Rectification of 3-phase VIRYA windmill generators

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1 Introduction

Up to now Kragten Design has developed thirteen electricity generating windmills with rotor diameters in between 1.2 and 4.6 metre. All these windmills are provided with 4-pole PM-generators which are made of standard asynchronous motors. The normal short-circuit armature is replaced by a permanent magnet armature for which neodymium magnets are used. All VIRYA windmills are used for 24 or 48 V battery charging and the 3-phase current coming out of the generator has therefore to be rectified.

For certain small VIRYA windmills the rectifier is incorporated in the generator. For the medium size VIRYA windmills the rectifier is situated near the batteries. For the biggest VIRYA windmills the rectifier is mounted in a box situated at the tower foot. The position of the rectifier has an influence on the cable losses which will be explained in chapter 5.

For some VIRYA windmills the generator is rectified in delta and for others it is rectified in star. This report is written to explain some basic knowledge about electricity and to explain how the rectification process works and how the generator has to be connected for the two different ways of rectification.

2 Different kind of currents and voltages

Three different kind of currents and voltages can be distinguished.
1) Direct current (DC).
2) 1-phase alternating current (1-phase AC).
3) 3-phase alternating current (3-phase AC).

2.1 Direct current

Direct current is supplied by an energy source like a battery or by a DC-motor. A direct current is constant for a constant voltage if the load is a resistance. For direct current, some very simple formulas are valid.

$$U = I * R \quad \text{(V)} \tag{1}$$

$$P = U * I \quad \text{(W)} \tag{2}$$

U is the voltage. The dimension of the voltage is Volt (V)
I is the current. The dimension of the current is Ampere (A).
R is the resistance of the load. The dimension of the resistance is Ohm (Ω).
P is the power. The dimension of the power is Watt (W).

(1) + (2) gives:

$$P = I^2 * R \quad \text{(W)} \tag{3}$$

$$E = P * t \quad \text{(Ws or Joule)} \tag{4}$$

In this formula E is the energy in Watt seconds (Ws) and t is the time. The dimension of the time is second (s). In stead of Ws one sometimes uses the dimension Joule.

If no load is connected to a battery, one measures the open voltage U_{open} but no current. A current is only flowing if a certain resistance R is connected to the plus and minus poles of the battery. The highest current is flowing for a connection with almost no resistance like it is the case for short-circuit. The current causes a certain reduction of the battery voltage which is caused by the internal resistance of the battery. The voltage reduction is higher as the current is higher and as de capacity of the battery is lower.

The capacity of a battery is an indication for the energy which can be extracted from a full battery till the voltage is reduced to a certain value, which is about 11 V for a 12 V battery.

Electrical energy is normally given in Ws but for the battery capacity one normally uses the unit Ampere hours (Ah). The capacity of a battery is normally measured for a discharge time of 10 hours. Suppose a 60 Ah, 12 V battery is chosen. So a full 60 Ah battery is discharged by a current of 60 / 10 = 6 A during a period of 10 hours. If the battery would be discharged in one hour with a current of 60 A, the minimum voltage of 11 V will be reached in less than 1 hour so the capacity will be less than 60 Ah. This is caused by internal heat produced in the battery because of the high current. If the battery is discharged with a current of 3 A, it will take more than 20 hours until the minimum voltage of 11 V is reached and the capacity will therefore be more than 60 Ah.

Suppose a 60 Ah, 12 V battery is discharged over 10 hours with I = 6 A. The open voltage of a full 12 V battery is about 12.5 V. The voltage during discharge with I = 6 A in ten hours will reduce from about 12 V in the beginning till about 11 V at the end. So the average discharge voltage will be about 11.5 V. Substitution of U = 11.5 V and I = 6 A in formula 2 gives a power P = 69 W. The discharge time is 10 hours or 10 * 3600 = 36000 s. Substitution of P = 69 W and t = 36000 s in formula 4 gives E = 2484000 Ws. So a capacity of 60 Ah for a 12 V battery corresponds to an energy E of about 2484000 Ws. So a capacity of 1 Ah for a 12 V battery corresponds to an energy E of about 2484000 / 60 = 41400 Ws.

The battery efficiency is about 0.7 (-). So the required energy to charge a 60 Ah, 12 V battery is about 2484000 / 0.7 = 3548570 Ws. For a charging current of 6 A and an average charging voltage of 13.5 V, the average charging power is 81 W. So the charging time is 3548570 / 81 = 43810 s or 12.17 hour.

