A REVIEW OF THE MULTIPHASE ELECTRIC MACHINES

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Abstract **– The electrical machines with increased number of phases (m>3) are destined for the equipment of the installations and apparatus that function in autonomic regime and presents a special importance for different industrial branches and electro-mechanical structures, because they have the reliability indexes and increased energetic parameters comparing to the three-phases or direct current electric machines. This paper's aim is the description of the technical documentation in the multiphase machines domain and the elaboration of a list with bibliographical references of the scientific works. Also, are named some of the most important domains of the utilization of the multiphase machines with the presentation of the respective pictures.**

Keywords*: multiphase machines, wind turbine, electro-mechanical structures, symmetrical machines, submersible motor, static converter.*

1. INTRODUCTION

This paper is referred to the description of the constructions of multiphase machines destined for functioning in autonom systems, for example: electric energy generation wind systems [1], [3], [14], [17], [37], electric traction [4], [39], alternators [40], exciters [38], electric propulsion submersible systems [4]. Also in this paper the six-phase asynchronous machine construction, that is destined for the functioning in generator regime, associated with a wind turbine, is analyzed in details. The proposed hexaphase construction gives the possibility of realizing a simple execution of the generator with two pole pairs, having a reduced value of the phase current. Because the voltage at the generator's terminals is not stable the voltage redresses and debits on an accumulator battery, that is ulterior converted and transmitted to the consumer. For the analysis of the electro-mechanical processes were elaborated the mathematical model and the state equations according to which were simulated on the computer the start and transient processes of the sixphases 1 kW asynchronous machine.

2. THE TECHNICAL DOCUMENTATION OF THE MULTIPHASE ELECTRIC MACHINES

2.1. Multiphase machine types

The multiphase machines are produced as generators in the synchronous and asynchronous variants [5], [10], [19], as well as asynchronous motors that can have usual, axial or radial constructions; the synchronous ones can be multiphase with magnetic reluctance of the rotor [21]. The multiphase electric machines (MPEM), by their number of phases are classified by the following expressions in three main categories:

$$m = f(\sigma ; h) = 2^{\sigma}(2h + 1) \qquad (1)$$

where: $\sigma, h = 0, 1, 2, 3, \ldots\ldots n$,

then preceding from this expression the classification of MPEM is made in the following way:

a) M.M with the odd number of phases

$$m \Rightarrow (\sigma = 0 ; h \neq 0), \; m = 3, 5, 7, 9, 11, \ldots$$

b) M.M with the even number of phases

$$m \Rightarrow (\sigma \neq 0 ; h \neq 0), \quad m = 2, 4, 8, 16, \ldots\ldots$$

c) M.M with even-odd number of phases

$$m \Rightarrow (\sigma \neq 0 ; h = 0), \; m = 6, 10, 12, 14, \ldots$$

By its constructive aspect the MPEM. are devised in symmetrical and asymmetrical machines, which is determined by the assembling of the phase winging in stator slots of the magnetic system, better performances having those that have the bigger number of phases: 5, 6, 9, 10, 12.

The asymmetrical machines are recommended in cases, when the supply voltage of the phases is not sinusoidal, in the rest of the cases the MPEM are done with the symmetrical stator winging, not depending on the machine's number of phases. In the symmetrical machines the phase of the winging are placed in space one comparing to the other under an angle of:

$$\beta = \frac{2\pi}{m} ; \qquad (2)$$

electric grades. This way the general scheme of phase repartition of a machine with a majored number of phases has the following form:

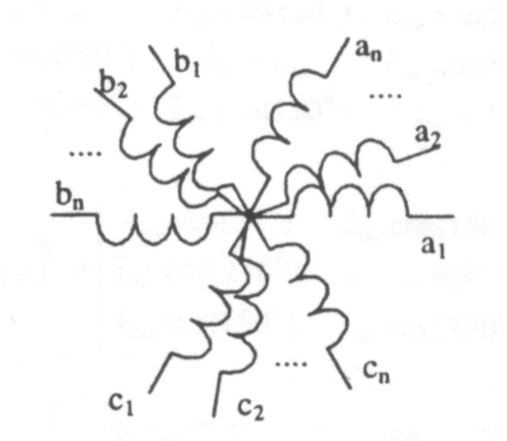

Figure 1 The winging phase repartition of the MPEM

For the voltage supply of the MPEM. is needed a symmetrical system of voltages with the respective number of phases and the following phase difference angle of the phase voltage

$$\alpha = \frac{2\pi}{m} \qquad (3)$$

electric grades, for the case when the machine functions in generator regime, the exit voltage will have the phase difference in accordance with the expression 3.

