Ideas about a big 48-pole direct drive PM-generator for the VIRYA-6.5 windmill using the housing, winding and armature of a 6-pole asynchronous motor frame size 200 L

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KD 777

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Contains page

1 Introduction

The VIRYA-6.5 is described in report KD 578 (ref. 1) and KD 579 (ref. 2). The original VIRYA-6.5 as described in KD 578, makes use of a 4 kW asynchronous motor which is used as generator and which is grid connected. The generator is connected to the rotor by an accelerating gear box with a gear ratio i of 12.4 or 15.3. The main disadvantage of this option is that the generator has a very steep P_{mech}-n curve and the C_p of the rotor is therefore only high for wind speeds around the point of intersection of the P_{mech}-n curve of the generator and the optimum cubic line of the rotor.

In chapter 7 of KD 579, the use of an alternative direct drive axial flux PM-generator is described. This generator is of the Chinese manufacture Hefei Top Grand and has the type: PMG-I-620-10kW-250R. This generator is grid connected by an inverter. It is assumed that the inverter can be programmed such that the optimum cubic line of the rotor is followed and so the rotor turns always at the tip speed ratio for which the C_p is maximal. The main disadvantage of this option is that the generator and the inverter are rather expensive.

The windmill is provided with the hinged side vane safety system which starts turning the rotor out of the wind at a wind speed of about 7 m/s and which results in a rated wind speed of about 11 m/s (see KD 578 figure 3). This safety system limits the maximum power for the asynchronous generator up to about 4.7 kW for i = 12.4 and to about 3 kW for i = 15.3 (see KD 578 figure 5) and to about 5.9 kW if the axial flux generator of Hefei Top Grand is used (see KD 579 figure 9). In this report KD 777 it is investigated if it is possible to design a direct drive PM-generator using the housing and winding of a 6-pole asynchronous motor frame size 200 L. The 3-phase current coming out of this generator can be grid connected by an inverter. Selection of the right inverter is out of the scope of this report. It is also possible to use the VIRYA-6.5 with this 6-pole generator for heating by means of three resistors.

2 Selection of the asynchronous motor for use as PM-generator

It is chosen to use a motor which has a stator and armature stamping of the German manufacture Kienle & Spiess because this manufacture gives detailed information about the dimensions of their stampings on their website. I have used this manufacture for other PM-generators like generators as described in report KD 718 (ref. 3). However, it appears that recently, the name of this company has changed into Feintool. Information about the geometry of armature and stator stampings of asynchronous motors is found by following the path: www.feintool.com – Online catalogue industry – Products – Induction Machines. One has to make an account with an e-mail address and a password to get access to the catalogue.

Very long ago a Dutch manufacturer of asynchronous motors has given me a page of a German folder on which an overview is given of the armature and stator dimensions depending on the frame size and the number of poles. This page can't be found on the website of Feintool but it is very handy to make a choice, especially because it also gives the armature and stator length L_{Fe}. I have scanned it and added it as figure 1. It is a bit dirty and full with remarks but it still works. D_a is the outside diameter of the stator stamping. D_i is the inside diameter of the stator stamping. d_i is the diameter of the hole in the armature stamping. The frame size is the height of a foot B3 from the centre of the shaft up to the bottom of the foot.

The outside diameter of the armature is somewhat smaller than D_i because of the air gap in between armature and stator but the value isn't given as this is chosen by the manufacturer of the motor. The number of stator slots is also not given but I have written it on the sheet for some frame sizes. This information is given on the website of Feintool if one goes to the selected stamping.

Information about the shaft dimensions is also not given. I have used a folder of the Dutch manufacturer ROTOR to find this information. However, ROTOR isn't using stampings of Feintool and so one can't use a motor of ROTOR for a prototype! A manufacturer which uses these stampings for their motors has still to be selected.

