Ideas about a 5-phase and a 9-phase PM-generator

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KD 712

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1 Introduction

Permanent magnet (PM) generators of wind turbines generally have three phases. Every phase generates an about sinusoidal voltage and there is a phase angle of 120° in between the phases. The generator winding is mostly rectified in star and the rectified DC current can be used to charge a battery. The development of the VIRYA generators is described in report KD 341 (ref. 1). Rectification of a 3-phase current is described in report KD 340 (ref. 2). The voltage fluctuation of the three phases U, V and W is given in figure 3 of KD 340.

A rectified 3-phase current has a small fluctuation of the DC voltage and the DC current. The current fluctuation is given in figure 8 and the voltage fluctuation is given in figure 9 of KD 340 for star rectification. The average DC voltage is a factor 0.955 times the peak value. The current fluctuation is normally no problem if a battery is the only generator load. However, if a certain load is connected to the battery which absorbs just the average battery current, it means that the battery is charged and uncharged with a pulsating current with a high frequency. This isn’t good for the lifetime of the battery.

This fluctuation problem also happens for axial piston pumps used for driving the wheels of heavy tractors. Generally one uses pumps with five or seven pistons to flatten the flow supplied by the hydraulic motor. It is expected that a 5-phase winding will flatten the current much stronger than for a 3-phase winding.

2 Voltage fluctuation of a 5-phase winding

For a 5-phase winding, there is a phase angle α = 72° in between the phases. The five phases are called U, V, W, X and Y. The voltage variation of a 5-phase winding is given in figure 1 if it is assumed that the voltage in one phase varies sinusoidal.

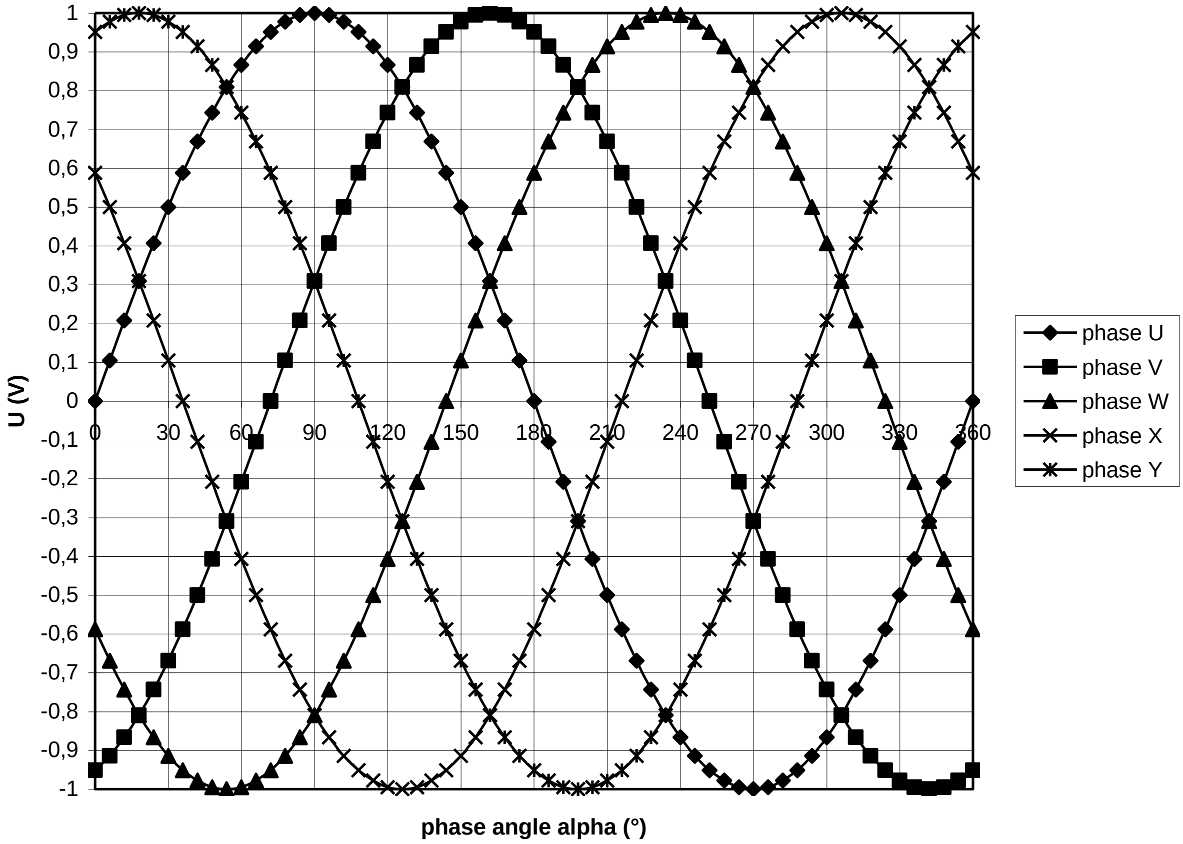

fig. 1 Voltage variation for phases U, V, W, X and Y as a function of α

3 Star rectification of a 5-phase current

Star rectification of a 3-phase current is shown by figure 5 of KD 340. One needs a 3-phase rectifier with six diodes. For star rectification of a 5-phase current one needs a 5-phase rectifier with 10 diodes. So one gets a similar picture but now there are five diodes D_1 – D_5 at the top and five diodes D_6 – D_{10} at the bottom.

One of the three phases has the highest voltage and one has the lowest voltage for a certain α domain. This is changing every 36°. This effect is important if a 5-phase current is rectified.

For 18° < α < 54°, phase Y has the highest voltage and phase W has the lowest voltage.
For 54° < α < 90°, phase U has the highest voltage and phase W has the lowest voltage.
For 90° < α < 126°, phase U has the highest voltage and phase X has the lowest voltage.
For 126° < α < 162°, phase V has the highest voltage and phase X has the lowest voltage.
For 162° < α < 198°, phase V has the highest voltage and phase Y has the lowest voltage.
For 198° < α < 234°, phase W has the highest voltage and phase Y has the lowest voltage.
For 234° < α < 270°, phase W has the highest voltage and phase U has the lowest voltage.
For 270° < α < 306°, phase X has the highest voltage and phase U has the lowest voltage.
For 306° < α < 342°, phase X has the highest voltage and phase V has the lowest voltage.
For 342° < α < 18°, phase Y has the highest voltage and phase V has the lowest voltage.

From the five upper diodes D_1, D_2, D_3, D_4 and D_5 only the one which has the highest voltage will conduct a current. This is because the current through a diode can flow only in one direction. From the five lower diodes D_6, D_7, D_8, D_9 and D_{10} only the one which has the lowest voltage will conduct a current. Which of the phases has the highest and which of the phases has the lowest voltage is given in the list above.

