite orientation. A difference in the flow velocities results in the appearance of a current which tends to diminish the difference between these velocities. The mean stabilizing current value depends on the average value of the flow rate perturbation and on the degree of the unavoidable pump design asymmetry.

Coil Design. The conventional winding for the cylindrical pump represents a one-dimensional series of equal elements arrayed along the flow. A travelling magnetic field is induced when the windings are connected to a three-phase network.

To stabilize the flow a winding design is proposed in the shape of a two-dimensional array, for example, of rectangular coils that are mutually displaced in both, the longitudinal and the transverse (azimuthal) directions relative to the channel axis.

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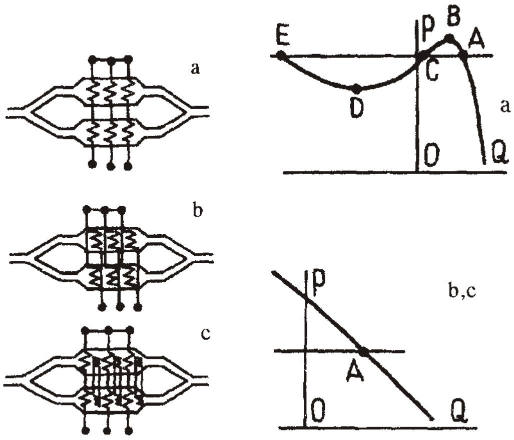

Fig. 1

The primary winding element is a coil having the dimensions $\tau x R\Delta\varphi$, which is wound using several turns of a conductor with an overall cross section S (Fig. 2, τ being the pole pitch). In a cylindrical pump, coils are used which are bent in the φ direction on the radius. A belt is formed of such coils; each coil is tilted relative to the preceding one by a $\delta\varphi = 2\pi/n$ angle. All coils in the given belt are connected in parallel. Each belt is displaced a distance δx with respect to the preceding one. The coils of the excitation winding belt are hooked up to a three-phase network. The coils used for stabilization are not connected to anything. Of course, for a placement of the coils in the magnetic yoke, a system both of longitudinal and transverse slots is required.

The design of the stabilizing coils can be simpler; they may consist of electrically insulated shorted-out turns in the form of the number 8 (Fig. 3).

The coils are displaced relative to each other by intervals $\delta\varphi$ and δx, as already described. This scheme produces a stabilizing effect on a smaller number of modes than the preceding scheme.

Calculation of the Stabilizing Effect. Regardless of whether one uses the winding (Fig. 2) for field excitation, or merely for stabilization, its stabilizing effect is the same. In this context we proceed to consider the case, where the excitation current flows through a discrete excitation winding with a linear load $\sqrt{2}A\exp[i(\alpha x - \omega t)]$, which is analogous to that in [1]. Let us assume that the total linear load for both windings is

$$A(x, \varphi, t) = \sqrt{2}\,A\,[1 + a(\varphi)]\exp[i\,(\alpha x - \omega t)]. \tag{1}$$

The remaining assumptions are the same as in [1]. $V_0 = \omega/\alpha = \omega\tau/\pi$, $Q_0 = 2\pi r\delta_h V_0$ are the synchronous velocity and the flow rate, $P_0 = L\lambda V_0^2/(2\delta_h)$ are the hydraulic losses at the synchronous velocity, $B(x, \varphi, t) = B(\varphi)\exp[i(\alpha x - \omega t)]$ is the magnetic field, $v(\varphi) = V(\varphi)/V_0$, $p = P/P_0$, $q = Q/Q_0$, $b(\varphi) = B(\varphi)\delta_m\alpha/(\sqrt{2}\mu_0 A)$ are the dimensionless velocity, pressure, flow rate and the field, respectively, $j^2 = 2\mu_0\sigma A^2\delta_h/(\lambda\rho\alpha\omega\delta_m^2)$ is the square of the dimensionless supply current, $k = (\alpha R)^{-2}$ and $\varepsilon = \mu_0\sigma\omega\delta_h/(\alpha^2\delta_m)$.

By expressing the field in terms of the current and equating the forces in the same manner, as in deriving equations (25) and (26) in [1], we obtain

$$\begin{gathered}\{kd^2/d\varphi^2 - 1 + i\varepsilon\,[1 - v(\varphi)]\}\,b(\varphi) = i\,[1 + a(\varphi)];\\ p = (j^2/\varepsilon)\,\mathrm{Re}\,\{b^*(\varphi)\,[1 + a(\varphi)]\} - v^2(\varphi)\,\mathrm{sign}\,v(\varphi).\end{gathered} \tag{2}$$

The stability limit is determined by the system (2) satisfying the solution

$$\begin{gathered}v(\varphi) = q + \delta v_m \cos m\varphi, \quad b(\varphi) = b_0 + \delta b_m \cos m\varphi,\\ b_0 = [i + \varepsilon\,(1 - q)]^{-1},\end{gathered} \tag{3}$$

where $m = 1, 2, 3, \ldots$; $|\delta v_m| << 1$; $|\delta b_m << |b_0|$.