Leistungsangaben in KW bei 50 Hz nach DIN 42 673 und 42 677

Bau-größe Frame size Hauteur d'axe	2-polig 3000 min⁻¹ KW	2-polig Da Di di	2-polig mm LFe	4-polig 1500 min⁻¹ KW	4-polig Da Di di	4-polig mm LFe	6-polig 1000 min⁻¹ KW	6-polig Da Di di	6-polig mm LFe	8-polig 750 min⁻¹ KW	8-polig Da Di di	8-polig mm LFe
56	0,09 0,12	80 40 15	45 55	0,06 0,09	80 45 15	45 55	0,04 0,06	80 50 15	45 55	0,03 0,04	80 50 15	45 55
63	0,18 0,25	90 45 18	45 60	0,12 0,18	90 50 18	45 60	0,09 0,12	90 55 18	45 60	0,06 0,09	90 55 18	45 60
71	0,37 0,55	106,5 55 20	50 65	0,25 0,37	106,5 62 20	50 65	0,18 0,25	106,5 70 20	50 65	0,12 0,18	106,5 70 20	50 65
80	0,75 1,1	120 62 25	60 80	0,55 0,75	120 70 25	60 80	0,37 0,55	120 80 25	70 90	0,25 0,37	120 80 25	70 90
90 S	1,5	135 70 30	75	1,1	135 80 30	75	0,75	135 90 30	75	0,45	135 90 30	75
90 L	2,2		100	1,5		100	1,1		100	0,55		100
100 L	3	150 80 36	90	2,2 3	150 90 36	90 120	1,5	150 103 36	120	0,75 1,1	150 103 36	90 120
112 M	4	170 90 38	110	4	170 103 38	140	2,2	170 115 38	140	1,5	170 115 38	140
132 S	5,5 7,5	200 110 50	90 120	5,5	200 125 50	125	3	200 135 50	125	2,2	200 140 50	100
132 M				7,5		170	4 5,5		150 180	3		135
160 M	11 15	240 135 55	130 180	11	240 150 55	160	7,5	240 165 55	165	4 5,5	240 170 55	125 165
160 L	18,5		215	15		215	11		225	7,5		225
180 M	22	270 150 65	190	18,5	270 170 65	200		270 180 65			270 190 65	
180 L				22		240	15		240	11		240
200 L	30 37	300 170 75	200 250	30	300 190 75	250	18,5 22	300 200 75	230 265	15	300 215 75	265
225 S		340 190 80		37	340 215 80	240		340 240 80		18,5	340 240 80	240
225 M	45		240	45		290	30		290	22		290
250 M	55	375 215 85	240	55	375 240 85	290	37	375 260 85	290	30	375 270 85	310
280 S	75	420 240 95	250	75	420 270 100	300	45	420 290 100	275	37	420 305 100	300
280 M	90		300	90		360	55		330	45		360
315 S	110	500 290 115	275	110	500 325 115	300	75	500 375 115	300	55	500 375 115	300
315 M	132 160		330 400	132 160		370 470	90 110 132		370 450 550	75 90 110		370 450 550
355 S	200 250	580 325	370 470	200 250	580 375	370 450	160 200	580 425	470 550	132 160	580 425	470 550
355 L	200 250 315	120	370 470 550	200 250 315	130	370 450 550	160 200	130	470 550	132 160	130	470 550

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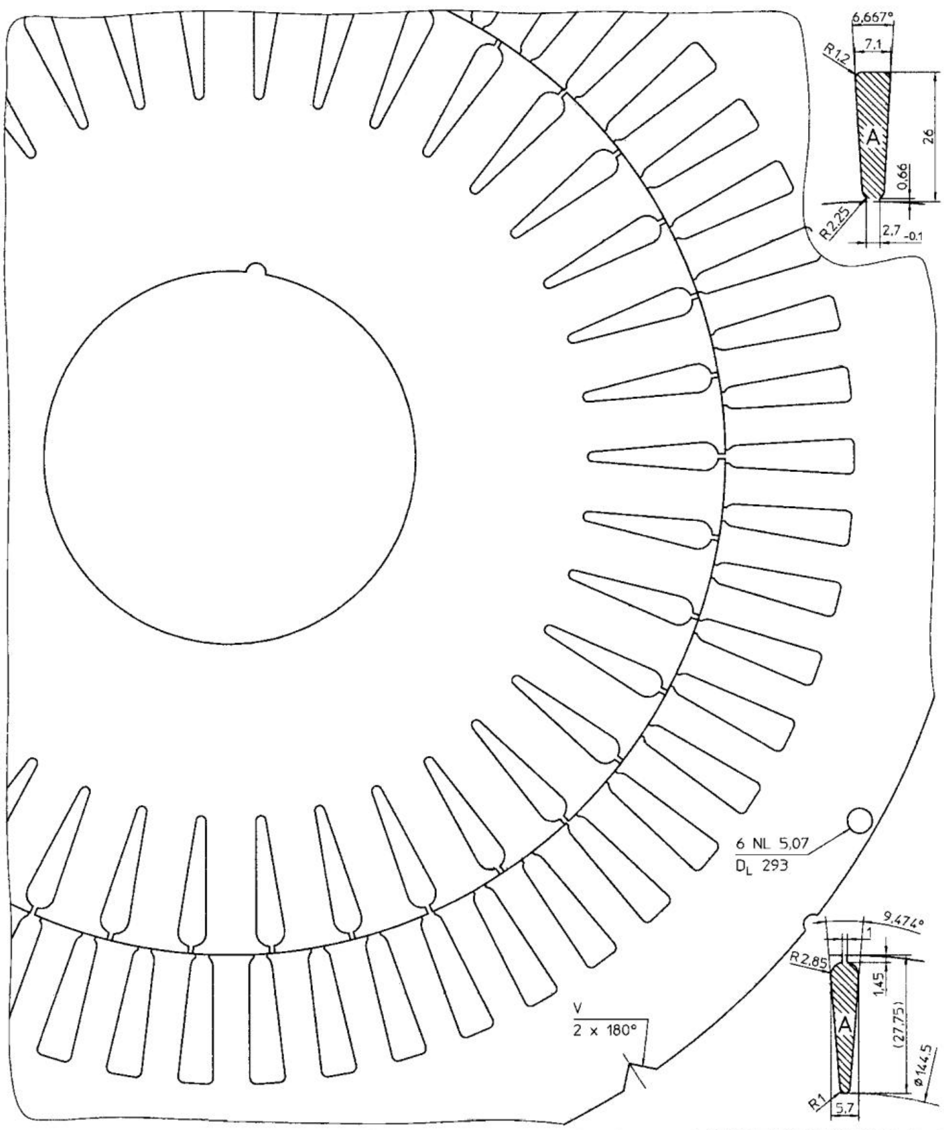
fig. 1 Overview of the geometries of the armature and stator stampings of asynchronous motors using a stator stamping of Kienle & Spiess (Feintool)