A 6 V battery with a certain capacity has half the energy content as for a 12 V battery with the same capacity! A 24 V battery with a certain capacity has double the energy content as for a 12 V battery with the same capacity!

2.2 1-phase alternating current

The voltage of a 1 phase alternating current is fluctuating sinusoidal with a certain frequency f. The frequency f is the number of oscillations per second. The dimension of the frequency is Herz (Hz). An oscillation is one complete sine wave so including one positive and one negative part of the curve. One complete sine wave corresponds to a phase angle α = 360°. The formulas for direct current are also valid for the momentary values of an alternating current if the load is a resistor. The momentary current is therefore also fluctuating sinusoidal and in phase with the voltage. If the load is a coil or a capacitor, voltage and current are no longer in phase. An example of a 1 phase sinusoidal voltage variation is given in figure 1. In figure 1 it is chosen that U_{max} = 1 V.

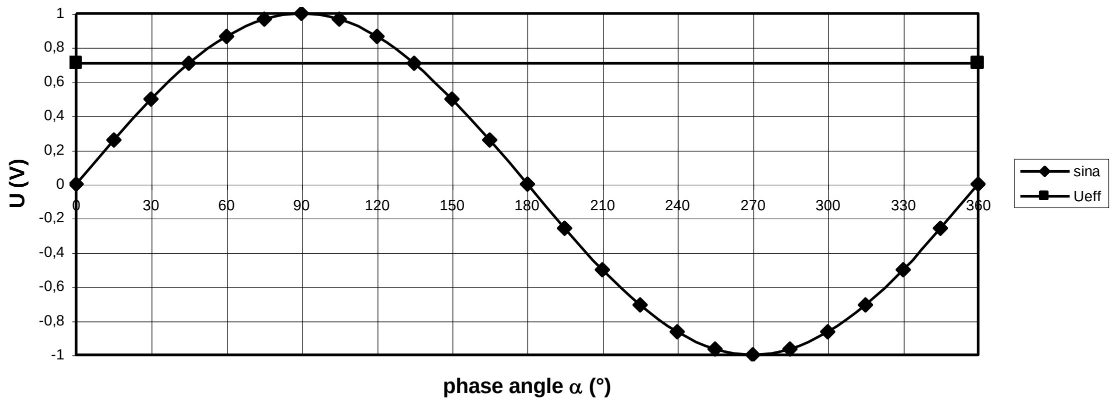

fig. 1 Sinusoidal voltage variation and effective voltage U_{eff} as a function of α

The grid frequency in Europe is 50 Hz but there are countries with a grid frequency of 60 Hz. The frequency of a 1-phase generator depends on the rotational speed n of the generator and on the number of armature poles p. n is the rotational speed in revolutions per minute (rpm). Sometimes p is used for the number of pole pairs which is half the number of poles but I use p for the number of poles. So for a 4-pole generator, p = 4. The frequency f is given by:

$f = n * p / 120$ (Hz) (5)

Suppose n = 1500 rpm and p = 4. Substitution of this values in formula 5 gives f = 50 Hz.

The voltage has a peak value U_{max} at a phase angle $\alpha = 90°$. The momentary voltage U is given by:

$U = U_{max} * \sin\alpha$ (V) (6)

The momentary current I, for a resistance as load, is given by:

$I = I_{max} * \sin\alpha$ (A) (7)

So the shape of figure 1 is also valid for the variation of the current as a function of α. For the momentary power P, formula 2 can also be used for an AC current if the load is a resistance. So (2) + (6) + (7) gives:

$P = U_{max} * I_{max} * \sin^2\alpha$ (W) (8)

The variation of P is given in figure 2 for I_{max} = 1 A and U_{max} = 1 V. This results in P_{max} = 1 W.

