ATEE-2004

LINE STARTING OF THE THREE-PHASE SQUIRREL CAGE INDUCTION MOTOR USING PARTIAL WINDING PARALLEL PATHS

Mihai V. CISTELECAN, Gloria CIUMBULEA, Mircea COVRIG

"POLITECHNICA" University, Bucharest

Abstract *The starting of the three phase induction motors using partial winding parallel paths is analysed in the paper taking into account the upper space harmonics of the air gap mmf. Using the Fourier analysis of the air gap field it is shown the best way to choose the parallel path connection, the average pitch of the coils and the number of turns/coil in order to minimise the noise during starting and to obtain satisfactory starting performance (torque and current). Examples are given for four poles, 48 slots induction motor, in order to compare different winding arrangements.*

INTRODUCTION

One of the lowest cost method of reducing the starting current for standard induction motors consists in applying the line voltage to only a part of the winding at first, and connecting the rest of the winding after the motor is started. Usually the three phase winding of the motor is designed with two parallel circuits (parallel path or parallel conductors) in each phase and the voltage is applied initially to only one circuit (half-winding starting). Whether or no the motor comes up to speed on the half winding, the other half is energized after a few seconds delay.

The decreasing of the line current is dependent on the design parameters of stator/rotor circuits, especially the phase resistance and leakage reactance. Usually the resulting impedance at standstill ranges from 125 to 175% of that when the two parts are connected together to the line. Thus, the current drawn from line is about 66% of the normal starting current and the starting torque is about 50% of it. This is the a major advantage of the method, and it offers the possibility of obtaining better starting performance in comparison with the known star-delta starting, by proper design of the motor parameters.

However, as it is noted in the literature [1, 2], even it is not deeply analysed, the part-winding starting is not free from noise problem, and dips in the torque curve are usually present with the connection that energizes only half of the winding. The noise may be too objectionable for many equipments and the dip or reduction in torque at some speed may prevent the motor from reaching full speed if the parallel circuits are not properly designed.

The problem of the part-winding starting is not at all a new one. Alger [3] and Courtin [4] have studied the fundamental conditions for separation of the winding paths in order to avoid the dips in the starting torque curve and the noise and vibration during starting. The general rules, proved experimentally and currently applied in the four poles motors, are related to uniform distribution of the phase coils of the paths around the periphery of the armature as alternate groups connection [4]. However the more recent papers [5] show that there are more improvements in the analysis method to be applied in order to obtain better performance regarding starting torques and starting currents.

In the paper the part-winding starting of the three phase induction motors is analysed from the air-gap magnetic field point of view regarding the winding factors of clockwise (CW) and counter-clockwise (CCW) waves. The special attention is paid to even order space harmonics which compulsory appear in the single path air gap mmf when the windings configurations are different from one pole to another. Examples of analysis are given for 4-poles, 48 slots induction motor in order to show how the mmf space harmonic content can be improved.

METHOD OF MAGNETOMOTIVE FORCE (MMF) ANALYSIS

The phase mmf can be analysed starting from the input current and the actual distribution of the coil branches in the slots. If the geometrical space angle of the slot k is θ_k and it contains N_{ck} conductors of phase A, w is the total number of turns per phase, c is the number of parallel path, $k_{w\nu}$ the ν-order phase winding factor and $\varphi_{\nu A}$ the space angle of the ν-order space harmonic, the general equations of the winding distribution are [6]:

$$2cwk_{w\nu A} = \sqrt{\left(\sum_{k\in\{K_A\}} N_{ck}\cos\nu\theta_k\right)^2 + \left(\sum_{k\in\{K_A\}} N_{ck}\sin\nu\theta_k\right)^2}\;;\quad \varphi_{\nu A} = \frac{1}{\nu}\,arctg\,\frac{\sum\limits_{k\in\{K_A\}} N_{ck}\sin\nu\theta_k}{\sum\limits_{k\in\{K_A\}} N_{ck}\cos\nu\theta_k} \tag{1}$$