Now lets take the domain 18° < α < 54°. For this domain phase Y has the highest voltage and phase W has the lowest voltage. So a current will flow only through these phases and no current will flow through the phases U, V and W. The current will flow in the following sequence: phase Y, phase W, diode D_3, load resistor R and diode D_{10}.

Now lets take the domain 54° < α < 90°. For this domain phase U has the highest voltage and phase W has the lowest voltage. So a current will flow only through these phases and no current will flow through the phases V, X and Y. The current will flow in the following sequence: phase U, phase W, diode D_1, load resistor R and diode D_6.

So every 36° one of the phases and one of the diodes is changing. The voltage difference ΔV in between the highest and the lowest phase is equal to the vertical distance in between the highest and the lowest curve. The voltage difference is calculated for α = 18°, α = 24°, α = 30°, α = 36°, α = 42°, α = 48° and α = 54° for U_{max} = 1 V using figure 1.
For α = 18° it was calculated that U_Y = 1 V and U_W = -0.809 V so ΔV = 1.809 V.
For α = 24° it was calculated that U_Y = 0.995 V and U_W = -0.866 V so ΔV = 1.861 V.
For α = 30° it was calculated that U_Y = 0.978 V and U_W = -0.914 V so ΔV = 1.892 V.
For α = 36° it was calculated that U_Y = 0.951 V and U_W = -0.951 V so ΔV = 1.902 V.
For α = 42° it was calculated that U_Y = 0.914 V and U_W = -0.978 V so ΔV = 1.892 V.
For α = 48° it was calculated that U_Y = 0.866 V and U_W = -0.995 V so ΔV = 1.861 V.
For α = 54° it was calculated that U_Y = 0.809 V and U_W = -1 V so ΔV = 1.809 V.

The voltage difference ΔV is highest for α = 36°. The value ΔV = 1.902 V for α = 36°. The voltage difference is lowest for α = 18° and for α = 54° for which ΔV = 1.809 V. The maximum ratio is 1.809 / 1.902 = 0.951. The voltage difference ΔV for the other 36° wide α domains varies in the same way.

For a 3-phase current it can be calculated that the maximum ratio is 1.5 / 1.732 = 0.866 which is a lot lower and which shows that the voltage for a 5-phase current is much better flattened than for a 3-phase current. The current varies with the same ratio as the voltage if the load is a resistance but the maximum DC current is the same as the maximum AC current of one phase.

If we look in figure 1 at the voltage fluctuation of phase U, it can be seen that phase U is the highest for 54° < α < 126° and the lowest for 234° < α < 306°. So for the other α domains no current will flow through phase U. So a current flows only during 2/5 of the time. The current flows during 2/3 of the time for a 3-phase winding. So a 3-phase winding has a more efficient use of the winding than a 5-phase winding if the winding is rectified. The variation of the current in phase U for 0° < α < 360° is given in figure 2 for which it is assumed that the maximum current is 1.

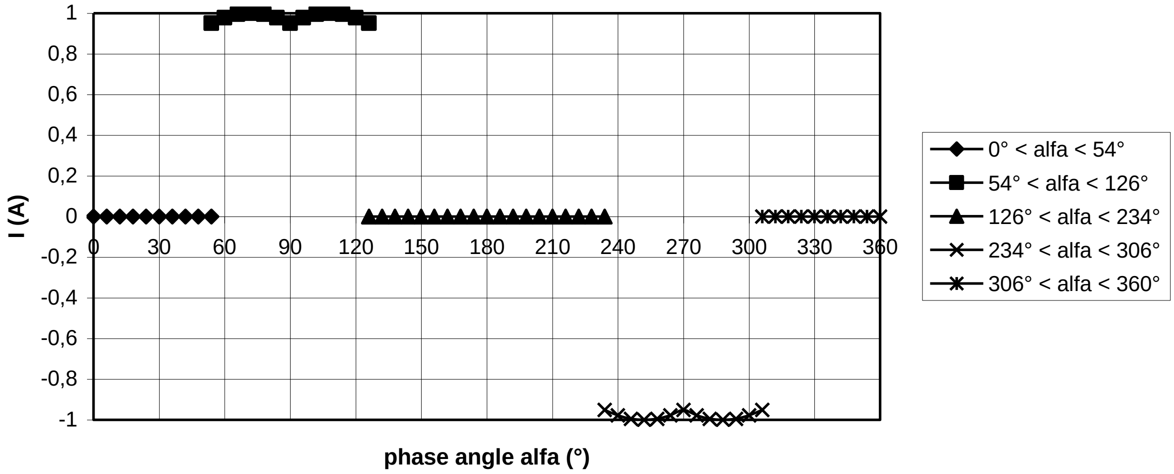

fig. 2 Variation of the current I in phase U

The variation of the rectified current, so in the load resistance R, is given in figure 3.

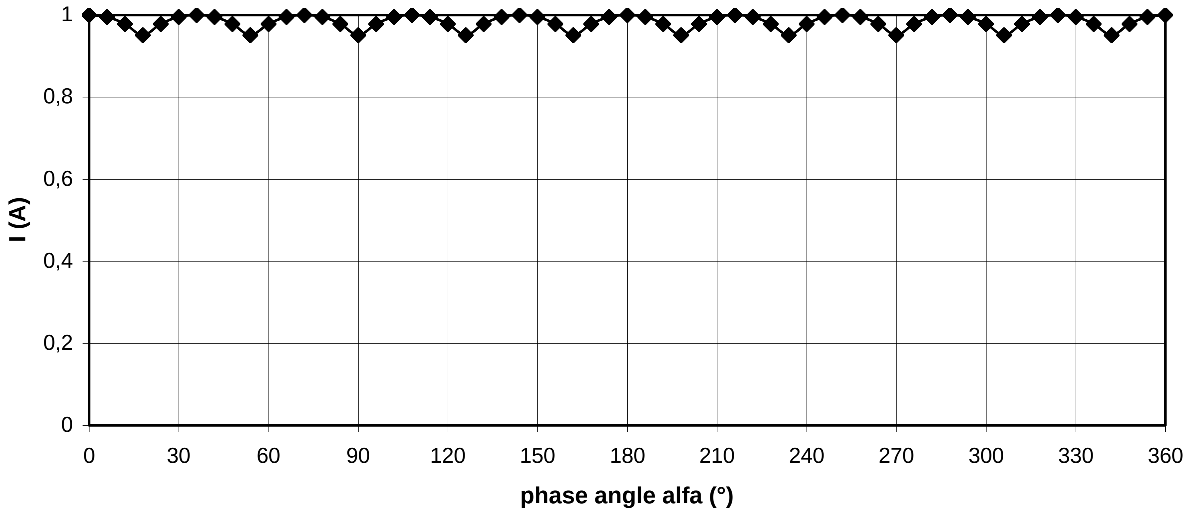

fig. 3 Variation of the rectified current in the load resistance R

If figure 3 is compared with figure 8 of KD 340, it can be seen that the rectified current for a 5-phase winding is more flattened than for a 3-phase winding.