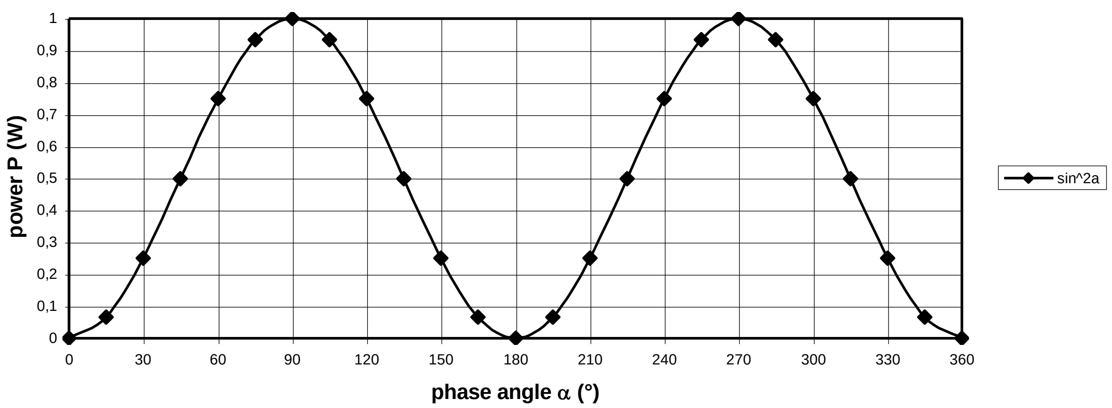

fig. 2 Power variation of a 1-phase current as a function of the phase angle α

In figure 2 it can be seen that the average power over 360°, so over one complete sine wave of the voltage and the current, is $0.5 * U_{max} * I_{max}$.

For a 1-phase sinusoidal voltage and current variation it is very common to speak about the effective voltage U_{eff} and the effective current I_{eff}. The effective voltage is the DC voltage for which the same power is generated in a resistance as for a voltage which is fluctuating sinusoidal. The effective current is the DC current for which the same power is generated in a resistance as for a current which is fluctuating sinusoidal.

It can easily be proven that:

$U_{eff} = 0.5 \sqrt{2} * U_{max}$ (V) (9)

$I_{eff} = 0.5 \sqrt{2} * I_{max}$ (A) (10)

If these values are substituted in formula 2 we find that $P = 0.5 * U_{max} * I_{max}$ and this is the same as the average power of figure 2. The effective voltage $U_{eff} = 0.5 \sqrt{2}\ U_{max} = 0.7071 * U_{max}$ is also given in figure 1. If the 1-phase alternating voltage or current is measured with a volt or an ampere meter, one measures the effective values.

2.3 3-phase alternating current

A 3-phase alternating current has three phases called U, V and W. For some countries like India, they are called R, Y and B according to the colours red, yellow and blue which are used for the three phases but I will use U, V and W. The phase angle in between the phases is 120°. The voltage variation of the three phases is given in figure 3.

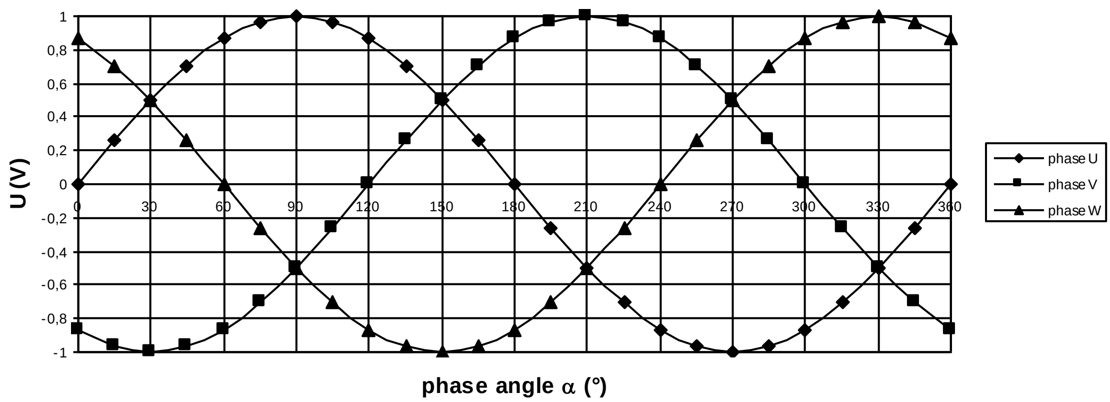

fig. 3 Voltage variation for phases U, V and W as a function of α

One of the three phases has the highest voltage and one has the lowest voltage for a certain α domain. This is changing every 60°. This effect is important if a 3-phase current is rectified.

For 30° < α < 90°, phase U has the highest voltage and phase V has the lowest voltage.
For 90° < α < 150°, phase U has the highest voltage and phase W has the lowest voltage.
For 150° < α < 210°, phase V has the highest voltage and phase W has the lowest voltage.
For 210° < α < 270°, phase V has the highest voltage and phase U has the lowest voltage.
For 270° < α < 330°, phase W has the highest voltage and phase U has the lowest voltage.
For 330° < α < 390°, phase W has the highest voltage and phase V has the lowest voltage.

3 Rectification

3.1 Rectification of 1-phase alternating current

Rectification of a 1-phase alternating current is done by means of four diodes which are connected in the form of a so called bridge. As the VIRYA generators are 3-phase generator this kind of rectification is not described in detail. The effect is that the negative part of the sine wave is becoming positive. So a rectified 1-phase current has the shape as given in figure 4. The current is positive but it has a very large ripple.

