Synthesis of High Performance PM Motors With Concentrated Windings

Jérôme Cros and Philippe Viarouge

***Abstract*—The windings concentrated around the teeth offer obvious advantages for the electrical machines with radial air-gap, because the volume of copper used in the end-windings can be reduced. The Joule losses are decreased, and the efficiency is improved. These machines are still limited to applications of sub-fractional power and they generally present a reduced number of phases. In the three-phase machines, the concentrated winding is too often restricted to a winding with a short pitch of 120 electrical degrees, i.e., to a winding with performances reduced compared to the traditional structures. But there is a significant number of three-phase structures which can support a concentrated winding if the number of poles is increased. In this article, the authors present a synthesis of the structures of three-phase machines with concentrated windings.**

1) **In the first part, the structures with a regular distribution of the slots are presented. A systematic method is proposed to determine the windings and the performances are discussed.**
2) **In the second part, the authors present original structures of three-phase machines with concentrated windings which use an irregular distribution of the slots. A specific method to identify these structures is described, and a comparative analysis of the performances of the original and traditional structures is performed by using a field calculation software.**

***Index Terms*—Brushless motors, concentrated windings, design of electrical machines, PM motors, windings.**

I. Introduction

THE use of windings concentrated around the teeth offer obvious advantages for the electric machines with radial airgap. With such windings, the volume of copper used in the end-windings can be reduced in significant proportions, in particular if the axial length of the machine is small. Furthermore, a significant reduction of the Joule losses is achieved, and the efficiency of the motor is improved when compared to more traditional structures with one slot per pole and per phase for example [1], [2], [10]. This winding structure is also easier to realize than a lap winding and the number of coils is reduced. However, the use of these machines is still limited to applications of sub-fractional power (lower than 50 W) such as motor for electric fans or computer peripherals [3], [11]. These motors also generally present a reduced number of phases (one or two) to respect the constraints of manufacturing cost [3].

In the case of the three-phase machines, the concentrated winding is too often associated and restricted to a winding with a short pitch of 120 electric degrees, i.e., to a winding with performances reduced compared to the traditional structures. But there is a significant number of three-phase structures which can support a concentrated winding if the number of poles is increased. These structures present a fractional number of slots per pole and per phase. The principal difficulty for the study of these machines lies in the determination of their winding and in particular the order of the phases under each pole.

The author present a synthesis of the structures of three-phase machines with concentrated windings. In the first part, the structures with a regular distribution of slots are presented. A systematic method is proposed to determine the windings and the performance are discussed. In the second part, the authors present original structures of three-phase machines with concentrated windings which use an irregular distribution of slots. These machines are simplified versions of traditional machines and offer similar performances. A specific method to identify these structures is then described, and a comparative analysis of the performances of the original and traditional structures is performed by use of a field calculation software.

II. Structures of Electrical Machines With a Regular Distribution of Slots

The various combinations of slots and poles which allow the realization of a balanced winding can be determined by the relation (1) in the case of the three-phase machines [4]

$$\frac{S}{[\mathrm{GCD}(S, 2p)]} = 3k \tag{1}$$

where S is the number of slots, p the number of pairs of poles and k an integer number. (GCD: Greatest Common Divisor). The number of slots per pole and per phase is defined by

$$S_{pp} = \frac{S}{2p \cdot m} \tag{2}$$

where m is the number of phase.

The three-phase machines which can be equipped with a concentrated winding have a number of slots per pole and per phase less than or equal to $1/2$. Table I in appendix gives a list of the various structures where it is possible to obtain a balanced concentrated winding. In this table, the winding coefficient of the fundamental component is used to characterize the performances of each structure. This coefficient is defined as the ratio between the flux embraced by each turn and the flux produced by the excitation mmf [5]. Its value is less or equal to unity. It will be shown that the performance of the machine is directly related to the value of this ratio for a sinusoidal current supply and also for a rectangular current supply. In the case of a traditional machine with one slot per pole and per phase, the winding coefficient of the fundamental component is equal to one in the case of an armature where the slots are not skewed. The same coefficient is reduced to 0.955 when the slots are skewed.