4 Construction of the stator winding

Assume that the generator is built in the same way as used for my 3-phase generators which are made from asynchronous motors and which are explained in chapter 4 of KD 341 (ref. 1). This means that for every coil, two stator grooves are used. Assume that the armature has four poles so the armature pole angle is 90°. This means that the optimum angle in between two legs of a coil is 90° too. So two coils can be laid for one phase and totally ten coils are needed for a 5-phase winding. This means that the stator must have 20 sleeves. If the armature has six poles, one needs a stator stamping with 30 sleeves. If the armature has eight poles, one needs a stator stamping with 40 sleeves. If the armature has 10 poles one needs a stator stamping with 50 sleeves. None of these numbers is a standard number for stator stampings. So a special stator stamping has to be made which is a large disadvantage.

Even if a stator stamping with the correct number of sleeves would be available, the winding is rather complex as it will have five layers. So there must be enough space to bend the coil heads of the first layer to the outside to make space for the wires of the other layers. It might be possible to lay the layers like tiles but this requires handling of all coils of all five phases together.

5 Alternative 9-phase winding

In chapter 4 it was found that there is no standard stator stamping which can be used for a 5-phase winding. It might be possible to use a standard stator stamping if more phases are used. I have investigated a 6-phase winding, but it appears that a 6-phase winding results in the same fluctuation of the rectified current as a 3-phase winding. A 7-phase winding also results in a non standard number of stator slots. A 9-phase winding might work.

Assume that we use a 4-pole armature. This means that the armature pole angle is 90°. The optimum angle in between the left leg and the right leg of a coil is also 90° and so one needs 4 stator slots for one phase and so 36 stator slots for a 9-phase winding. A stator with 36 slots is very standard for medium size stampings.

The armature can be made like described in report KD 718 (ref. 3) for a 4-pole armature with a normal 3-phase winding. Every magnetic north pole is formed by four rows of magnets. Every magnetic south pole is formed by four iron poles. The south poles are rotated 1.25° with respect to the north poles to make that the armature has 288 preference positions per revolution. This results in a very small fluctuation of the sticking torque.

Every phase has two coils. The alphabet isn’t long enough to add six more letters behind the normal three phases U, V and W and therefore I use the following letters Q, S, T, U, V, W, X, Y and Z. The letter R is cancelled because this gives confusion with R used for the resistance.

The phase angle α in between the phases of a normal 3-phase winding is 120°. So the phase angle α in between the phases of a 9-phase winding is 40°. The sinusoidal voltage fluctuation of a 9-phase winding is given in figure 4.

For a 9-phase winding, the coils should be laid as roof tiles. A phase angle α = 40° corresponds to a rotational angle β = 20° for a 4-pole armature. So the angle in between the coils is 20°. The stator slots are numbered right hand 1 – 36. The coils are laid in the following sequence and make use the following slot numbers: Q1 1 + 10, S1 3 + 12, T1 5 + 14, U1 7 + 16, V1 9 + 18, W1 11 + 20, X1 13 + 22, Y1 15 + 24, Z1 17 + 26, Q2 19 + 28, S2 21 + 30, T2 23 + 32, U2 25 + 34, V2 27 + 36, W2 29 + 2, X2 31 + 4, Y2 33 + 6, Z2 35 + 8. The left legs of coils Q1, S1, T1 and U1 can only be pushed in the stator slots after mounting of coils W2, X2, Y2 and Z2.

The same principle of a 9-phase winding can also be used for a 6-pole armature and a stator with 54 slots or for an 8-pole armature and a stator with 72 slots but it is easiest to build a prototype of a medium size 4-pole armature and a stator with 36 slots to prove that the idea really works. But I will not do that.

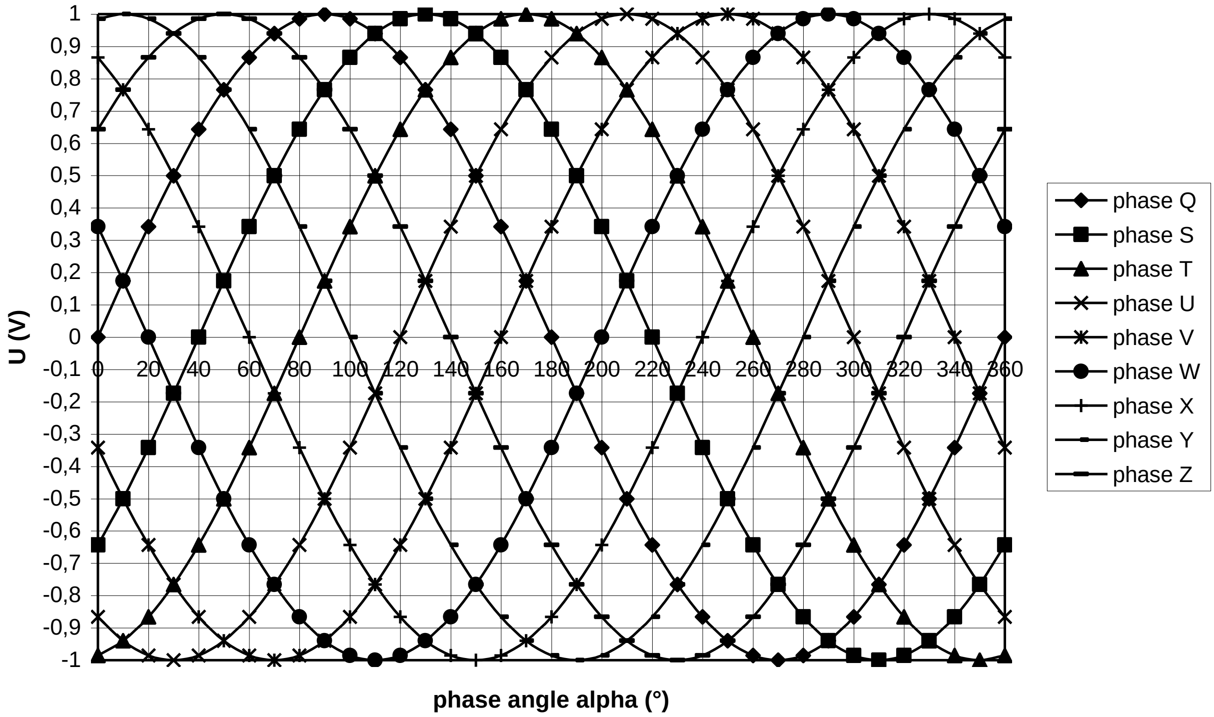

fig. 4 Voltage variation for phases Q, S, T, U, V, W, X, Y and Z as a function of α

6 Star rectification of a 9-phase winding

A 9-phase winding can be rectified in two ways. The first way is similar to star rectification of a 3-phase winding and all nine phases have one common star point. However, one needs a rectifier with eighteen diodes instead of six diodes. A rectifier with six diodes is given in figure 5 of report KD 340. So for a 9-phase rectifier, one gets nine diodes D_1 – D_9 at the top and nine diodes D_{10} – D_{18} at the bottom. The second way is that one makes three separate 3-phase windings, so one with the coils Q, U and X, one with the coils S, W and Y and one with the coils T, W and Z. Every 3-phase winding has its own 3-phase rectifier and the DC terminals of the three rectifiers are connected in series which results in a much higher voltage at the load resistance.