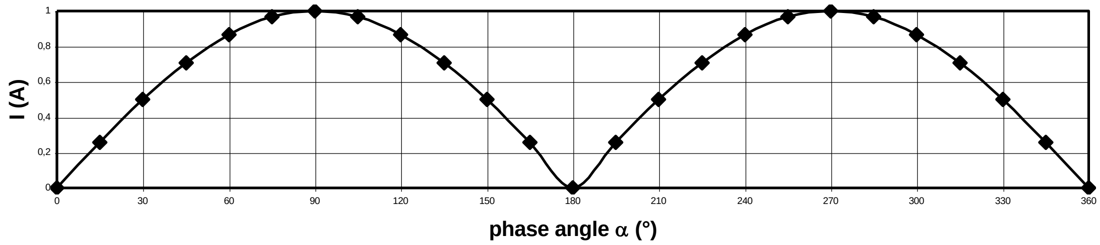

fig. 4 Variation of the current I as a function of α for 1-phase rectification

3.2 Rectification of 3-phase alternating current

A three phase current can be rectified in star or in delta. The disadvantage of delta rectification is that higher harmonic currents can circulate in the generator winding resulting in a lower efficiency. However, the advantage of delta rectification is that the maximum torque level is higher which is especially important if the generator is used as a brake. A difference in between star and delta rectification is that the rectified voltage for star rectification is a factor $\sqrt{3}$ higher than for delta rectification. For almost all VIRYA generators a standard 230/400 V or 400/690 V, 3-phase winding is used. A standard winding in combination with a certain battery voltage sometimes requires delta rectification to realise a good matching in between rotor and generator.

A three phase rectifier contains 6 diodes. There are integrated 3-phase rectifiers available which are rather expensive but one can also make a 3-phase rectifier from six separate diodes or from three blocks of two diodes. It is even possible to make a 3-phase rectifier from three 1-phase bridge rectifiers if the AC points of the bridge rectifiers are connected. In this case two diodes are connected in parallel.

Diodes are specified for a maximum voltage and for a maximum current. The maximum voltage is normally not reached for battery charging. However, the maximum current is only allowed for a very low diode temperature. The cooling of the rectifier can be enlarged by placing the rectifier on a heat sink. But even if a heat sink is used, my experience is that the rectifier should not be used for currents larger than about half the nominal value other wise the life time of the rectifier will not be long enough.

A diode is an electronic component which guides current only in one direction. The symbol of a diode is a triangle with a bar on one of the points. The triangle is placed in the line of the wire diagram with the bar perpendicular to the line. The current can flow only in the direction of the point of the triangle.

High power diodes are made out of silicon. Except for very low currents, there is a voltage drop of about 0.7 V in the direction of the current. For a 3-phase rectifier only two of the six diodes are conducting current, so the total voltage drop over the rectifier is about 1.4 V. So the energy loss in the rectifier is 1.4 times the current. Voltage and current of the VIRYA generators are measured after the rectifier, so the energy loss in the rectifier is incorporated in the generator efficiency. The wire diagram for star rectification is given in figure 5 and for delta rectification is given in figure 6.