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TABLE I
COMBINATIONS OF NUMBER OF SLOTS (S) AND POLES ($2p$) ALLOWING THE REALIZATION OF THREE-PHASE MACHINES WITH A BALANCED CONCENTRATED WINDING

S \ 2p	2	4	6	8	10	12	14	16	18	20	22	24
3	1/2 .866	1/4 .866		1/8 (.866)	1/10 (.866)		1/14 (.866)	1/16 (.866)		1/20 (.866)	1/22 (.866)	
6		1/2 .866		1/4 (.866)	1/5 (.866)		1/7 (.866)	1/8 (.866)		1/10 (.866)	1/11 (.866)	
9			1/2 .866	3/8 .945	3/10 .945	3/12 (.866)	3/14 (.945)	3/16 (.945)		3/20 (.945)	3/22 (.945)	
12				1/2 .866	***2/5*** .966		***2/7*** (.966)	1/4 (.966)		1/5 (.866)	***2/11*** (.966)	
15					1/2 .866		5/14 .866	5/16 .866		1/4 (.866)	5/22 (.951)	
18						1/2 .866	3/7 .945	3/8 .945		3/10 .945	***3/11*** (.902)	1/4 (.866)
21							1/2 .866	7/16 .932		7/20 .953	7/22 .953	
24								1/2 .866		***2/5*** .966	***4/11*** .957	

In Table I, the winding coefficient lies between brackets when it is possible to artificially increase the winding pitch by using the tooth tips like horns of the traditional pole pieces used in DC or synchronous machines to collect and concentrate the air-gap flux. This situation occurs when the number of slots per pole and per phase is lower than $1/3$.

The structures which can use a concentrated winding with only one layer, are also identified in Table I (S_{pp} underlined) character. In these machines, the reduced number of coils equal to $S/2$ greatly simplify the realization and the assembly.

A. Determination of the Winding

Generally, to localize the conductors of each phase in the slots, it is preferable to apply a method similar to that used for the large synchronous machines with a fractional number of slots per pole and per phase [4]–[6].

This method is based on the decomposition of the number of slots per pole and per phase S_{pp}. For values below unity, S_{pp} must be reduced to a fraction of two non divisible integers b and c

$$S_{pp} = \frac{b}{c}. \tag{3}$$

A repeatable sequence of 0 and 1 specific to the winding can be derived from this relation. It is a list of c numbers which characterizes the number and the distribution of the larger and smaller pole-phase groups under $c/3$ poles. The structure of the whole winding of the machine can be derived from a periodic distribution of the structure under c poles described by 3 consecutive repeatable sequences if c is an even number. If c is an odd number, this distribution is antiperiodic. The number of "1"

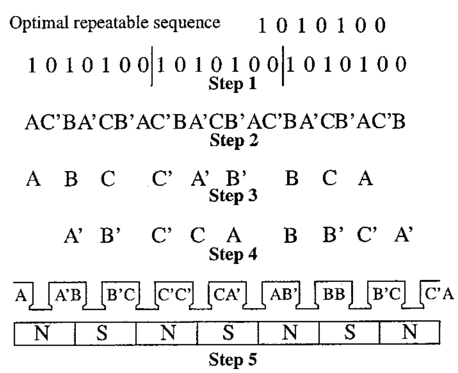

Fig. 1. Determination of the concentrated winding of a three-phase machine with 18 slots and 14 poles (antiperiodic symmetry of the winding under seven poles).

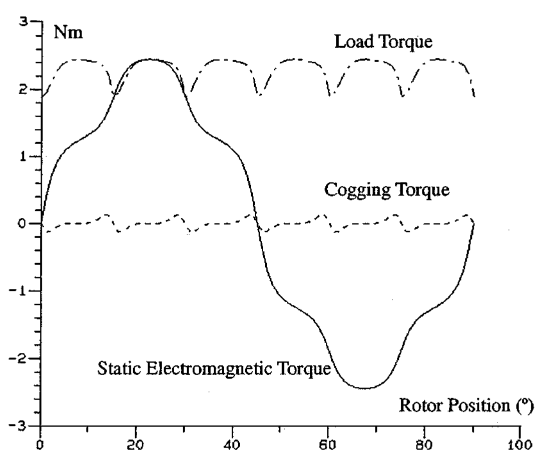

Fig. 2. Torque components of a machine with $S_{pp} = 1/2$ and a rectangular distribution of induction in the air-gap.