As supply source of the motor regime functioning machines can serve the static converters of frequency, invertors with voltage PWM modulation with or without current regulation fig. 2:

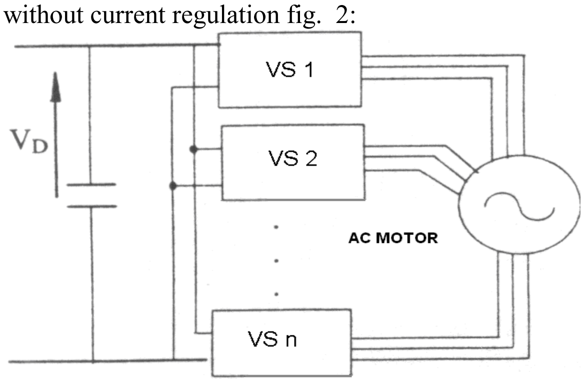

Figure 2 The MPEM connections through invertors

or a group of three-phase transformers with the respective connection group, in the case when the motor has 6 or 12 phases. In the majority of the cases is preferable the fact of supplying them from a inverter because it is possible to study the their behavior as in the symmetrical regimes as well as in asymmetrical regimes [13], plus we are offered a series of advantages at the respective machines' command [2], [7], [10], [14], [16], [20]. The study of the multiphase machines can be made proceeding either from their mathematical model or from the orthogonal coordinates [34], through the repartition of the magnetic flux by domains, or in another words through the finite elements method. The vectorial command gives us the possibility to control the machine through different means, as torque control or the current of frequency control[22], [28], [29], [30], [36].

2.2. The constructive particularities of the multiphase machines

The influence of the phase number on the machine's construction is a quality factor that does not impose essentially changes in construction, with the exception of the stator winging, the number of the phases that varies proceeding from the following expression:

$$m = Z \cdot a / (2p) ; \qquad (4)$$

The stator winging can be realized in a layer or two, having the diametral pitch or shorted for the reduction of the influence of the superior order harmonics, in accordance with the 3 a) and 2 b) figures.

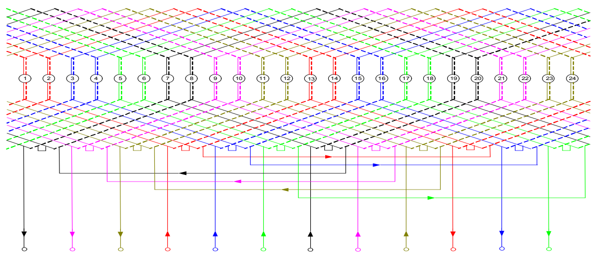

Figure 3. a). The stator winging with diametral pithc step of the hexaphase IM

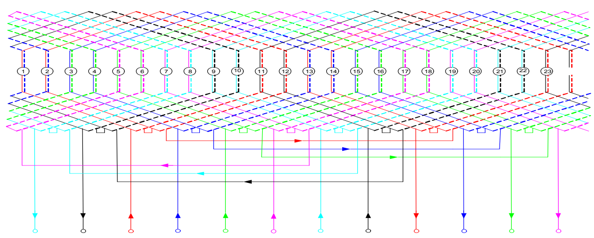

Figure 3. b). The notch winging with shorted pitch of the hexaphase IM

2.3. The multiphase machines utilization domains

The machines with the majored number of phases are applied successfully in the construction of the regulated electric drives that functioning in autonomic regime, like electric propulsion submersible apparatuses (fig.4), electro locations and electro mobiles (fig.5), multiphase synchronous exciters (fig.6), denims and alternators (fig.7), wind installations (fig.8), controlled fans etc. Following are presented the figures of some enumerated domains where are implemented the majored phase number machines.

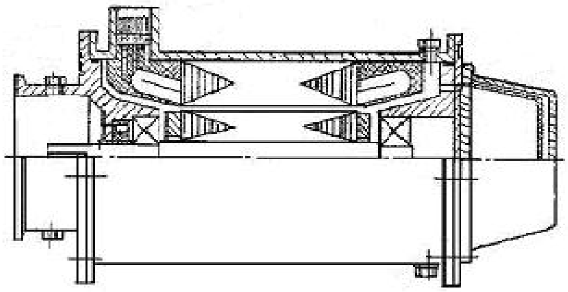

Figure 4. Submersible asynchronic motor with 12 phases for aquatic apparatuses

Figure 5. The multiphase asynchrony motor driven trolleybus

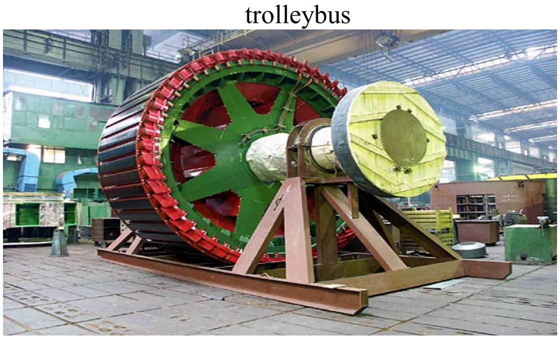

Figure 6. Rotor with 9 phases of the synchronous exciter of a hydrogenerator produced at UCM Reşiţa