The VIRYA-6.5 has a rotor diameter of 6.5 m. It is assumed that the rotor hub is mounted directly on the generator shaft and so the shaft must be strong enough. It appears that a motor with frame size 200 has a shaft with a diameter of 55 mm and a length of 110 mm and it is expected that this shaft is strong enough. The shaft of the gear box as used in KD 578 has a diameter of 48 mm and it can be doubted if this shaft is strong enough.

Only frame size 200 L is mentioned at figure 1. The outside diameter D_a of the stator stamping is 300 mm for all pole numbers. The inside diameter D_i of the stator stamping depends on the pole number and is 200 mm for a 6-pole motor. The armature volume depends on the armature diameter and length. The maximal length is 265 mm for a 22 kW motor.

The maximum torque level of a PM-generator is proportional to the armature volume if a certain flux density in the air gap is realised. It is assumed that the air gap in between the armature and the stator is 0.4 mm and so the armature diameter is 199.2 mm. The stator stamping has 54 slots. The nominal motor power is 22 kW. The synchronic rotational speed is 1000 rpm for a grid frequency of 50 Hz.

The armature stamping has the same length as long as only the iron stamping sheets are taken into account. However, aluminium bars are cast into the armature stamping and these bars are connected at both sides of the armature by an aluminium disk with cooling fans at the outside. The real length of the armature is therefore much longer than the stator length. A detailed picture of the chosen armature and stator stamping is given on the website of Feintool and this picture is copied and given as figure 2.



IEC 200/6.200	Maße und Varianten				
	D_a	D_i	N	A	b_z
SB 300.03.X.00	300 +0,01	200 ±0,057	54	144,6	7,42
01 wie Abbildung					
RB 200.01.Y.00		d_a	N	A	b_z
d_i		200	38	101,1	10,11
03 75 +0,046 M	04 105 +0,054 M				
Blechdicke SB und RB	0,5				

FEINTOOL

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fig. 2 Stamping Feintool IEC 200, 6-pole

In figure 2 it can be seen that the stator stamping has 54 slots and so 54 mechanical stator poles. So the angle in between the mechanical stator poles is 360 / 54 = 6.6667°.

The number of magnetic stator and armature poles depends on the stator winding. It is assumed that the standard 400 / 690 V, 3-phase winding of a 6-pole motor is used and so the stator and the armature will have six magnetic poles. The magnetic armature pole angle for a 6-pole PM-generator is 360 / 6 = 60°. So the optimum angle in between the right and the left leg of a stator coil should be 60° too. However, this isn't possible for a stator with 54 slots. This problem is solved by making a coil bundle consisting out of three coils which are lying around each other. The legs of the inner coil make an angle of 46.6667° with each other. The legs of the middle coil make an angle of 60° with each other. The legs of the outer coil make an angle of 73.3333° with each other and so the average angle is 60°.

27 coils can be laid in 54 stator slots. Nine coils are of phase U, nine coils are of phase V and nine coils are of phase W. A 6-pole motor must have a 3-layers winding. This is because nine isn't divisible by two. So first the nine coils of phase U are laid. The coil heads of these nine coils are bent to the outside to make place for the coils of the second and third layer. Next the nine coils of phase V are laid. One side of the coil heads is bent to the outside. Next the nine coils of phase W are laid. All coils have the same winding direction. All nine coils of one phase are connected in series. The ends of the nine coils of one phase are connected to the terminal box.