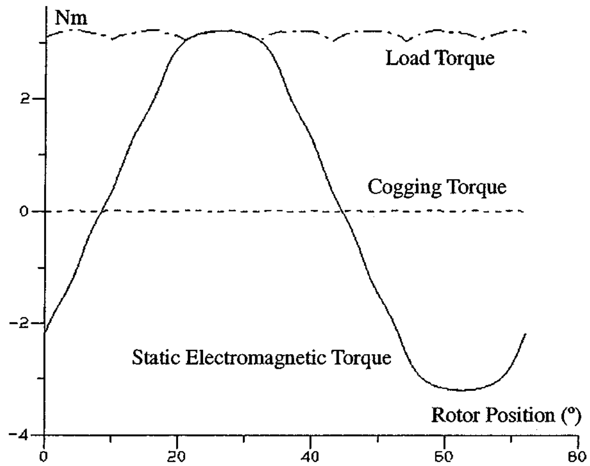

Fig. 3. Torque components of a machine with $S_{pp} = 2/5$ and a rectangular distribution of induction in the air-gap.

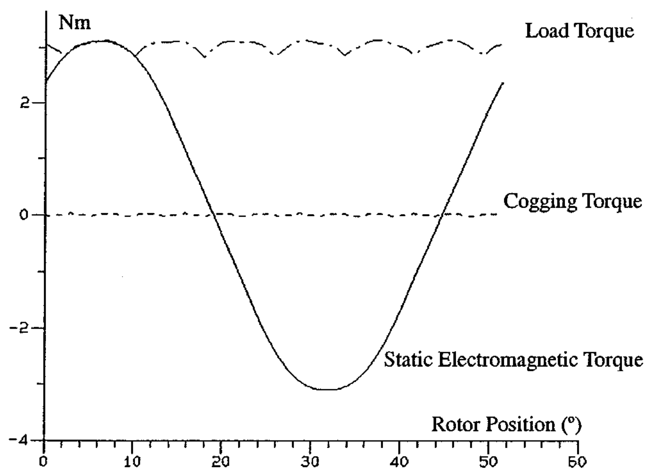

Fig. 4. Torque components of a machine with $S_{pp} = 2/7$ and a rectangular distribution of induction in the air-gap.

in the sequence is equal to b and the number of "0" is equal to $b - c$. The initial repeatable sequence can then be described by

$$\overbrace{\underbrace{0\,0\,0 \cdots 0}_{c-b} \quad \underbrace{1\,1\,1 \cdots 1}_{b}}^{c}.$$

For a given structure, the winding with the highest performance can be obtained by the most regular distribution of the numbers "1" among the numbers "0." For example, in the case of a three-phase machine with 18 slots and 14 poles ($S_{pp} = 3/7$), the initial repeatable sequence of the winding is composed of four "0" and three "1"

Initial repeatable sequence 0 0 0 0 1 1 1.

The winding with the highest performance can be obtained with the following repeatable sequence.

The structure of the whole winding can be determined in five steps (cf. Fig. 1).

1) In a first step, the repeatable sequence is reproduced three times.

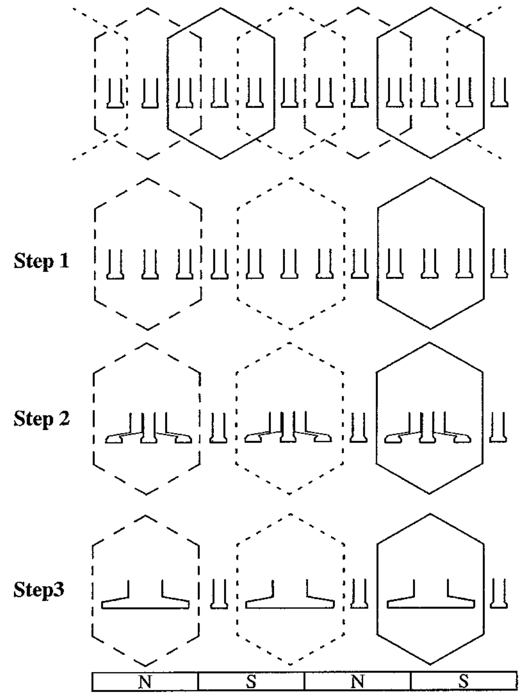

Fig. 5. Determination of a machine with concentrated windings and an irregular distribution of slots from an initial machine with 12 slots and four poles.