6.1 Using one star point for all nine phases and one 9-phase rectifier

The current flows only through the coils which have the highest and the lowest voltage at a certain moment. In figure 4 it can be seen that phase Q has the highest voltage for $70° < \alpha < 110°$. However, for this α interval, phase V has the lowest voltage for $70° < \alpha < 90°$ and phase W has the lowest voltage for $90° < \alpha < 110°$. This means that there is a change of the active phase every 20°.

The voltage difference ΔV is now determined for five values of α and it is found that:
$\alpha = 70°$ gives that $\Delta V = 0.940 + 1 = 1.940$ V.
$\alpha = 80°$ gives that $\Delta V = 0.985 + 0.985 = 1.970$ V.
$\alpha = 90°$ gives that $\Delta V = 1 + 0.940 = 1.940$ V.
$\alpha = 100°$ gives that $\Delta V = 0.985 + 0.985 = 1.970$ V.
$\alpha = 110°$ gives that $\Delta V = 0.940 + 1 = 1.940$ V.
So ΔV is minimal at $\alpha = 70°$, 90° and 110° and maximal at $\alpha = 80°$ and 100°. The ratio in between the minimum and the maximum voltage is $1.940 / 1.970 = 0.985$.

So there is a peak in the voltage every 20° and the voltage fluctuation is very low. The rectified DC voltage is the same as the voltage difference ΔV. The variation of the DC voltage is given in figure 5. The peak value is 1.970 * U_{max} in which U_{max} is the peak value of one phase. This is higher than for a 3-phase winding for which the peak value is $\sqrt{3}$ * U_{max} = 1.732 * U_{max}.

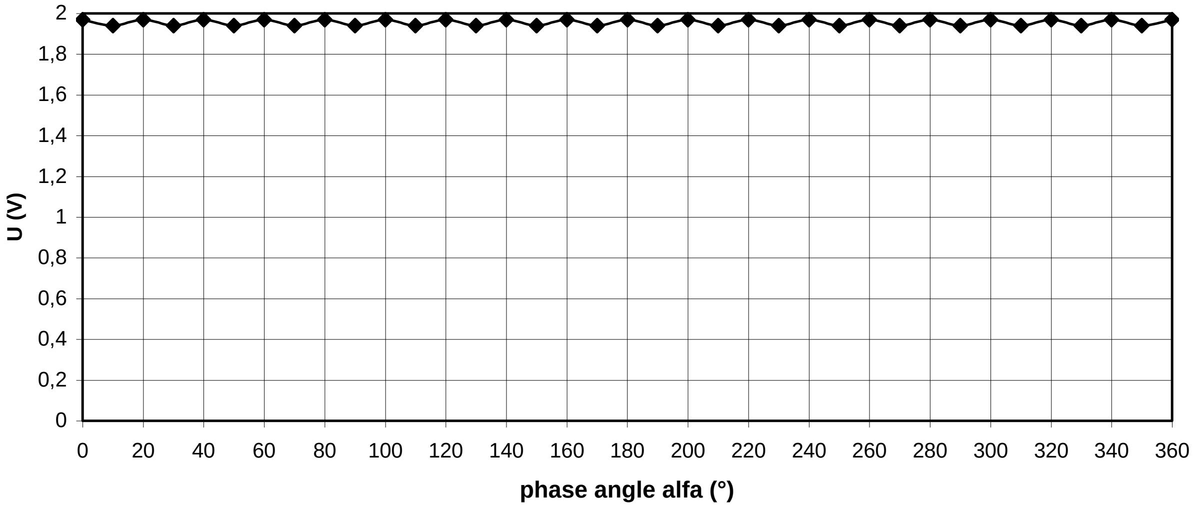

fig. 5 Variation of the DC voltage

The phase current is proportional to the phase voltage if the load is a resistance. The variation of the current in phase Q is given in figure 6 if the maximum current is 1 A.