The synchronic rotational speed of a 6-pole motor is 1000 rpm for a grid frequency of 50 Hz. The loaded rotational speed is somewhat lower because a short-circuit current is only created in the aluminium bars of the armature if the armature has a certain slip with respect to the rotating magnetic field which is created in the stator if the stator is connected to the grid. In the folder of ROTOR it was found that the nominal rotational speed for a 22 kW, 6-pole asynchronous motor is 973 rpm. So the slip is only 27 rpm at the nominal power. The nominal torque is 216 Nm. For a PM-generator there is no slip and so the frequency is 50 Hz at n = 1000 rpm.

3 Choice of the permanent magnet armature construction (see figure 3)

There are several ways how an asynchronous armature can be transformed into a permanent magnet (PM) armature. For my older 4-pole VIRYA generators, I have made a complete new armature and a new stainless steel shaft. This procedure is described in report KD 341 (ref. 4). The magnets are positioned radial in grooves which make a certain angle with the generator shaft to prevent fluctuation of the cogging torque. The shaft must be made out of stainless steel to prevent magnetic short-circuit in between the armature poles. These generators have good characteristics but manufacture of the armature is rather complicated and the generator costs are rather high. It is a pity that the original shaft and armature can't be used. So for this new VIRYA-6.5 generator, it is investigated if it is possible to use at least the stator winding, the original motor shaft and if possible, also the short-circuit armature. There are three ways to make an armature using the original motor shaft.

1) Assume that the original short-circuit armature is removed from the shaft and replaced by a mild steel bush with a diameter of 200 mm and a length of 280 mm. This bush is turned to a diameter of 199.2 mm after pressing it onto the shaft and so the air gap is 0.4 mm. The grooves for the permanent magnets are made in this bush. However, this is a very heavy bush and it is a pity that the original short-circuit armature isn't used.

2) Assume that the original armature is turned to a diameter of 153 mm. So the aluminium short-circuit bars are almost completely removed. The fans at both sides of the armature are also removed. A 280 mm long bush made out of seamless thick walled steel pipe size 203 * 153 is glued to the reduced armature with epoxy glue or anaerobe glue. This bush is turned to a diameter of 199.2 mm after gluing and so the air gap is 0.4 mm. The grooves for the permanent magnets are made in this bush. This bush is still rather heavy and it can be questioned if a piece with a length of only 280 mm can be obtained from the supplier MCB, Valkenswaard, The Netherlands. It might be that one has to buy a standard pipe length of 6 m and this will be very expensive for a prototype.

3) Assume that the original armature is used and that the grooves for the magnets are made directly in this armature. This option isn't possible for a motor with a 6-pole winding but it is described in report KD 760 (ref. 5) for a motor with an 8-pole winding. However, making of the required inclined magnet grooves just in between the aluminium short-circuit bars is rather complicated.

So option 2 is chosen for a generator made from a motor with a 6-pole winding. The length of the armature bush is chosen 280 mm and so the armature juts out 7.5 mm at each side of the 265 mm long stator. If a 280 mm long piece of thick walled pipe isn't available, one has to use a 200 mm diameter massive bar for a prototype and turn a 153 mm hole in it.

It is chosen to use neodymium magnets size 40 * 10 * 10 mm. These magnets are supplied by the Polish company Enes Magnets website: www.enesmagnets.pl. The magnet quality is N38 which means that the remanence B_r is about 1.24 T. The current price including VAT but excluding costs of transport is € 1.78 per piece if a minimum number of 80 magnets is ordered.

Magnets are only used for the north poles. The south poles are formed by the remaining armature material. A magnetic north pole is formed by eight mechanical north poles. Each mechanical north pole is formed by a row of seven magnets. So the total length of seven magnets is 7 * 40 = 280 mm which is equal to the length of the armature bush. The total number of magnets is 7 * 8 * 3 = 168 and so the total magnet costs are about € 300 which is certainly acceptable for this big PM-generator.

The armature gets 48 mechanical poles. The pitch angle in between the magnet grooves is 360 / 48 = 7.5°. The pitch at the outside of the armature is π * 199.2 / 48 = 13.04 mm. The magnet grooves have a width of 10.2 mm and a depth of 10.3 mm. The extra 0.3 mm makes that a magnet isn't jutting out of the armature.

To make that there are also eight 10 mm wide mechanical south poles for one magnetic south pole, a 3 mm wide and 5 mm deep groove is made in between the south poles. It is started to make 48 of those 3 mm wide grooves at an angle of 7.5°. The magnet grooves are made afterwards and so in between adjacent magnets, there is no iron up to a depth of 5 mm.

If seven magnets are glued in each magnet groove, there are eight mechanical armature north poles opposed to nine mechanical stator poles. This means that only the magnets in one of the eight magnet grooves will be just opposite a mechanical stator pole. This results in 8 * 9 * 6 = 432 preference positions per revolution. This is a very high number and the generator will therefore have only a small peak on the cogging torque.