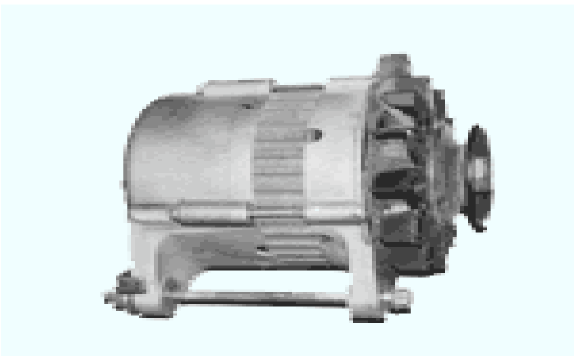

Figure 7. Automotive synchronous generator with 5 phases for tractors with auto-propulsion

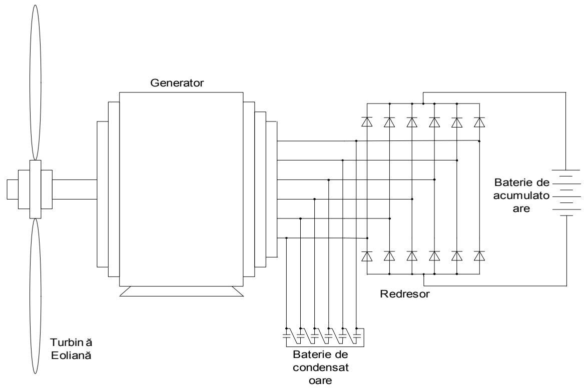

Figure 8. Wind system with six-phase asynchronous generator of the AOL series

3. THE MATHEMATICAL MODEL OF THE HEXAPHASE INDUCTION MACHINES

The hexaphase induction machine represents a machine with 6 phases windings on the stator and the rotor, while the phases can be placed one comparing to another under an angle of 60 electric grades. For the hexaphase induction machine the referential hexaphase study will be more difficult because of the number of the equations that will have to be solved and of these theoretical reasons there sets out to the elaboration of the biphase model of the motor in an referential d – q axes fixed by the stator. At the elaboration of the biphase mathematic model of the hexaphase induction machine general hypothesis of the classic induction machine previously described are accepted, this way obtaining the following model from fig.9.

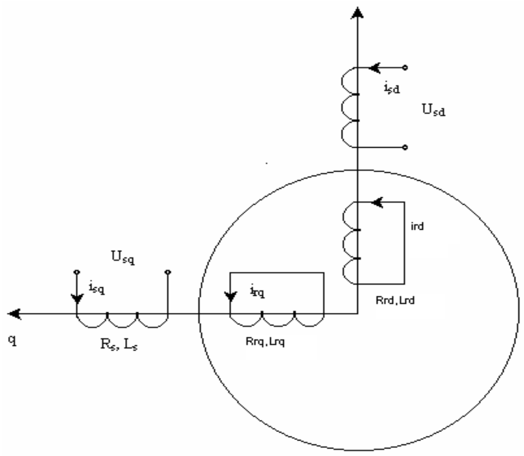

Figure 9. Mathematical model of the hexaphase motor in an referential d – q axes fixed by the stator

For the calculation of the transient processes, in accordance with the adopted work hypothesis is defined the complex spatial vector of the six-phases system by the expression (5):

$$\underline{\Phi}=\frac{2}{m}\left(\underline{1}\Phi_A+\underline{a}\Phi_B+\underline{a}^2\Phi_C+\underline{a}^3\Phi_D+\underline{a}^4\Phi_E+\underline{a}^5\Phi_F\right) \quad (5)$$

where: $\underline{\Phi}$ - represents the six-phase system's space vector that is true for six-phases voltage, current or , flux ; $\underline{1}$, $\underline{a}$, $\underline{a}^2$, $\underline{a}^3$, $\underline{a}^4$, $\underline{a}^5$ – hexaphase system of unitary vectors that is used in this case for positioning and identification in space of the axles of the motor's hexaphase winging.