2) In the second step, the usual phase sequence AC'BA'CB' is associated to the whole sequence (A' characterizes the return conductor corresponding to conductor A).
3) In the third step, the conductors associated to the numbers "1" of the sequence are selected to make the first layer of winding. Generally, this layer of winding cannot be directly realized to form a concentrated winding but this realization is possible in particular cases listed in Table I.
4) In the fourth step, the second layer of the winding is obtained by reproducing and shifting the initial layer by a tooth or a slot width.

The direction of the each conductor must be also reversed. The final structure of the winding of a three-phase machine with 18 slots and 14 poles can be checked in the last step.

B. Performance Analysis of the Machines With a Regular Distribution of Slots and Concentrated Windings.

The machines with a number of slots per pole and per phase equal to $1/2$ are structures with concentrated windings and a short pitch of 120 electric degrees. Their performances are relatively low in the case of a supply with sinusoidal currents. The winding coefficient of the fundamental component is only equal to 0.866. In the case of a rectangular current supply and with a smooth rotor using surface-mounted permanent magnets, the no-load emf generated in the windings does not present a flat portion with a sufficient width. The torque ripple is then important when the motor is loaded (cf. Fig. 2). This kind of machine can be used only for low power applications where there is no particular constraint on the torque ripple.

The machines with a number of slots per pole and per phase between $1/2$ and $1/3$, generally present higher performances than the preceding structures [10], [12], [13]. The machine with 12 slots and ten poles is particularly interesting: it can support a

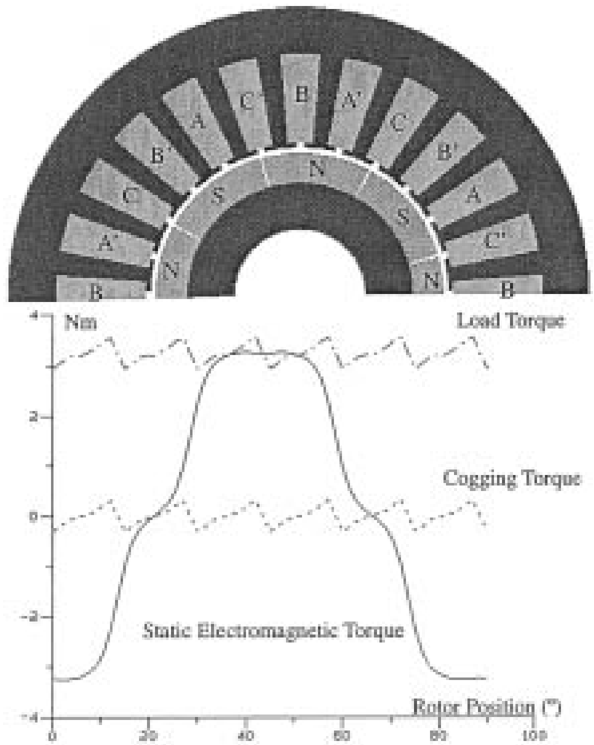

Fig. 6. Structure and torque components of a machine with 24 slots-8 poles ($S_{pp} = 1$). Full pitch winding.