The magnets are glued in the grooves by epoxy glue or by anaerobe glue such that the north pole of all magnets is facing outwards. One has to develop a tool with which a magnet can be held on both 10 * 10 mm sides during mounting. The magnets have a tolerance on the width of ± 0.1 mm. So the width of the grooves must be 10.2 mm to make that the magnets always fit. As the magnet thickness is the same as the magnet width, the magnets have to be marked with an N at the north side after piling up all magnets. In this way it can always be verified if a magnet is mounted correctly.

Eight magnetic loops are coming out of the eight rows of magnets of the north poles N1 up to N8. The four loops coming out of N1 – N4 are turning left hand and are guided through the stator iron to the south poles S24, S23, S22 and S21. The four loops coming out of N5 - N8 are turning right hand and are guided through the stator iron to the south poles S1, S2, S3 and S4. A magnetic loop passes two air gaps. The air gap at the south poles is 0.4 mm. The average air gap at the north poles is about 0.6 mm. So the total air gap is about 1 mm. The magnet thickness is 10 mm

The flux density in the air gap is reduced by the total air gap. The flux density B in the air gap is calculated for a remanence B_r = 1.24 T and it is found that B is about 1.127 T which is very high. So the generator will be very strong. It is expected that the magnetic flux which is supplied by the 7.5 mm long parts of the outer magnets which are jutting outside the stator is lost.

The stator stamping is provided with six 5.07 mm holes at a pitch circle of 291 mm. These holes can be used to press all sheets together but they are a resistance for the magnetic flux flowing through the stator stamping. The resistance can be reduced if 5 mm iron rods are put in these holes but I don’t know if this is possible if the winding has already been laid. The problem with these six holes is that they can result in six extra rather strong preference positions per revolution as there are six positions of the armature for which the holes give almost no resistance. So if possible, an iron bar with a diameter of 5 mm and a length of 265 mm should be shifted in each hole.

A front view of the armature and a side view of eight rows of magnets are given in figure 3. The remaining parts of the aluminium bars are not given in the front view. An advantage of using the original armature for the south poles is that the magnets can’t touch the stator when the armature in mounted in the stator. The armature is only centred in the stator after mounting of the bearing covers.

I think that the VIRYA-6.5 is big enough to use the generated power for heating during winter of a well isolated house. This procedure is described for the VIRYA-7 with stainless steel blades in chapter 10 of report KD 763 (ref. 6). Three resistors are needed which are connected in star for low wind speeds and in delta for high wind speeds. The correct value of the resistance can only be determined after building a prototype of the generator and measuring it for a range of resistance loads connected in star and in delta.