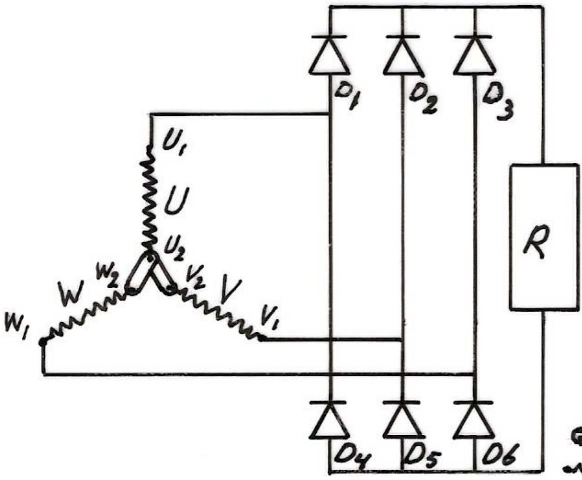

fig. 5 Star rectification

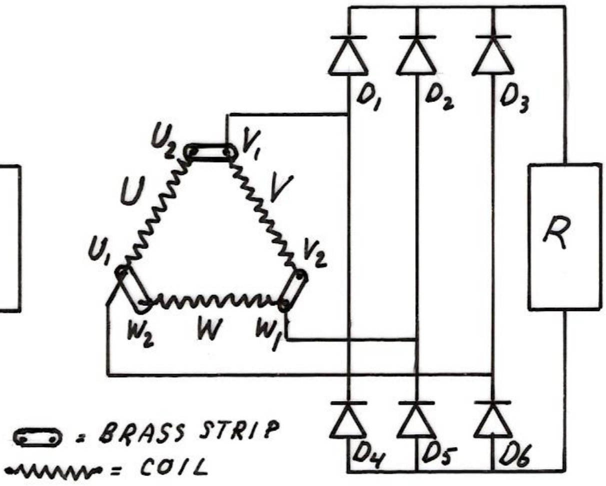

fig. 6 Delta rectification

3.2.1 Star rectification

From the three upper diodes D_1, D_2 and D_3 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 three lower diodes D_4, D_5 and D_6 only the one which has the lowest voltage will conduct a current. In figure 3 it can be seen which of the phases has the highest and which of the phases has the lowest voltage at a certain angle α.

Now lets take the domain $30° < \alpha < 90°$. For this domain phase U has the highest voltage and phase V has the lowest voltage. So a current will flow only through these phases and no current will flow through phase W. The current will flow in the following sequence: phase V, phase U, diode D_1, load resistor R and diode D_5.

Now lets take the domain $90° < \alpha < 150°$. 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 phase V. The current will flow in the following sequence: phase W, phase U, diode D_1, load resistor R and diode D_6.

So every 60° 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 will now be calculated for $\alpha = 30°$, $\alpha = 45°$, $\alpha = 60°$, $\alpha = 75°$ and $\alpha = 90°$ for $U_{max} = 1$ V using figure 3 .
For $\alpha = 30°$ it can be seen that $U_U = 0.5$ V and $U_V = -1$ V so $\Delta V = 1.5$ V.
For $\alpha = 45°$ it can be seen that $U_U = 0.7071$ V and $U_V = -0.9659$ V so $\Delta V = 1.673$ V.
For $\alpha = 60°$ it can be seen that $U_U = 0.8660$ V and $U_V = -0.8660$ V so $\Delta V = 1.732$ V.
For $\alpha = 75°$ it can be seen that $U_U = 0.9659$ V and $U_V = -0.7071$ V so $\Delta V = 1.673$ V.
For $\alpha = 90°$ it can be seen that $U_U = 1$ V and $U_V = -0.5$ V so $\Delta V = 1.5$ V.
The voltage difference ΔV is highest for $\alpha = 60°$. The value $\Delta V = 1.732$ V for $\alpha = 60°$ corresponds to $\Delta V = \sqrt{3} * U_{max}$. So ΔV varies in between $\Delta V = 1.5 * U_{max}$ and $\Delta V = \sqrt{3} * U_{max}$. The current will vary with the same rate if the load is a resistance.

The voltage difference ΔV in between phase U and phase W will vary in the same way for $90° < \alpha < 150°$. So a current will flow through phase U which has a maximum value at $\alpha = 60°$ and at $\alpha = 120$. For the domain $150° < \alpha < 210°$ no current will flow through phase U because the voltage is laying in between the voltage of phase V and phase W. For the domain $210° < \alpha < 330°$ we have the same variation of the current except that the current is negative. The variation of the current in phase U for $0° < \alpha < 360°$ is given in figure 7.

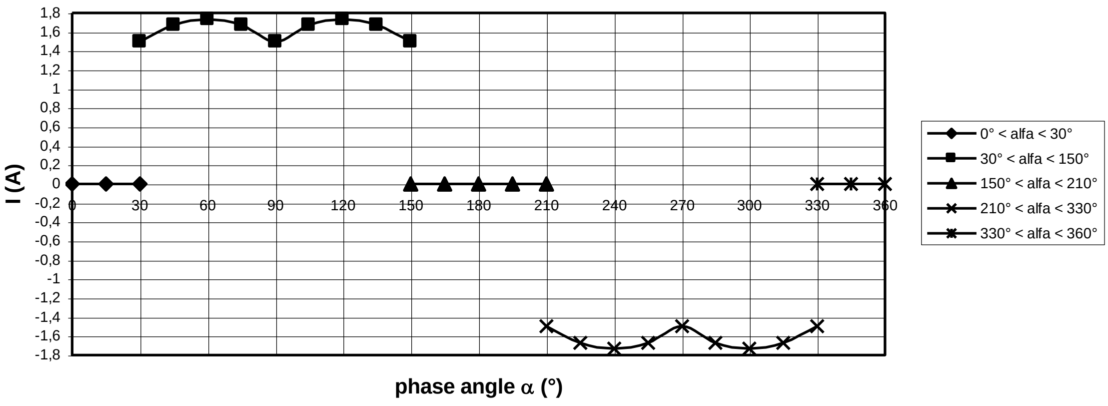

fig. 7 Variation of the current I in phase U

The variation of the rectified current, so in the load resistance R, is given in figure 8.