The set of the armature's slots containing conductors of phase A was noted by K_A. The number of conductors N_{ck} is including the sign (±) depending on the current sense in the respective slot. Taking into account that generally the windings of the three phase machines are space delayed by $2\pi/3$ the amplitude of the CW and CCW mmf waves are given by:

$$(CW)_\nu = \frac{2}{3}\sqrt{C_{1\nu}^2 + C_{2\nu}^2}\;;\quad (CCW)_\nu = \frac{2}{3}\sqrt{D_{1\nu}^2 + D_{2\nu}^2} \tag{2}$$

where the coefficients C, D, for odd and even harmonics are:

$$\begin{aligned} C_{1\nu} &= \frac{1}{2}\left[k_{wA\nu}\cos\varphi_{\nu A} + k_{wB\nu}\cos(\varphi_{\nu B} + \frac{2\pi}{3}) + k_{wC\nu}\cos(\varphi_{\nu C} - \frac{2\pi}{3})\right] \\ C_{2\nu} &= -\frac{1}{2}\left[k_{wA\nu}\sin\varphi_{\nu A} + k_{wB\nu}\sin(\varphi_{\nu B} + \frac{2\pi}{3}) + k_{wC\nu}\sin(\varphi_{\nu C} - \frac{2\pi}{3})\right] \end{aligned} \tag{3}$$

$$\begin{aligned} D_{1\nu} &= \frac{1}{2}\left[k_{wA\nu}\cos\varphi_{\nu A} + k_{wB\nu}\cos(\varphi_{\nu B} - \frac{2\pi}{3}) + k_{wC\nu}\cos(\varphi_{\nu C} + \frac{2\pi}{3})\right] \\ D_{2\nu} &= -\frac{1}{2}\left[k_{wA\nu}\sin\varphi_{\nu A} + k_{wB\nu}\sin(\varphi_{\nu B} - \frac{2\pi}{3}) + k_{wC\nu}\sin(\varphi_{\nu C} + \frac{2\pi}{3})\right] \end{aligned} \tag{4}$$

The amplitudes of the magnetic waves calculated by eq. (2) are calibrated by the factors 2/3 in order to be comparable by the phase mmf winding factors. Starting from the Fourier analysis of the mmf developed in the air-gap by the separate parallel paths of the winding, it can be pointed out, using the previous equations, the existence of the even space harmonics, the most important being the 2-th and 4-th space harmonics. These harmonics do exist always when the winding structure under one pole is different from the winding structure under the adjacent pole. This is generally the case when the parallel paths are divided using the criteria of "alternate poles connection" [1, 2] where all the "north" poles and all the "south" poles are connected together in the two different parallel paths. It these cases, smaller the coil pitch in comparison with the diametrical pitch leads to bigger even space harmonics [3, 4].

In the literature it is pointed out that it is always desirable to connect alternate magnetic poles in one half winding. This ensures balanced air-gap forces, and if the two layers winding is used, the second (and generally the even) space harmonics of the air gap mmf can be kept to the low values. However, as show results from the analysis developed in the paper, the even space harmonics of the two parallel path of the winding are in opposition from the phase point of view, that means they are cancelling in the normal running condition. This fact proves that the criteria to design winding with parallel paths in order to use part-winding starting are different from the general criteria for dividing the phase current and to use thinner wire. As it will be proved in the next section of the paper, the method to cancel the second order mmf space harmonic is to mix the coils under all the poles (north and south) in each parallel path.

In case of irregular windings it happens to have even so called “impure” waves that means the same space harmonic could have simultaneously CW and CCW component. It is the case, for example, of some arrangements from the totally of ten studied in the Courtin’s paper [4]. However, as it is known, the CW upper harmonics are more dangerous then the CCW harmonics as the crawling point (proper synchronous speed) is situated in the range of the main space harmonic.

RESULTS OF ANALYSIS

The results of the analysis lead to the possibility of using two parallel conductors as two parallel paths as the best way to avoid the noise during starting and the dips in the starting torque. In this case there are no any difference between the mmf of the paths and the total, resulting mmf. However in this case there are some limitations in dividing the cross section of the wires in order to perform the windings using normal coils. The space harmonic content of the mmf is exactly the same in the part winding starting and the total winding in the normal running period, that means all the even space harmonics will be cancelled if the starting winding is a regular one. The problems regarding the noise increase or torque dips are avoided in that case.