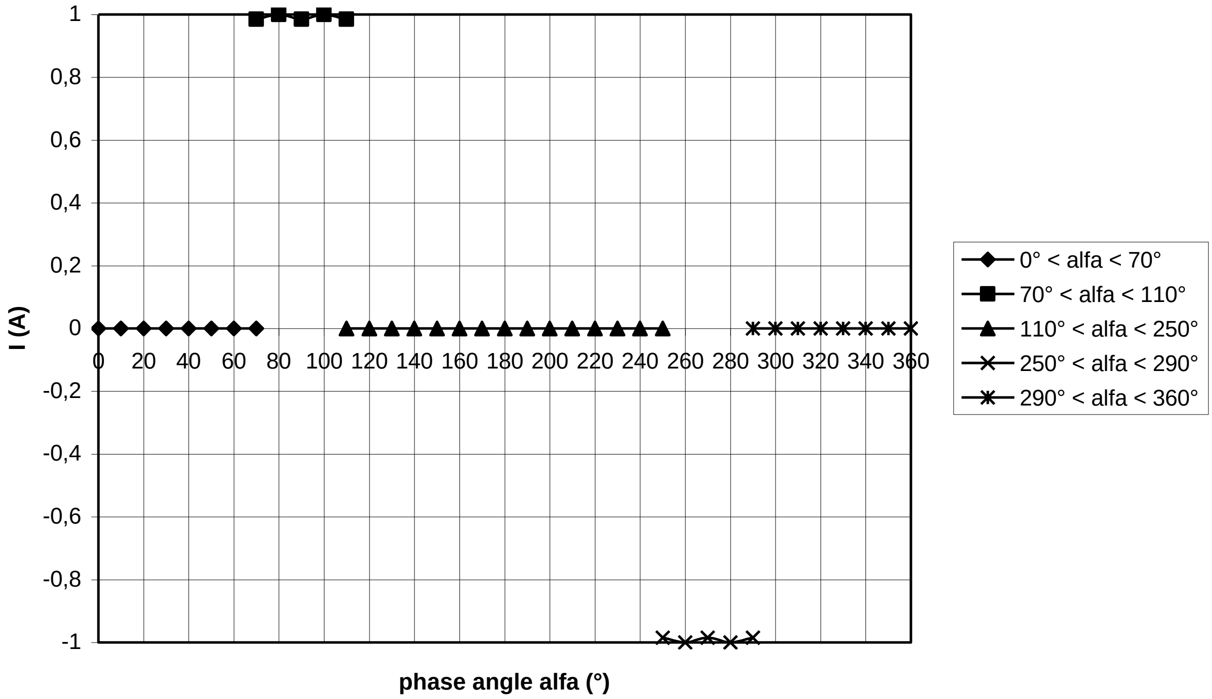

fig. 6 Variation of the current I in phase Q

The rectified current is proportional to the rectified voltage if the load is a resistance. The variation of the rectified current, so in the load resistance R, is given in figure 7 if the maximum current is 1 A.

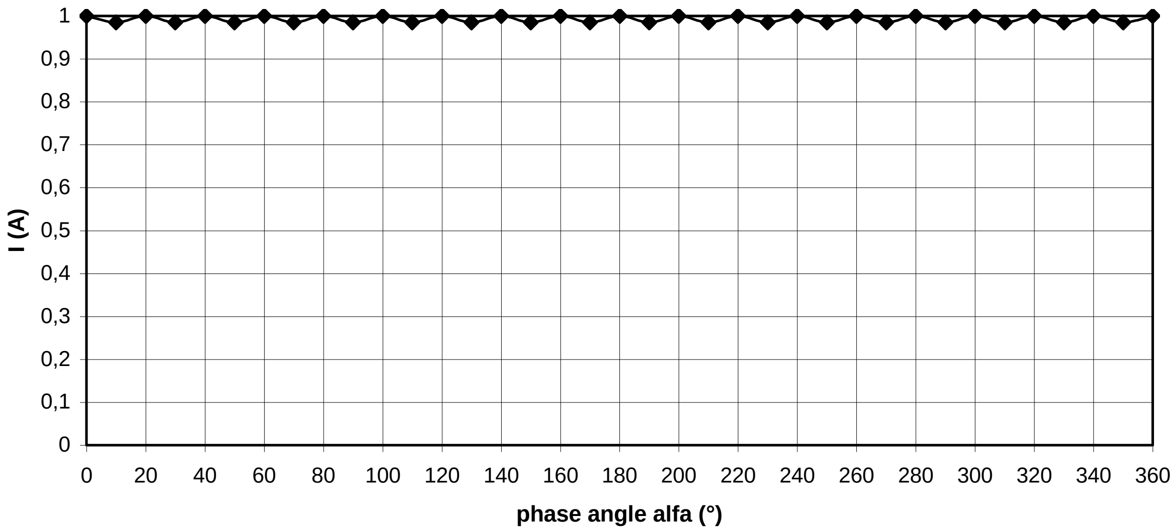

fig. 7 Variation of the rectified current in the load resistance R

In figure 7 it can be seen that the variation of the current is very low and much lower than for a 3-phase current as given in figure 8 of KD 340. However, in figure 6 it can be seen that the coil of a certain phase is only used for 40° of half a sine wave, so only for 2/9 of the time. This makes that a certain phase generates only a small part of the power which can be generated if the phase would be used all the time. For a 3-phase winding, a coil is used during 2/3 of the time and this results in a small power loss of only about 7 %.

The power generated in one phase, if it is used all the time, is given by figure 2 of KD 340. The power generated in a 40° α-range symmetrical around the maximum voltage is about 42 % of the power generated over 180°. So about 58 % of the possible power isn't generated during the time for which the phase isn't active. This is a big disadvantage of this way of rectification with one star point for all nine phases and a 9-phase rectifier.

6.2 Using three separate 3-phase windings and three 3-phase rectifiers

The nine phases are divided into three separate 3-phase windings. So there is no common star point. Every 3-phase winding is rectified with its own 3-phase rectifier and the DC terminals of the three rectifiers are connected in series. The wire diagram is given in figure 9. The first 3-phase winding makes use of the coils Q, U and X. This winding is called winding$_{QUX}$. The phase angle in between the coils of this winding is 120° and so it is a normal 3-phase winding. The second 3-phase winding makes use of the coils S, W and Y. This winding is called winding$_{SWT}$. The third 3-phase winding makes use of the coils T, W and Z. This winding is called winding$_{TWZ}$.

As every winding is now a normal 3-phase winding, the variation of the voltage and the current in each phase is now the same as the variation as given in figure 9 and 8 of report KD 340. So every phase is now used for 2/3 of the time and the power loss in the 1/3 of the time when a phase isn't used, is only about 7 %. This means that about 93 % of the potential power of a phase is used and this is much more favourable than for the way of rectification with one star point as described in chapter 6.1.

So for one of the three 3-phase windings, there is a change of the active phase every 60°. This results in a peak in the voltage and the current every 60°. However, there is a phase angle of 40° in between the three different windings and the peaks therefore don't coincide. As the three rectifiers are connected in series, the three generated DC voltages have to be added.

The voltage variation of the three windings is given in figure 8. The voltage fluctuation of one phase is the same as that of figure 9 out of report KD 340. So the DC peak voltage is taken a factor √3 = 1.732 of the peak voltage of one phase U_{max}. It is assumed that U_{max} = 1 V. The sum of all three voltages is called U_{tot} and U_{tot} is also given in figure 8.