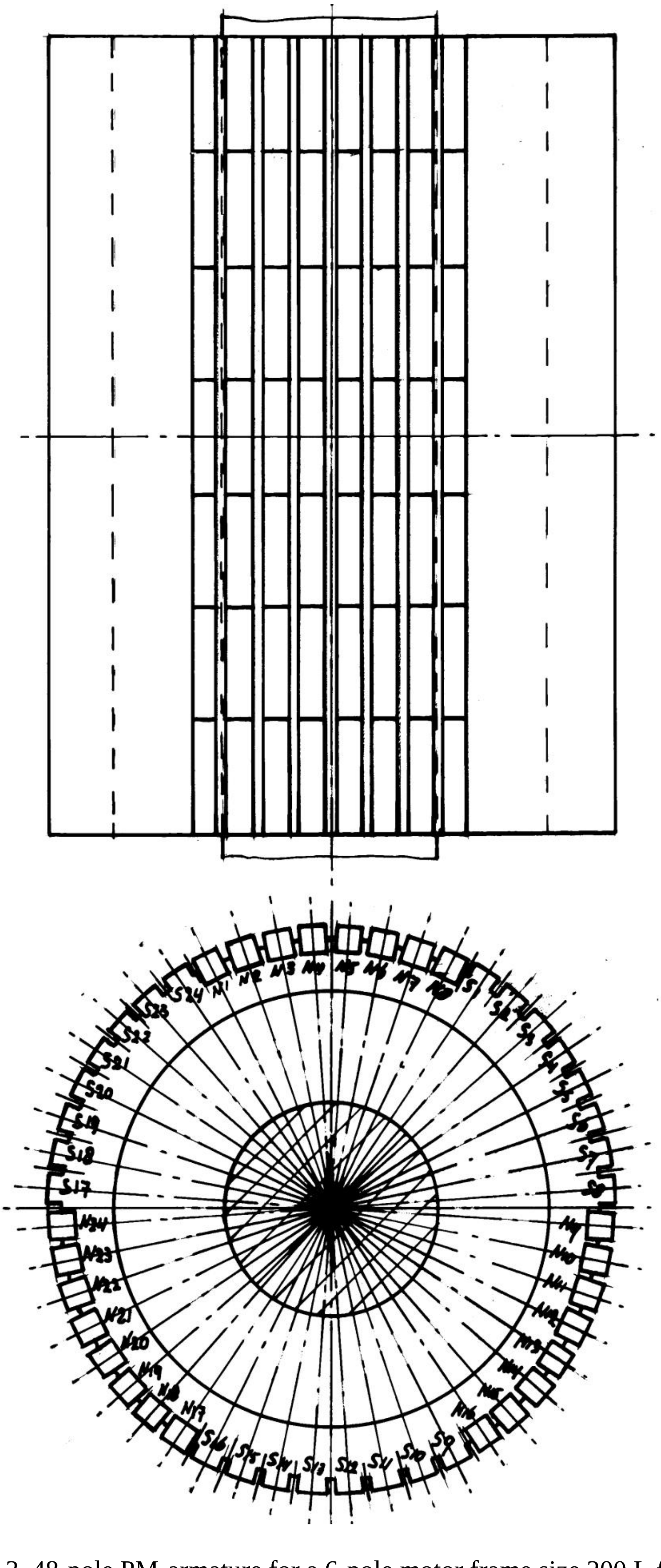
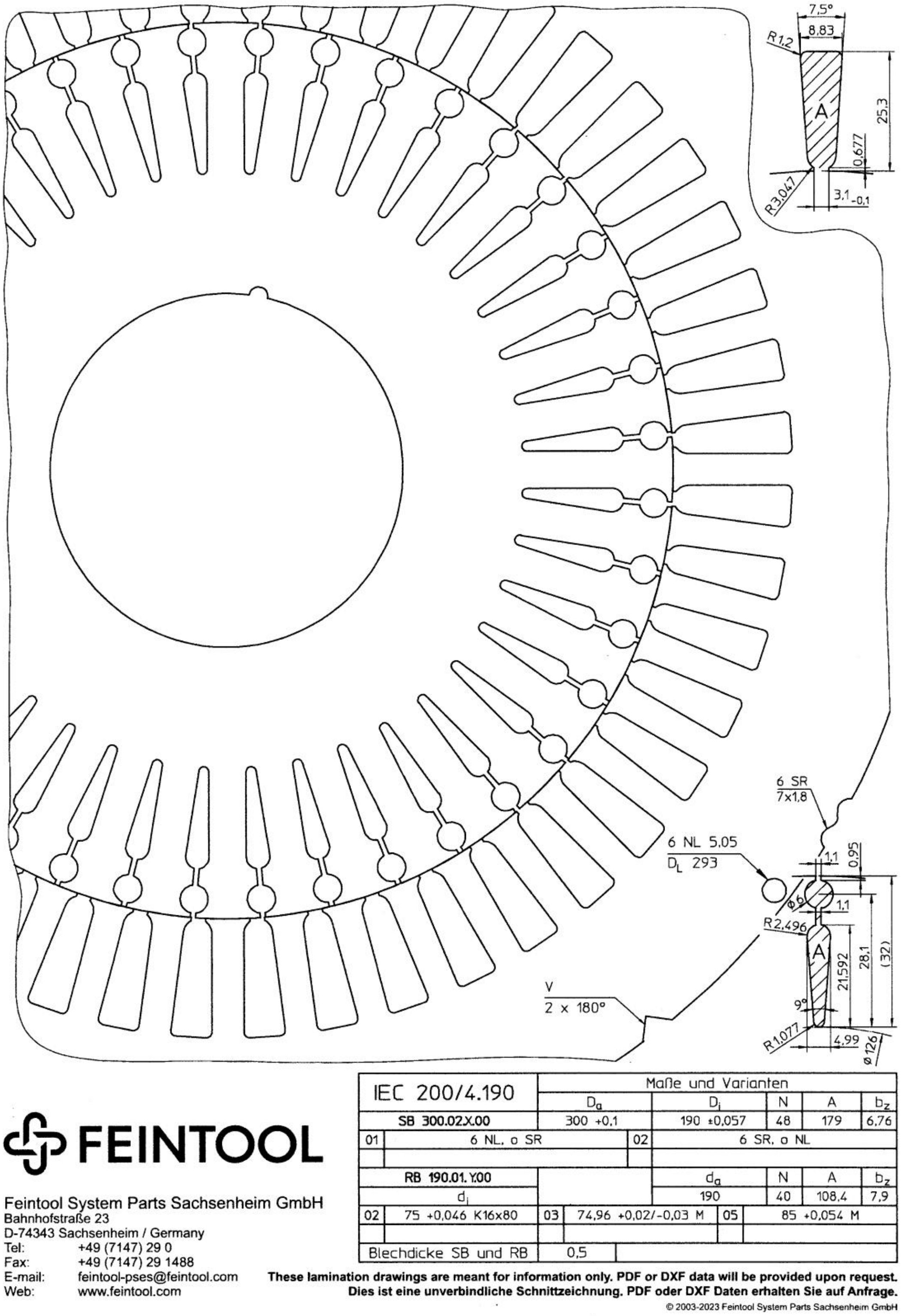