A usual case is that of 4-poles, 48 slots winding, used for induction motors up to 100 kW. The double layers, lapped equal coils, 10-slots pitch is presented in the figure 1. For more clarity only one phase is full represented in the drawing, the resulting two phases having exactly the same connections between the coils. This is why only the beginnings of the phases B, C are shown, delayed by 8 and 16 slots, respectively. The first connected is the path A_1-A_1’ and after starting the second parallel path A_2-A_2’ is connected to the line voltage.

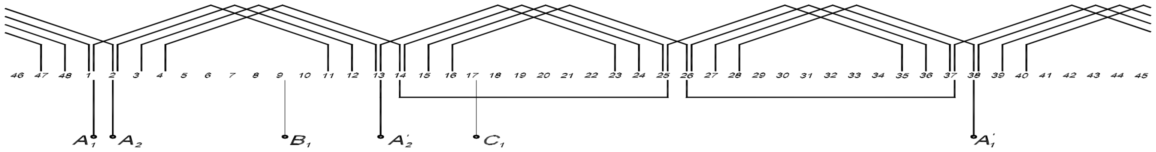

Fig. 1 Double layer, lapped coils, 48-slots, 4-poles, 2-parallel paths
3-phase alternate pole connected winding

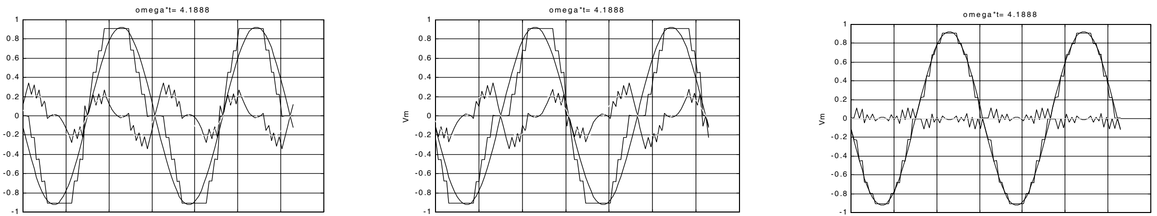

Fig. 2. The air gap mmf vs. space angle (first path, second path, full winding)
for 48 slots, equal lapped coils, 4-poles, double layer motor (figure 1)

In the figure 2, the air gap mmf analysis (resulting – stair curve, fundamental – close to the stair curve and differential) is presented for the two parallel path working separately and together, for the winding in the figure 1. The mmf is scaled as for the phase fundamental winding factor. The harmonic content of the rotating waves is given in table 1 up to 11-th order space harmonics.. One can see the difference between the resulting mmf of single path operation (there are even space harmonics) and the full winding operation. The result could be explained by the fact that the even space harmonics are in opposition in the two parallel path and in the case of the full winding, when the two parallel path are working together, the even harmonics are cancelling each other.

However one can see the magnitude of the 2-nd space harmonic, as this is the main component in the differential mmf (figure 2). The differential mmf in the full winding is almost negligible. In all the cases, what it is usual, the third and generally the 3k-th space harmonics are cancelling together because they are in-phase for regular windings. As one can see the full winding will produce only pure odd harmonics of orders 1, 5, 7, 11, ...(6k±1).

Table 1. Resulting winding factors vs. space order ν for winding in figure 1

Harmonic order, ν	Path no. 1		Path no. 2		Full winding	
	CCW	CW	CCW	CW	CCW	CW
1	-	0.9250	-	0.9250	-	0.9250
2	-0.4183	-	0.4183	-	0	-
4	-	-0.3750	-	0.3750	-	0
5	-0.0531	-	-0.0531	-	-0.0531	-
7	-	-0.0408	-	-0.0408	-	-0.0408
8	0.2165	-	-0.2165	-	0	-
10	-	-0.1121	-	0.1121	-	0
11	-0.1218	-	-0.1218	-	0.1218	-