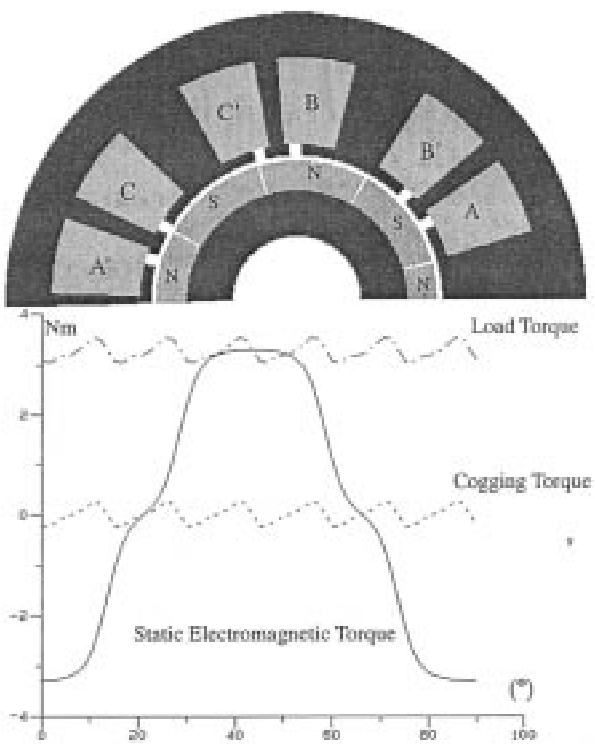

Fig. 7. Structure and torque components versus rotor position of a machine with concentrated windings, six coils, eight poles and an irregular distribution of slots with two different widths.

concentrated winding with one layer (cf. Fig. 3) and its torque ripple is low. Moreover, these structures present also a no-load cogging torque of low amplitude taking into account the high

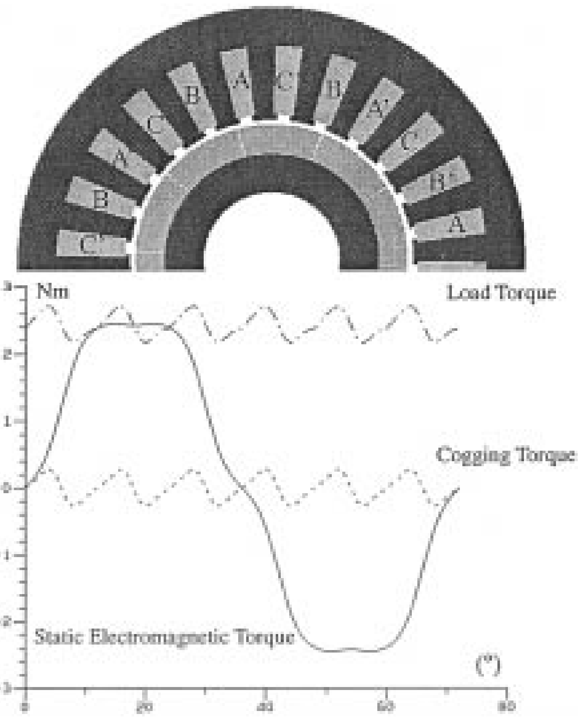

Fig. 8. Structure and torque components versus rotor position of a machine with 30 slots, ten poles, and a winding with diametral pitch ($S_{pp} = 1$).

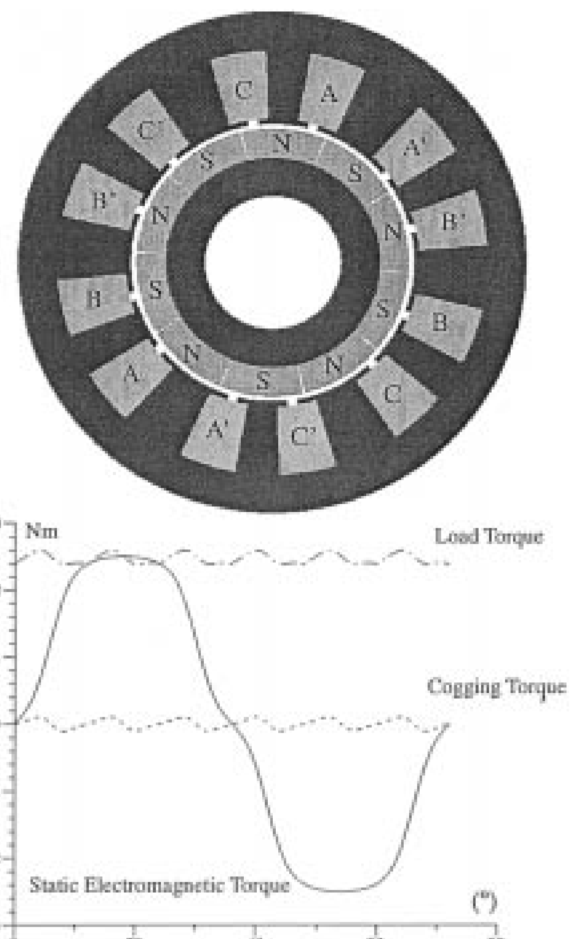

Fig. 9. Structure and torque components versus rotor position of a machine with six concentrated coils, ten poles, and an irregular distribution of slots.