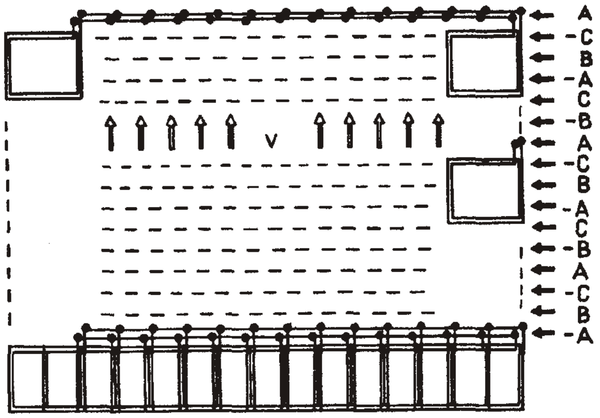

Fig. 2

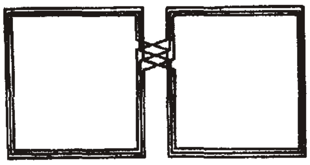

Fig. 3

Compared to [1], a new a(φ) term has appeared in (2). In order to express a(φ) in terms of b_m, it is necessary to apply the Kirchhoff's and induction laws for each belt. It is assumed that the number of coils is sufficiently large, such that the adjacent coils can be considered to be insignificantly displaced relative to each other both in the azimuthal and the axial directions ($\delta\varphi << 1$ and $\delta x << \tau$). Summing all currents, we find that

$$a(\varphi) = -\varepsilon\eta(m)\,\delta b_m \cos m\varphi, \tag{4}$$

where

$$\eta(m) = (\varepsilon_c/\varepsilon k)\,(2/m\Delta\varphi)^2 \sin^2(m\Delta\varphi/2) \tag{5}$$

for the winding shown in Fig. 2 and

$$\eta(m) = (\varepsilon_c/\varepsilon k)\,(2/m\Delta\varphi)^2 \sin^4(m\Delta\varphi/2) \tag{6}$$

for the winding illustrated in Fig. 3. Then $k = 1 + \pi/(\alpha R\Delta\varphi)$ is the winding elongation coefficient, $\varepsilon_c = \mu_0\sigma_c\delta_c\omega/(\alpha^2\delta_m)$, $\delta_c = 2S\Delta\varphi/(\delta x\delta\varphi)$ and σ_c are the effective thickness and conductivity of the stabilizing winding.

By linearizing (2) we obtain the equations

$$\begin{gathered}[-m^2k - 1 + i\varepsilon(1 - q)]\,\delta b_m = i\varepsilon b_0\delta v_m - i\varepsilon\eta\delta b_m;\\ j^2 \operatorname{Re}(\delta b_m - \varepsilon\eta b_0^*\delta b_m) = 2\,|\,q\,|\,\varepsilon\delta v_m.\end{gathered} \tag{7}$$

Equations (7) define the zero stability condition

$$p_m = \frac{2\,|\,q\,|\,(1 - q)\,\{(1 + m^2k)^2 + \varepsilon^2\,[1 - q + \eta(m)]^2\}}{\varepsilon^2\,(1 - q)^2 - 1 - m^2k - \varepsilon^2\eta^2(m)} - q\,|\,q\,| \tag{8}$$

with the additional requirement that $\varepsilon^2(1 - q)^2 - 1 - m^2k - \varepsilon^2\eta^2(m) > 0$.

In contrast to (31) in [1], equations (7) contain the parameter η(m) specified by the formulas (5) and (6). Since $\eta(m) > 0$, the proposed windings will always enhance the stability. The mode with $m = \pi/\Delta\varphi$ is suppressed by both windings to an equal degree. For the remaining modes the winding corresponding to Fig. 2 is more effective. As an example, one can

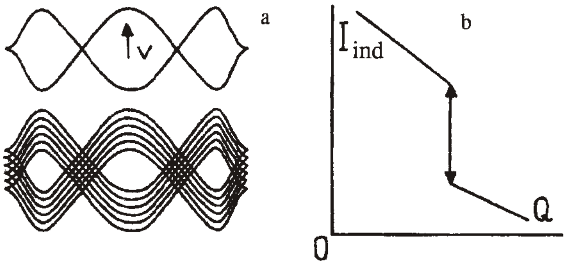

Fig. 4

consider a square-shaped ($R\Delta\varphi = \tau$) copper coil. Its electrical conductivity is five times higher than that of sodium ($\sigma_c/\sigma \approx 5$). If the volume of the stabilizing winding equals that of the sodium in the pump channel, all modes with $m < \pi R/\tau$ within the entire pump volume are found to be suppressed. At the nominal operating point of large pumps, the slippage is selected to be small in order to increase the efficiency. Therefore, there is no need to stabilize the entire pump volume and the stabilizing winding can have a smaller mass. To find out to what extent the instability region can approach the operating point, it is necessary to analyze the excitation level of all modes. Using careful fabrication and alignment, all technological inaccuracies must be reduced to a minimum. In such case, the stabilizing winding must suppress only those perturbations which are produced by the flow turbulence, or exist for other unavoidable reasons.

A Preliminary Experiment. We used an old plane induction pump with two inductors on both sides of the channel. The upper inductor was removed and a stabilizing winding was attached to the upper channel surface. The upper inductor was then replaced. The non-magnetic gap was naturally widened by the thickness of the stabilizing winding, which consisted of shortened turns shaped as a double figure of eight (Fig. 4a), since in plane pumps the principal perturbations arise at the two near-wall channel regions. The stabilization effect was confirmed to some degree in the tests. In one of the turns the induced current was measured; its drop for a specified slippage was also recorded (Fig. 4b).

Conclusions. The proposed stabilizing windings can at least in principle stabilize the azimuthal mode. The windings are complicated and expensive and significantly increase the non-magnetic gap. Nonetheless, they represent means of stabilizing the large pump regime.

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