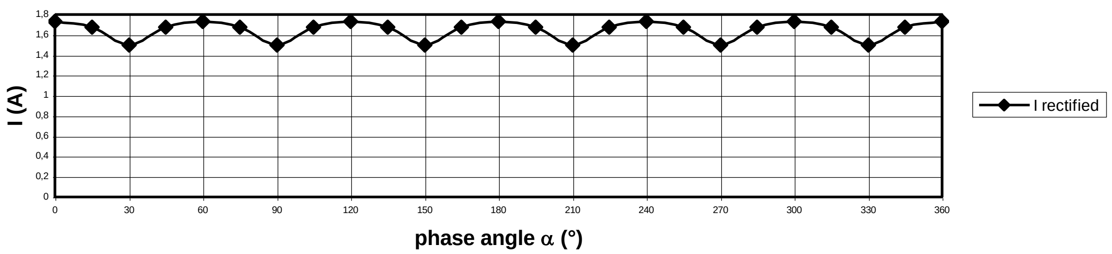

fig. 8 Variation of the rectified current in the load resistance R

The variation of the current given in figure 7 and 8 is only relative. The real magnitude of the current depends on the load resistance R and on the strength of the generator. The rectified voltage varies in the same way as the variation of the current given in figure 8. For the voltage curve, the given voltage is the absolute value if the U_{max} of one phase is 1 V. The variation of the rectified voltage is given in figure 9.

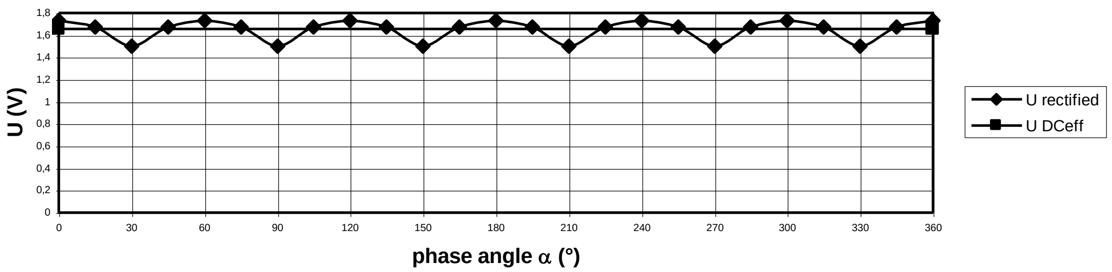

fig. 9 Variation of the rectified voltage after the rectifier

So the DC voltage has a small ripple on it but the variation is much lesser than for a rectified 1-phase current. For the rectified DC voltage it is also possible to calculate an effective value U_{DCeff}. It can be proven that this effective value is 0.955 times the peak value. The peak value is a factor $\sqrt{3}$ times U_{max} (U_{max} is the peak value of the voltage of one phase) resulting in:

$$U_{DCeff} = 0.955 * \sqrt{3} * U_{max} \qquad (V) \qquad (11)$$

U_{DCeff} is also given in figure 9.

Formula 9 can be written as:

$$U_{max} = \sqrt{2} * U_{eff} \qquad (V) \qquad (12)$$

(11) + (12) gives:

$$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff} \qquad (V) \qquad (13)$$

The term $0.955 * \sqrt{2} * \sqrt{3} = 2.339$, so star rectification results in a rather large increase of the rectified voltage compared to the effective phase voltage. Formula 13 is true if the voltage drop over the rectifier $U_{rect} = 1.4$ V is neglected. If this voltage drop is not neglected, formula 13 changes into:

$$U_{DCeff} = 0.955 * \sqrt{2} * \sqrt{3} * U_{eff} - 1.4 \qquad (V) \qquad \text{(star rectification)} \qquad (14)$$

The voltage drop over the rectifier can't be neglected if the nominal battery voltage is rather low, for instance 12 V. For 24 V or 48 V systems, the voltage drop over the rectifier is relatively small.

The effective phase voltage U_{eff} depends on the generator winding, on the PM-armature, on the rotational speed and on the load. The loaded voltage for a certain rotational speed will always be lower than the unloaded voltage.