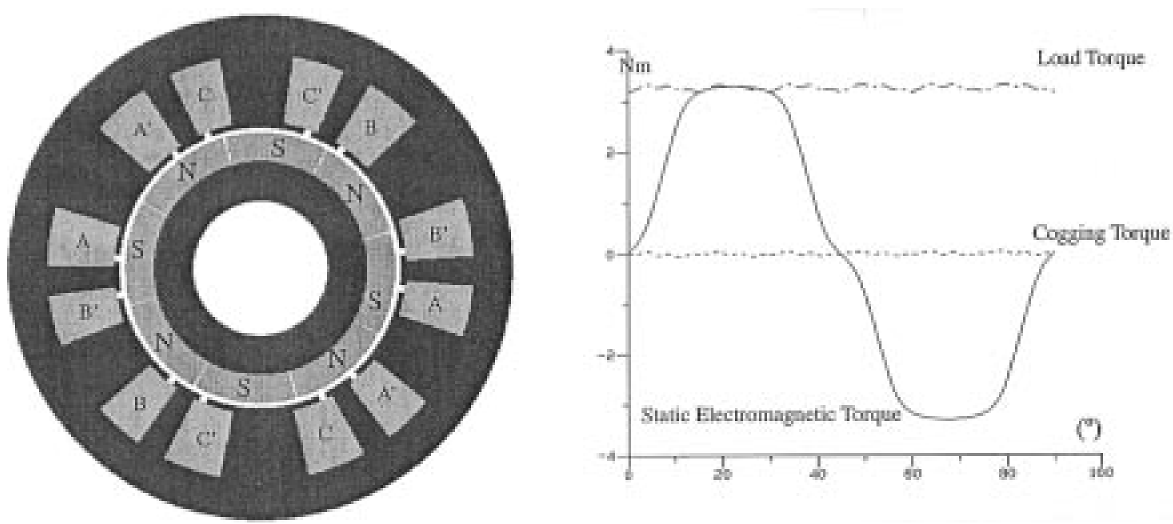

Fig. 10. Structure and torque components versus rotor position of a machine with six concentrated coils, eight poles, and an irregular distribution of slots with three different widths.

relative value of its frequency. For each revolution of the rotor, the number N of pulsations of this no-load cogging torque can be derived from the least common multiple of S and $2p$

$$N = \mathrm{LCM}(S, 2p). \tag{4}$$

To cancel the no-load cogging torque, it is possible to skew the slots with an angle equal to a fraction of the slot pitch. The skewing angle α can be derived from

$$\alpha = \frac{2\pi}{S}. \tag{5}$$

In the case of the machines with a number of slots per pole and per phase lower than $1/3$, it is possible to adjust the width of the tooth tips to a value close to the dimension of the pole pitch to increase the magnetic flux embraced by the winding.

The structures with a number of slots per pole and per phase between $1/3$ and $1/4$ are the most interesting and the value of their winding coefficient is high. The structure with 12 slots and 14 poles is using a winding with one layer and its static electromagnetic couple is more sinusoidal than in the preceding structure (cf. Fig. 4). This structure is more suitable for a supply with sinusoidal currents.

The torque developed by the structures with a number of slots per pole and per phase equal to $1/4$ or lower is more sinusoidal but decreased. In the case of a rectangular current supply, it is then preferable to use stators with an irregular distribution of slots which present higher performances.

III. Special Machines With Concentrated Windings and an Irregular Distribution of Slots

A. Determination of the Machines With Concentrated Windings and Irregular Distribution of Slots

These machines can be derived from machines with a number of poles higher than two. The arrangement of the stator coils must be modified to eliminate the tangle of the end-windings and to concentrate the winding. The total quantities of iron and copper used in the machine must be preserved to respect the constraints of saturation and to preserve the performances of the original machine.