In the literature it is usual to characterise the upper harmonics (including the fractional harmonics) by the coefficient of differential leakage τ_d [6]. If L denotes the total inductance of the winding, inclusive of all higher harmonics and sub-harmonics inducing in the same winding a voltage mains frequency and L_p is the inductance corresponding to a working field having p pole pairs, then the differential leakage coefficient is defined by:

$$\tau_d = \frac{L}{L_p} - 1 = \frac{\sum\limits_{\nu} L_\nu}{L_p} - 1 = \sum_{\nu \neq p} \left(\frac{k_{w\nu}}{\nu} \right)^2 \tag{5}$$

For the analysed winding in figure 1 one can obtain τ_d=0.071 (single parallel path) and τ_d=0.0061 for the full winding. Comparing with the known windings from literature the single parallel path of the winding in figure 1 has the behaviour as the known concentrated winding [6].

The space harmonic content, especially from the even order harmonics point of view can be improved if each of the parallel paths contains coils under all of the poles. As it is presented in the figure 3 the 48-slots, 4-poles winding can be developed using concentric coils with openings of 11, 9 and 7 slots pitch. The biggest coil is situated alone in the slots as a single layer, the medium coil (9 slots pitch) and smallest coil (7 slots pitch) have situated their branches together in the same slots. In order to have the same slot filling factor the number of turns of the last two coils have to be determined correspondingly.

Each parallel path (for example full line in the figure 3) contains two concentric coils under a pole (the group with 11/7 slots pitch) connected in series with the single coil (9 slots pitch) under the adjacent pole. To cancel the 2-th space harmonic one can use the simple formula for winding factors in the case of concentric groups [7]:

$$k_{w\nu} = \sum_i w_i^{'} \sin\frac{\nu\gamma_i}{2} - (-1)^\nu \sum_k w_k^{'} \sin\frac{\nu\gamma_k}{2} \tag{6}$$

where the first inner sum corresponds to the coils placed under a pole and the second one to the coils under the adjacent pole; the magnetic axis of the two groups of coils are delayed with

π and the mono-axial character of the winding can be observed. The number of turns of the coils is expressed in p.u. related to the total number of turns per pole pair and the openings of the coils (γ_i, γ_k) are expressed in electrical units. One can observe that if the 11-slots pitch coil has half (0.5) of total number of turns, the 9-slots pitch coil has 0.366 turns and the 7-slots pitch coil has 0.134 turns, the 2-th space harmonic will disappear. In this case the 4-th space harmonic will have a reduced value (0.049 instead of 0.375) and all the slots will contain the same number of conductors, that means constant filling factor. In figure 4 are presented the air gap mmf for the first path, the second, and for the full winding.

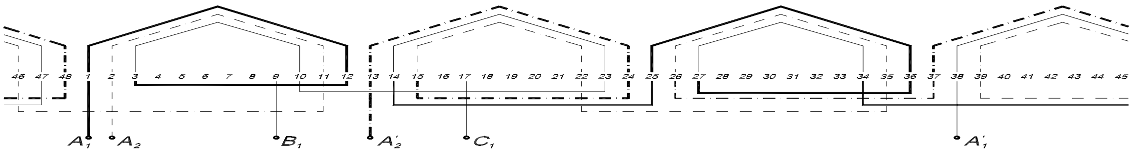

Fig. 3 Partial single/double layer (50%), concentric coils, 48-slots, 4-poles, 2-parallel paths special connected 3-phase winding

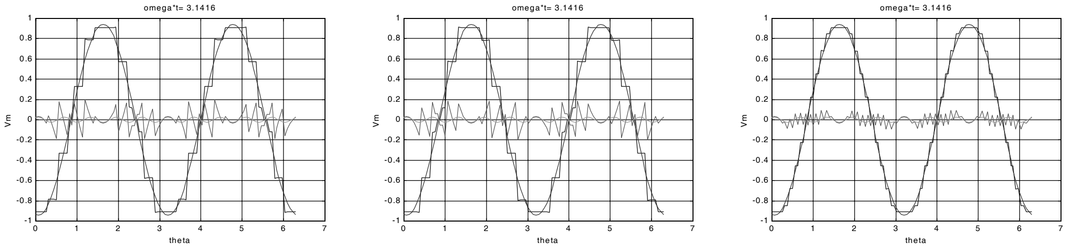

Fig. 4 The air gap mmf vs. space angle (first path, second path, full winding) for 48 slots, concentric coils, 4-poles, single/double layer motor (figure 3)

In the table 2 are given the performance of the winding from figure 3. One can see that the winding have a better behaviour than the initial one, even the main space harmonic winding factor is 1.64% bigger (0.9402 instead of 0.925). The differential leakage coefficient is in this case 0.0216 for single parallel path operation (instead of 0.0711 in the first case) and 0.0064 for full winding operation.