3.2.2 Delta rectification

Description of delta rectification is more complicated than of star rectification. The reason is that for delta rectification there is no period for which no current is flowing through one phase. For delta rectification, the maximum and minimum voltage are determined by only one phase winding. The voltage difference for one phase winding is the vertical distance in between the curve of a certain phase and the α-axis (see figure 3).

Now lets take the domain 60° < α < 120°. For this domain phase U has the highest voltage. The absolute value of the voltage for both phase V and phase W is lower. So phase U is determining that D_1 and D_6 are conduction. So a current I_U will flow in the following sequence: phase U, diode D_1, load resistor R and diode D_6. However, parallel to the current in phase U there will also flow a current I_{VW} in phase V and W. These phases are connected in series and have together the double resistance as phase U. The current I_{VW} is therefore half the current I_U. So I_U is 2/3 * I of and I_{VW} is 1/3 * I. I is the total current I which is going through the resistor and diodes D_1 and D_6.

The voltages difference will now be calculated for α = 60°, α = 75°, α = 90°, α = 105° and α = 120° for $U_{max} = 1$ V using figure 3 .
For α = 60° it can be seen that $U_U = 0.8660$ V, $U_V = -0.8660$ V and $U_w = 0$ V,
so $U_V + U_W = -0.8660$ V.
For α = 75° it can be seen that $U_U = 0.9659$ V, $U_V = -0.7071$ V and $U_w = -0.2588$ V,
so $U_V + U_W = -0.9659$ V.
For α = 90° it can be seen that $U_U = 1$ V, $U_V = -0.5$ V and $U_w = -0.5$ V,
so $U_V + U_W = -1$ V.
For α = 105° it can be seen that $U_U = 0.9659$ V, $U_V = -0.2588$ V and $U_w = -0.7071$ V,
so $U_V + U_W = -0.9659$ V.
For α = 120° it can be seen that $U_U = 0.8660$ V, $U_V = 0$ V and $U_w = -0.8660$ V,
so $U_V + U_W = -0.8660$ V.

So the absolute value of $U_v + U_w$ is the same as U_U for every value of α. This means that no current will circulate in the delta connection of the three coils. However, in reality the voltage variation will not be exactly sinusoidal and therefore some current will circulate in delta. This causes a higher unloaded and higher short-circuit torque for delta rectification than for star rectification.

The direction of the current in a phase is taken positive if the current is flowing right hand. So the current in phase U is positive but the current in phase V and W is negative for 60° < α < 120°. The variation of I_U as a function of α is given in figure 10.

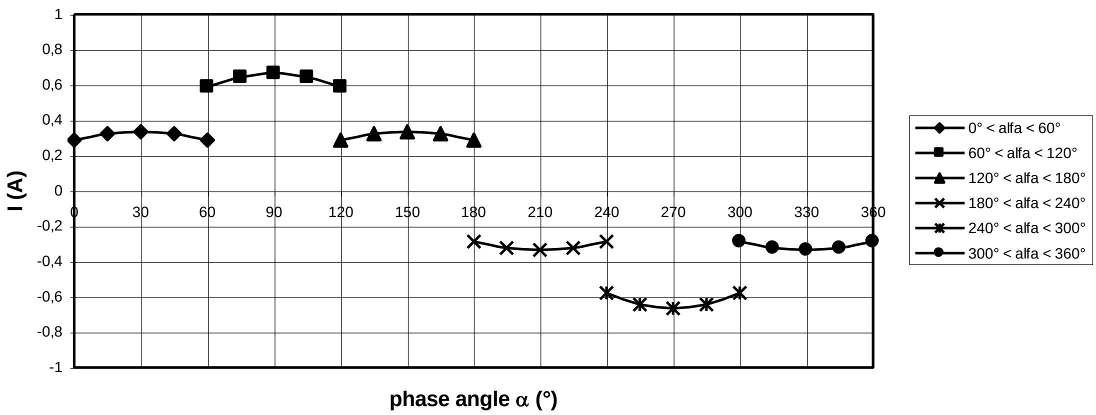

fig. 10 Variation of the current I_U

The variation of the rectified current is given in figure 11.