A machine with 12 slots and four poles $(S_{pp} = 1)$ is chosen for the illustration of this approach. In a first step, the coils which prevent a concentration of the winding are removed (cf. Fig. 5). It is obvious that it is necessary to remove the same number of coils in each phase to keep a balanced winding. During the second step, one modifies the arrangement of the stator slots by an association of the teeth which are localized on each side of the empty slots. The original widths of the teeth are preserved to respect the constraints of saturation. With this method, the remaining slots can be increased to preserve the total quantity of copper used in the slots of the original machine. During the final step, the space between the tips under the main teeth is filled to obtain a true polar horn. One obtains a final structure of machine with three coils, three main teeth and three auxiliary teeth. Because the teeth do not have the same width (cf. Fig. 5), it is possible to define this structure as a machine with concentrated windings and an irregular distribution of slots. The respective performances of the new and original machine are similar, but the performances of the new structure are higher than in the case of a machine with a regular distribution of three slots and four poles $(S_{pp} = 1/4)$. Furthermore, a significant reduction of the copper volume and the Joule losses in the end-windings has been obtained in the new machine, when it is compared to the original machine with 12 slots and four poles.

B. Analysis of Machines With Irregular Distribution of Slots

In this part, several structures of three-phase machines using a smooth rotor and surface-mounted magnets (i.e., with a rectangular spatial distribution of induction in the air-gap), supplied by rectangular currents are analyzed. One compares the performances of machines with an irregular distribution of slots with the original machine by taking care to preserve identical dimensions for the rotor and the air-gap, the same volume of copper in the machine, the same quantity of iron in the teeth and the yoke and the same value of rated current.

The first example relates to a machine with 24 slots and eight poles (cf. Fig. 6) which can be modified to obtain a machine with six coils, eight poles, six main teeth and six auxiliary teeth according to the preceding method (cf. Fig. 7). One can note a very good agreement between the torque characteristics of both structures. The electromagnetic torque which presents the same shape as the no-load line to line emf, is similar in both machines. In this comparative analysis, one did not try to minimize the cogging toque but it is always possible to use various techniques to reduce its amplitude (slots skewing, optimization of the relative widths of the tooth tips and the magnets) [2], [7].

In this second example, the machine with an irregular distribution of slots is derived from a three-phase machine with 30 slots and 10 poles $(S_{pp} = 1)$ (Fig. 8). A machine with six coils, 10 poles, six main teeth which support the winding and six auxiliary teeth (Fig. 9) is obtained. One can still note a very good agreement between the respective torque characteristics which are presented on Figs. 8 and 9.

The last example shows that it is also possible to design a machine with concentrated windings and an irregular distribution of slots by starting from an original machine with a fractional number of slots per pole and per phase. It is interesting because it is possible with these specific structures to directly minimize the cogging torque without skewing the slots [8]. Some coils can also be removed to maximize the winding coefficient of the fundamental component [8]. The following machine is obtained by starting from an original three-phase machine with 45 slots and eight poles with a winding coefficient of the fundamental component equal to 0.99. There are six coils and an irregular distribution of teeth with three different widths (cf.). One can note that the cogging torque of this machine is weak (cf. Torque components on Fig. 10). The electromagnetic torque presents also a flat portion of sufficient width to limit the torque ripple at the rated point of operation. Thus, a machine with concentrated windings which presents excellent performances has been obtained.

IV. Conclusion

A synthesis of the three-phase structures with concentrated windings has been presented which demonstrates the performances of these machines compared to traditional machines with one slot per pole and per phase. The performances of the machines with concentrated windings are higher than the performances of the traditional machines, because the minimization of both copper volume and Joule losses are reducing the manufacturing costs and improving the output characteristics. The industrial development of these structures should increase in the near future and it should also not be restricted only to low power applications. The production process of these machines will be also simplified by use of new soft magnetic composites (SMC): with this type of material, indeed, it is possible to produce the stator in several pieces, to install the pre-fabricated concentrated windings in the fully opened slots, and to complete the final assembly by installing the tooth tips [2], [9], [10].

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