Table 2. Resulting winding factors vs. space order ν for winding in figure 3

Harmonic order, ν	Path no. 1		Path no. 2		Full winding	
	CCW	CW	CCW	CW	CCW	CW
1	-	0.9402	-	0.9402	-	0.9402
2	0	-	0	-	0	-
4	-	0.0490	-	-0.0490	-	0
5	0.1238	-	0.1238	-	0.1238	-
7	-	0.0513	-	0.0513	-	0.0513
8	0.3170	-	-0.3170	-	0	-
10	-	0.7765	-	-0.7765	-	0
11	0.0067	-	0.0067	-	0.0067	-

It is interesting to note that the new winding has approximately the same total differential leakage coefficient like the initial winding. What is changed is the distribution of the winding factors, from lower orders (2, 4) to bigger (8-10) taking into consideration that smaller order space harmonics are more annoying as the bigger order are damped themselves.

CONCLUSIONS

The design of the three phase winding with parallel paths to be used for part-winding starting should have another criteria than the regular parallel path winding. The parallel path have to work separately in the starting period that means special measures have to be considered to keep the space harmonics in the prescribed limits. The most dangerous space harmonics are the 2-th and the 4-th space harmonics which compulsory appear when the winding structure under one pole has another constitution in comparison with the winding structure under the adjacent pole. The 2-nd space harmonic is CCW and has a brake influence on the rotor but the 4-th space harmonic is CW that means it could produce dips in the starting torque characteristic.

The developed method for winding analysis and synthesis provides a basis for the design of space harmonic free half winding in order to allow for the induction motors to accelerate smoothly from locked rotor to full speed.

To reduce the even space harmonics the winding coils could be mixed on the parallel paths so that each parallel path to contain coils under all the poles. The example developed in the paper for 4-poles, 48 slots, concentric coils, have the advantages of bigger fundamental factor, lower space harmonic content, lower end winding length and easier manufacturing because of single/double layer structure. The winding with concentric coils developed in the paper could be used also for the normal motors taking into account he technological advantages of single/double layers manufacturing.

REFERENCES

[1] M.E. El-Hawary: *Principles of Electric Machines with Power Electronic Applications*, A Reston Book, Prentice Hall, Englewood Clifs, NJ 07632, 1986

[2] Enrico Levi & Marvin Pantzer: *Electromechanical Power Conversion*, Robert E Krieger Publishing Co., Malabar, Florida, 1982

[3] Alger P.L.: “Performance calculation for part-winding starting off 3-phase motors”, AIEE Trans., February 1957, Vol. 75, Part III, p.1535-1543

[4] Courtin J.J.: “Ten part-winding arrangements in Sample 4-pole induction motor”, AIEE Trans., DEc. 1955, vol. 74, Pt. III, p.1248-1254

[5] Rajaraman K.C.: “Theory and design of part winding starting”, IEEE Trans. on Energy Conversion, Vol. 14, No.1, March 1999, p. 31-36

[6] Heller B., Hamata V.: *Harmonic Field Effects in Induction Machines,* Academia Publishing House, Prague, 1977

[7] Cistelecan M.V., Demeter E.: “A new approach of the three phase mono-axial unconventional windings for a.c. machines”, Int. Conf. IEEE-IEMDC, Seattle, Washington USA May 1999 , TP1: Induction/Linear mach. p.323-325

[8] Sarbu M.A., Cistelecan M.V., Wang S., Demeter E.: "Part-winding starting of the three phase squirrel cage induction motor: airgap magnetic field analysis", 11-th International Symposium on Electromagnetic Fields in Electrical Engineering ISEF-2003, Maribor Slovenia, Sept. 2003, p.143-148