fig. 3 48-pole PM-armature for a 6-pole motor frame size 200 L for the VIRYA-6.5

4 Using a 4-pole motor frame size 200 L and a 44-pole armature

A 4-pole motor is more common than a 6-pole motor and therefore might be easier available. The same principle as used in chapter 3 for a 6-pole motor can also be used for a 4-pole motor frame size 200 L. However, the number of stator slots is 48 for a 4-pole motor frame size 200 L if a stator stamping of Feintool is used. This stamping is given in figure 4.



IEC 200/4.190		Maße und Varianten					
		D_a		D_i	N	A	b_z
SB 300.02.X.00		300 +0,1		190 ±0,057	48	179	6,76
01	6 NL, o SR		02	6 SR, o NL			
RB 190.01.Y.00				d_a	N	A	b_z
d_i				190	40	108,4	7,9
02	75 +0,046 K16x80	03	74,96 +0,02/-0,03 M	05	85 +0,054 M		
Blechdicke SB und RB		0,5					

fig. 4 Stamping Feintool IEC 200, 4-pole

The inside diameter of the stator is 190 mm. Assume that the air gap in between stator and armature is 0.4 mm. This gives an armature diameter of 189.2 mm. In figure 1 it can be seen that the length of the stator is 250 mm for a motor with a nominal power of 30 kW. As the stator has 48 slots, it has 48 mechanical poles. It is chosen that the armature has 44 mechanical poles. So 11 armature poles are opposed to 12 stator poles. This results in 11 * 12 * 4 = 528 preference positions per revolution which is higher than the 432 preference positions of the 48-pole armature in combination with a housing of a 6-pole motor with 54 stator slots. So the peak on the cogging torque will be smaller for this 44-pole generator.

The original short-circuit armature is turned to a diameter of about 138 mm and a 250 mm long bush made out of pipe size 193.7 * 138 mm is glued to the armature by epoxy or anairobe glue. This pipe is turned to an outside diameter of 189.2 mm after gluing.

The torque level is proportional to the armature volume for a certain flux density in the air gap. The armature volume of the 44-pole generator is a factor $(189.2 / 199.2)^2$ * 250 / 265 = 0.851 lower than for the 48-pole generator but it is expected that the 44-pole generator is still strong enough for the VIRYA-6.5. Measurements executed on a prototype must prove that this assumption is true.

The stator length is 250 mm. It is assumed that six magnets size 40 * 10 * 10 mm are used in one row combined with one magnet size 10 * 10 * 10 mm. The magnet costs of a magnet size 10 * 10 * 10 mm are € 0.57 including VAT if at least 100 magnets are ordered.
A magnetic north pole is formed by 11 rows of magnets. As there are two magnetic north poles, there are totally 22 rows of magnets containing totally 22 * 6 = 132 magnets size 40 * 10 * 10 mm and 22 magnets size 10 * 10 * 10 mm. So the total magnet costs for one generator including VAT (but excluding costs of transport) are 132 * € 1.78 + 22 * € 0.57 = € 247.50. So this is more than € 50 cheaper than for the 48-pole generator.

The south poles are formed by 22 rims which are separated by 4 mm wide and 5 mm deep grooves. It is advised to start with 44 of those grooves at an angle of 360 / 44 = 8.1818° and to make the 22 magnet grooves afterwards. This automatically makes that there is a 5 mm high rim in between adjacent magnets.

The winding of a 4-pole motor is different from the winding of a 6-pole motor. As the stator has 48 slots, 24 coils can be laid. 8 coils are of phase U, 8 coils are of phase V and 8 coils are of phase W. The armature pole angle is 90° for a 4-pole armature. This means that the optimum angle in between the left and the right leg of a stator coil is 90° too. However, this isn’t possible for a stator with 48 slots. This problem is solved by lying four coils around each other. The inner coil has a coil angle of 67.5°. The next coil has a coil angle of 82.5°. The next coil has a coil angle of 92.5°. The outer coil has a coil angle of 112.5°. So the average coil angle of the four coils in one bundle is 90°.

The stator has a 2-layers winding which means that first four coils of each phase are laid. The coil heads of these coils are bent to the outside. The four coils of a coil bundle must be connected in series because the generated voltage isn’t the same for all coils. The two coil bundles of one phase are normally connected in series. The ends of the first and the eighth coil are connected to the terminal. The winding can be connected in star or in delta. Star connection gives the lowest cogging torque because no higher harmonic currents can circulate in the winding.