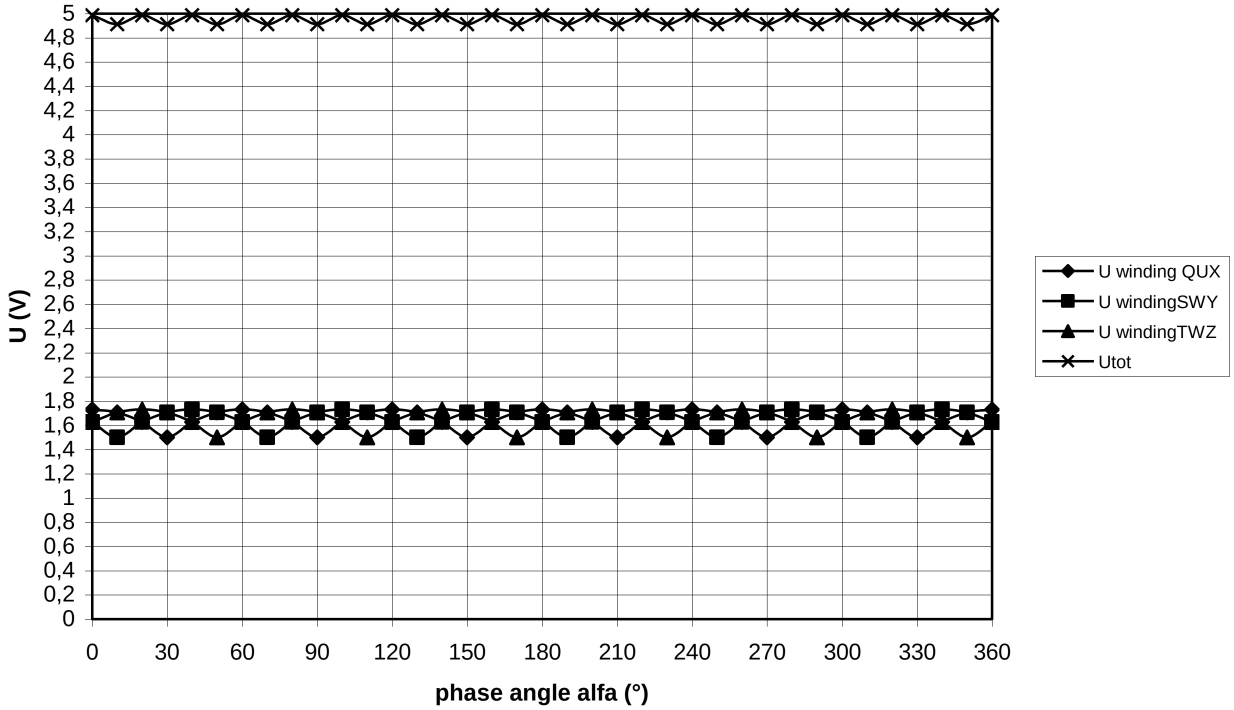

fig. 8 Voltage variation of winding_{QUX}, winding_{SWY} and winding_{TWZ} and sum U_{tot}

In figure 8 it can be seen that the U_{tot}–α curve has a peak value every 20°. So the relative voltage fluctuation is the same as given in figure 5. However, the DC voltage line is lying much higher. The maximum DC voltage is 4.988 * U_{max} and the minimum DC voltage is 4.912 * U_{max}. So the maximum voltage for this way of rectification is a factor 4.988 / 1.970 = 2.52 higher than for the way of rectification as described in chapter 6.1.

The rectified DC voltage has a certain effective value U_{DCeff} which is only a little lower than the peak value of U_{tot}. It can be determined that:

$$U_{DCeff} = 4.962 * U_{max} \quad (V) \qquad (1)$$

The line for U_{DCeff} isn't given in figure 8 because the voltage fluctuation of U_{tot} is very small. The relation in between U_{max} and the effective AC voltage of one phase U_{eff}, is given by formula 9 of report KD 340. This formula can be written as:

$$U_{max} = \sqrt{2} * U_{eff} \quad (V) \qquad (2)$$

(1) + (2) gives:

$$U_{DCeff} = 7.017 * U_{eff} \quad (V) \qquad (3)$$

Formula 3 is valid if the voltage drop over the rectifier diodes is neglected. The current always flows through six diodes. Assume that the voltage drop over one diode = 0.7 V. So the total voltage drop is 4.2 V. Including the voltage drop, formula 3 changes into:

$$U_{DCeff} = 7.017 * U_{eff} - 4.2 \quad (V) \qquad (4)$$

The current will vary in the same way as the voltage and figure 7 is also valid for this second way of rectification if the maximum current is 1 A. So there will be only a very small fluctuation of the current for this second way of rectification of a 9-phase winding. But the maximum power which can be withdrawn from the winding is much larger because every phase is used for 2/3 of the time instead of 2/9 of the time for rectification with one star point for all nine windings.

So using three separate 3-phase windings and three separate 3-phase rectifiers connected in series is a much better option. I think that a 9-phase winding with three separate 3-phase windings therefore has a big advantage above a normal 3-phase winding if a small fluctuation of the DC current is wanted. The very small variation which remains, can be flattened with small capacitors if needed. The wire diagram is given in figure 9.

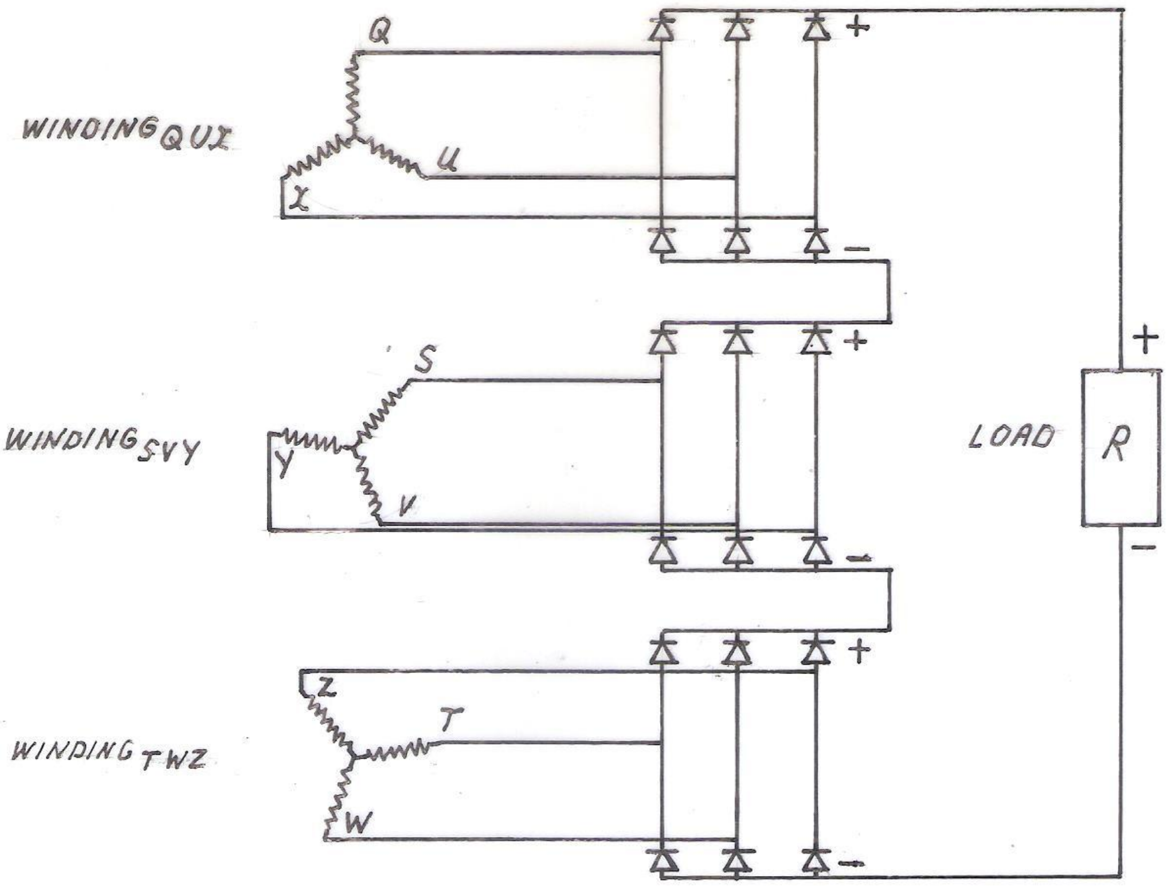

fig. 9 Rectification in star of a 9-phase winding with three separate 3-phase windings