For avoiding of solving a big number of 12 differential equations that contain inductivities dependent on the rotor's position the hexaphase real machine is replaced by a biphase equivalent machine. The formulas of the base change from 6 to 2 phases is made by the help of proper spacial vector, if over the hexaphase system is superposed a orthogonal system of axles d – q with axles A and d superposed, then the same spatial vector can be expressed by the components of the axles from the stator fixed biphase axles' referential, by the expression:

$$\underline{\Phi} = \underline{\Phi}_d + j\underline{\Phi}_q \quad (6)$$

This way by projecting the spatial vector on the d-q axles for realizing the changing of the motor's equations from the hexaphase to the biphase the following passing matrix is obtained:

$$\begin{bmatrix} \Phi_A \\ \Phi_B \\ \Phi_C \\ \Phi_D \\ \Phi_E \\ \Phi_F \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/2 & \sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \\ -1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ 1/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} \Phi_d \\ \Phi_q \end{bmatrix} \quad (4)$$

With the help of the passing relations from the hexaphase to biphase axle system and through MATLAB programming medium there were simulated transient processes at the functioning and at the start by the following figures 10-12. In accordance with the

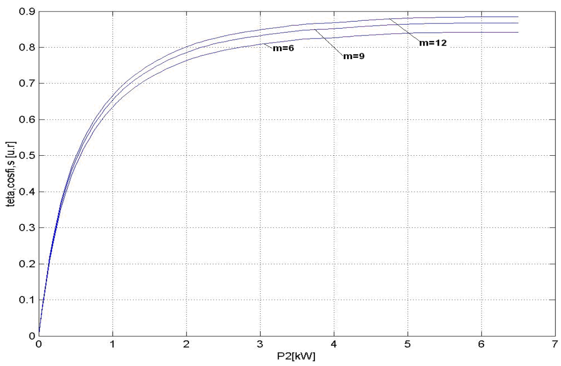

Figure 10. - The M.A.M.'s function characteristics

transient processes modeling the behavior of the multiphase electric machine is studied, and the functioning and start parameters show the grade of stability and determine the function duration. Also through the computer modeling of the multiphase machines can be studied and other advantages that it possesses, like the ones from the projects that follow [6], [8], [9], [11], [15], [18], [20].

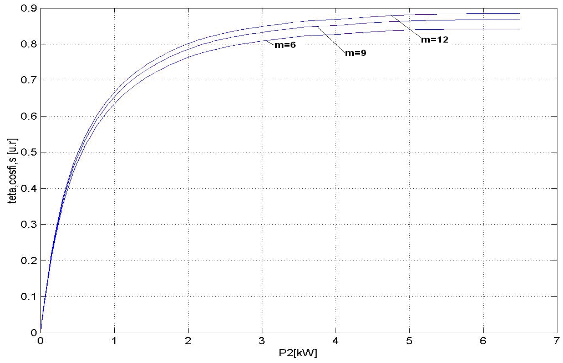

Figure 10. - The hexaphase ansyncronous motor.'s operation characteristics

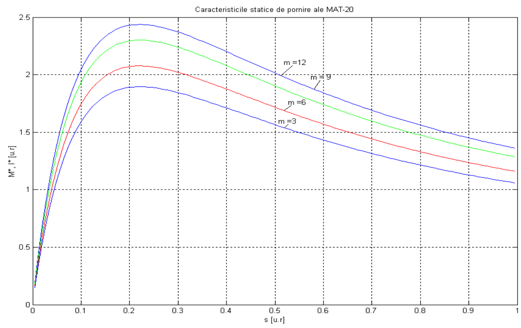

Figure 11. - The mechanical characteristics family M=f(s) at the phase number for the same power

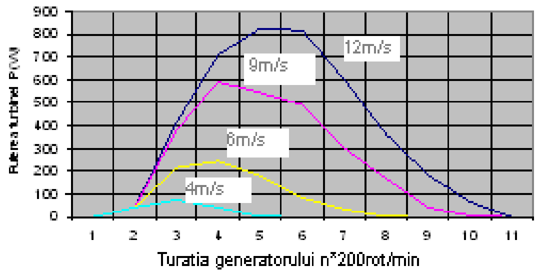

Figure 12. Diagram P=f(n) of the 1 kW 6-phase asynchronous generator

4. CONCLUSIONS

The asynchronous and synchronous machines with the majored number of phases can be successfully used in the construction of different mechanized unit in autonomic regime, because they have the better mechanical characteristics, having majored couples (fig.11) and increased energetic parameters (fig.10). In the construction of the wind installations these can be used in association with a controlled static converter or directly for heating the water or illumination.

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