The voltage is halved and the current is doubled if the four coils of the first layer are connected in parallel to the four coils of the second layer. A 30 kW motor normally has a 400 / 690 V winding if it is used in combination with a 230 / 400 V grid. The motor is started in star and connected in delta when it has reached about the nominal rotational speed. This procedure limits the starting current. However, a 400 / 690 V winding will give a rather high DC voltage if the motor is transformed into a PM-generator. The generator runs at a much lower rotational speed than the nominal motor speed if it is used in combination with the VIRYA-6.5. If the VIRYA-6.5 is used for 48 V battery charging, it might be required to modify the standard 400 / 690 V winding into a 200 / 345 V winding. For grid connection using an inverter, a high voltage is no problem and then the original winding can be used.

A sketch of the 44-pole armature is given in figure 5.

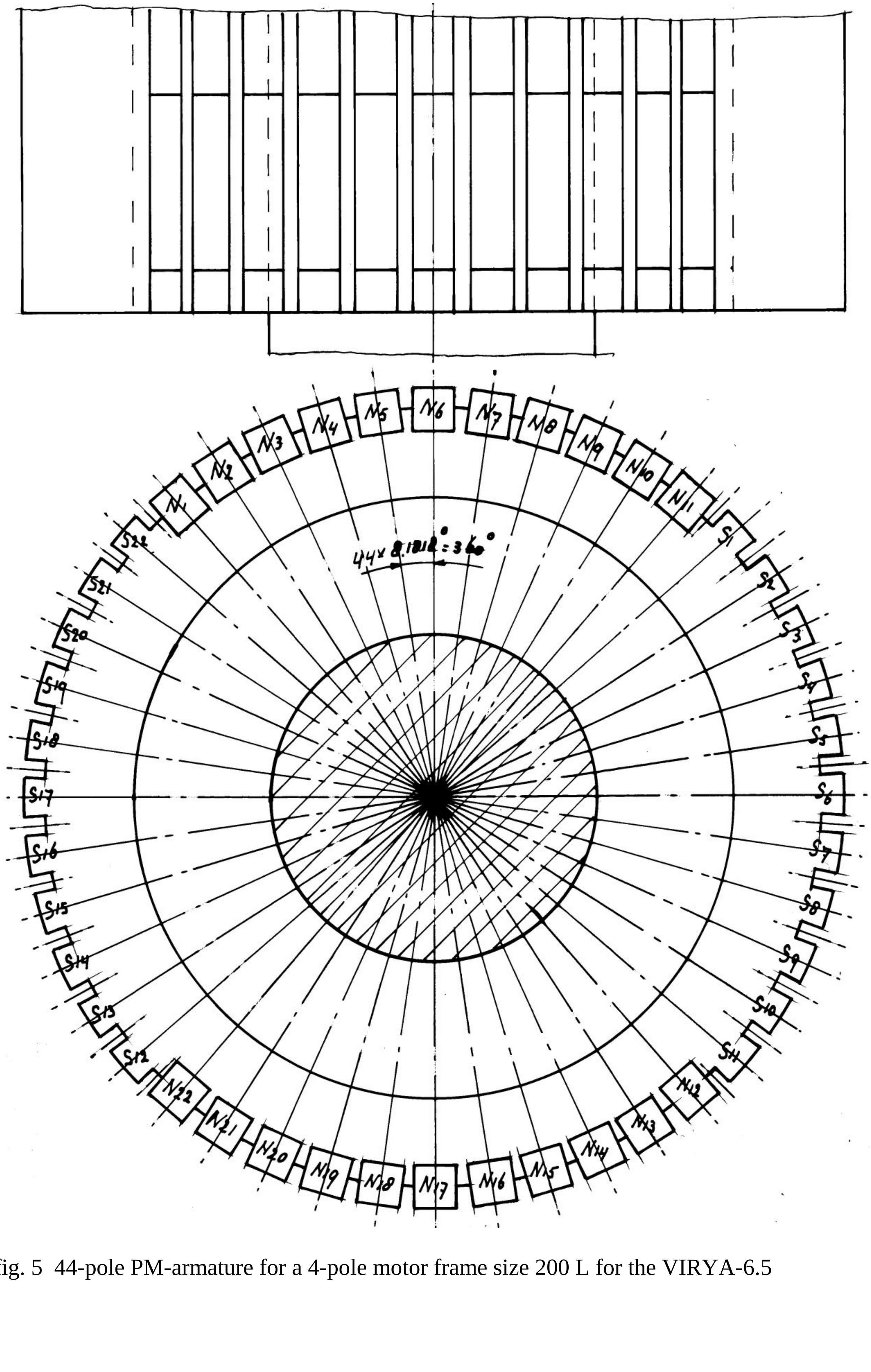


fig. 5 44-pole PM-armature for a 4-pole motor frame size 200 L for the VIRYA-6.5

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