Grid connected wind turbines normally make use of a 3-phase generator for which the winding is rectified in star. A 3-phase inverter is used to connect the generator to the 3-phase grid with a frequency of 50 Hz and a voltage which depends on the grid voltage. The output power of this inverter isn’t fluctuating because the sum of the power of the three phases is constant. So if the input power is also not fluctuating, no capacitors are needed to absorb the fluctuations. A normal 3-phase winding gives a rather strong fluctuation of the DC voltage and current and so an even stronger fluctuation of the DC power. So capacitors are certainly needed for a 3-phase generator and grid connection.

There might be other reasons than grid connection why a very small fluctuation of the DC current is wanted and so there might be other reasons why a 9-phase winding is a better choice than a 3-phase winding.

A 9-phase winding has another advantage above a 3-phase winding which has nothing to do with the much smaller fluctuation of the DC current. A 4-pole armature has a pole angle of 90° and so the optimum angle in between the left leg and the right leg of a coil is 90° too. This is realized for the 9-phase PM-generator if the stator stamping has 36 slots.

The optimum number of stator slots for a 4-pole, 3-phase armature is 3 * 4 = 12 because then all coils have an angle of 90° in between the left and the right leg of a coil. However, a stator stamping with 36 slots is very often used for 4-pole asynchronous motors and 4-pole PM-generators. The fact that the number of stator slots is a factor three too high is solved by mounting three coils around each other. The inner coil has an angle in between the left and the right leg of 70°, the middle coil has an angle of 90° and the outer coil has an angle of 110°. Such a winding is given in figure 1 of report KD 341 (ref. 1).

So the angle of the inner and the outer coil deviates from the optimum angle of 90° and therefore a magnetic flux which is about a factor 70/90 = 7/9 lower than for the middle coil is flowing through the inner and outer coil. This means that a much lower voltage is generated for these coils than for the middle coil if all coils have the same number of turns per coil. All three coils are connected in series but the inner coil and the outer coil produce about a factor 7/9 less power than the middle coil.

A 4-pole asynchronous motor can be transformed into a 4-pole PM-generator if the short-circuit armature is replaced by a PM armature. This procedure is described in chapter 4 of report KD 341 (ref. 1). So a 4-pole, 9-phase PM-generator can produce more power than a 4-pole, 3-phase generator if both make use of the same PM-armature, the same stator stamping with 36 slots, the same amount of copper in the slots and run at the same rpm.

The advantage of a 9-phase winding for a PM-generator might also be valid for a 9-phase PM-motor if the energy source is a battery. So a constant power extraction from the battery results in an almost constant mechanical power of the motor and so in a very constant torque level. For this use, the motor must also have three separated 3-phase windings and one needs three, 3-phase inverters connected in series. There must be a phase angle of 40° in between the phase angles of corresponding phases of the three inverters.

7 Ideas about a 32-pole generator with a 9-phase winding

The 9-phase winding of the 4-pole motor as described in chapter 5 is rather complex. This is because the nine coils of nine phases must be laid like tiles around each other. It appears to be possible to get a much simpler 1-layer winding if 32 armature poles are chosen for a stator with 36 poles. So the ratio in between the number of armature poles and the number of stator poles is 8 : 9. This idea also works for an armature with 48 poles and a stator with 54 poles and for an armature with 64 poles and a stator with 72 poles. But it will be described for the simplest version, so for an armature with 32 poles and a stator with 36 poles.

It is chosen to use the stator stamping of a 2.2 kW, 6-pole motor frame size 112M of manufacture Kienle & Spiess. The geometry of this stamping can be found on the website: www.kienle-spiess.de. The outside diameter of the stator stamping is 170 mm. The inside diameter of the stator stamping is 115 mm. The length of the stator stamping is 140 mm. This stamping has 36 slots in which the coils are laid. Eighteen coils can be laid in the 36 slots of a stator with 36 poles. One coil is laid around one stator spoke. So the coil head is very small resulting in little copper losses in the coil heads. The coils are laid in the sequence: Q1, S1, T1, U1, V1, W1, X1, Y1, Z1, Q2, S2, T2, U2, V2, W2, X2, Y2 and Z2. The nine phases are rectified such as described in chapter 6.2. So the winding is seen as three different 3-phase windings.

It is assumed that the original motor shaft and bearing covers are used but that the short-circuit armature is removed from the shaft and replaced by an iron bush with an outside diameter of 115 mm and a length of 140 mm. This bush is turned to an outside diameter of 114.4 mm. So the air gap in between the armature and the stator is 0.3 mm.

Sixteen 10 mm wide and 4.4 mm deep grooves are milled in the bush in parallel to the armature axis and at an angle of 22.5° with respect to each other.

The chosen magnets have size 40 * 10 * 4 mm. These magnets have quality N38 and are supplied by the Polish company Enes Magnets website: www.enes-magnets.pl. The price is € 1.80 per piece (December 2022) including VAT but excluding costs of transport if 250 magnets are ordered. The length of the armature is 140 mm, so 3 ½ magnets have to be glued in one groove. The means that a 40 mm long magnet has to be broken in two 20 mm long parts which can be done by first making a deep scratch in the middle. So totally 16 * 3 ½ = 56 magnets are needed and the total magnet costs are about € 101 which is certainly acceptable.

As the coil heads are much smaller than the coil heads of the original 6-pole motor, there is space for a longer stator with a length of 160 mm. Assume that a 160 mm long stator can be obtained. So now the length of the armature becomes 160 mm and four magnets are glued in each groove. The total number of magnets required is now 16 * 4 = 64.

All magnets are glued such that the north pole is pointing to the outside of the armature. The south poles are formed by the remaining material in between the magnets. To make that the south poles also have a width of about 10 mm, a 1.2 mm wide and 3 mm deep groove is made at each side of a magnet groove. These grooves also prevent magnetic short-circuit in between the sides of the magnets. A side view of armature and stator is given in figure 10.

The stator pole angle is 360° / 36 = 10°. The armature pole angle is 360° / 32 = 11.25°. So the difference is 1.25°. It is assumed that the armature has a preference position if an armature pole is just opposite a stator pole. So this happens every 1.25° and this means that the armature has 360 / 1.25 = 288 preference positions per revolution. It can be expected that the fluctuation of the sticking torque is almost flattened for these many preference positions.

The stator poles are numbered 1 – 36. The magnetic poles are numbered N1, S1, N2, S2, N3, S3 and so on. The armature is drawn such in figure 10 that the armature pole N1 is just opposite to stator pole 1. The winding Q1 lies around stator pole 1. The winding S1 lies around stator pole 3. The winding T1 lies around stator pole 5 and so on. So the angle in between two adjacent stator coils is 20°

The angle in between two adjacent north poles is 22.5°. This means that the armature has the same magnetic orientation if it has rotated 22.5° So a mechanical angle $\beta = 22.5°$ corresponds to a phase angle $\alpha = 360°$. So a mechanical angle $\beta = 1°$ corresponds to a phase angle $\alpha = 16°$.

In figure 10 it can be seen that the angle β in between north pole N1 and coil Q1 is 0° and it is assumed that the phase angle $\alpha = 0°$ for this position of the armature.

In figure 10 it can be seen that the angle β in between the north pole N1 and the coil S1 is 20°. So the phase angle $\alpha = 16 * 20° = 320°$ for this position of the armature. A phase angle of 320° is the same as a phase angle of 320° - 360° = -40°. This corresponds to the required difference in phase angle of 40° for a 9-phase winding.

In figure 10 it can be seen that the angle β in between the north pole N1 and the coil T1 is 40°. So the phase angle $\alpha = 16 * 40° = 640°$ for this position of the armature. A phase angle of 640° is the same as a phase angle of 640° - 2 * 360° = -80°. So this also corresponds to the required difference in phase angle of 2 * 40° for a 9-phase winding. In the same way it is found that there is also a phase angle of 40° in between the other phases. So the chosen geometry of the coils results in a 9-phase winding if the armature has 32 poles. The two coils of one phase are connected in series. All eighteen coils must have the same winding direction.

The original front motor shaft has a diameter of 28 mm, a length of 60 mm and an 8 mm wide key groove. This shaft might be strong enough to be used for a 3-bladed windmill rotor with a maximum rotor diameter of 3 m if the windmill has a proper safety system. Determination of the winding of the generator, such that the P_{mech}-n curve of the generator for the chosen load matches optimal to the cubic line of the chosen rotor, is out of the scope of this report.

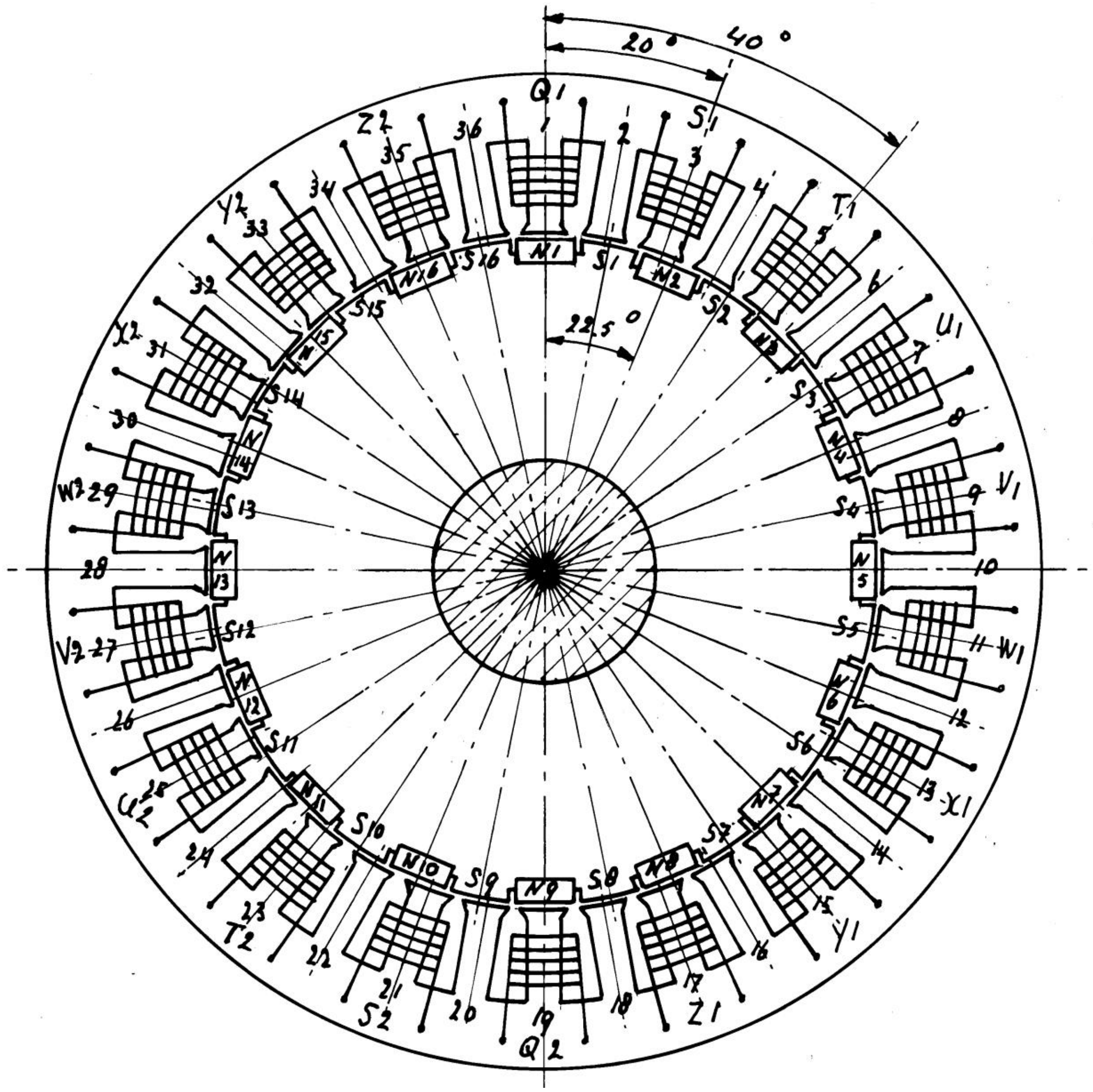

fig. 10 32-pole generator and a stator with a 9-phase winding

It is easy to prove that a 9-phase current is also generated if the armature has 40 poles. Using the same magnets size 40 * 10 * 4 mm, now a 6-pole housing frame size 132M can be used.

8 References

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