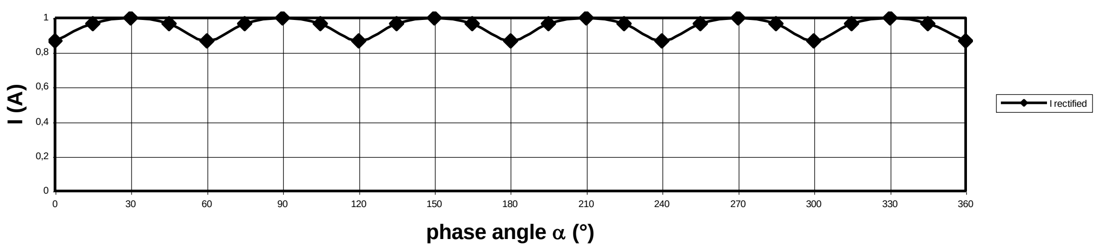

fig. 11 Variation of the rectified current I in the load resistance R

The variation of the current given in figure 10 and 11 is only relative. The real magnitude of the current depends on the load resistance R and on the strength of the generator. The variation of the rectified voltage is given in figure 12. This figure is almost the same as figure 9 except that it is shifted 30° and that the voltage is a factor $\sqrt{3}$ lower.

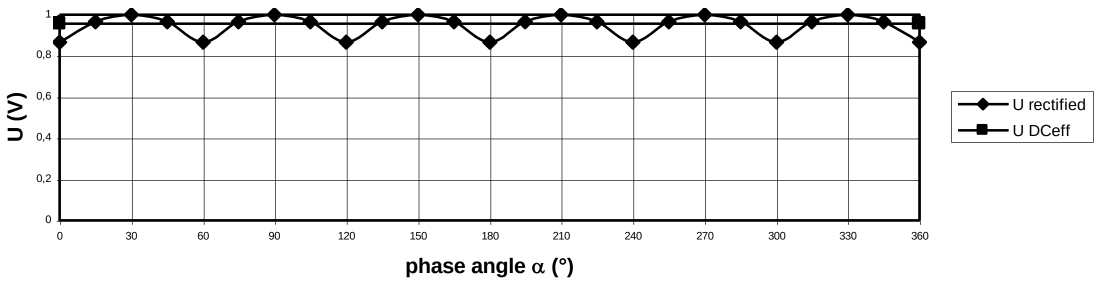

fig. 12 Variation of the rectified voltage after the rectifier

The rectified voltage for delta rectification is a factor √3 lower than for star rectification. So the formula for U_{DCeff} is given by:

$$U_{DCeff} = 0.955 * \sqrt{2} * U_{eff} - 1.4 \quad (V) \quad \text{(delta rectification)} \qquad (15)$$

4 Strip positioning at the terminal for star and delta connection

A three phase winding basically contains three coils U, V and W. It practice a phase coil is build up from several smaller coils which are normally connected in series but this phenomenon is neglected for this moment. So each coil has two ends which are indicated by the indices 1 and 2. So three coils are having six the coil ends U_1, U_2, V_1, V_2, W_1 and W_2.

The terminal is situated in the terminal box which is positioned on top of the generator. The terminal has six connecting points in two rows of three points. The lowest points are called U_1, V_1 and W_1. The highest points are called W_2, U_2 and V_2. The name of the connecting point is the same as the name of the coil end which is connected to it. So point U_1 is opposite point W_2, point V_1 is opposite point U_2 and point W_1 is opposite point V_2. The three external cables to the rectifier are called L_1, L_2 and L_3. L_1 is connected to U_1, L_2 is connected to V_1 and L_3 is connected to W_1. These definitions are used by the Dutch manufacturer ROTOR which supplies the housings of the VIRYA generators.

The terminal is supplied with three brass strips which are used to connect certain connecting points to each other. For delta connection three strips are required. For star connection only two strips are enough but mostly one strip is doubled to prevent strip lost.

For star connection points W_2, U_2 and V_2 are connected to each other (see fig. 5). For delta connection point U_1 is connected to point W_2, point V_1 is connected to point U_2 and point W_1 is connected to point V_2 (see fig. 6) and all three strips are mechanically in parallel.

5 Effect of the rectifier position on the cable losses

The effect of the rectifier position on the cable losses will be explained for star rectification but it is the same as for delta rectification. Three different positions are used for the rectifier depending on the type of VIRYA windmill.

For some small VIRYA windmills the rectifier is mounted in the terminal box which is situated on top of the generator housing. This has as advantage that DC current comes out of the generator and that cable twist can be prevented by using a swivel with only two contacts. One contact is formed by the head bearings and the remaining contact is axial loaded and positioned in the hart of the head bearing housing. The swivel can therefore be very small.

For other small VIRYA windmills the rectifier is positioned near the batteries. This has as advantaged that the short-circuit switch, which is used to stop the rotor, can be positioned before the rectifier in the same room where the batteries are standing. The advantage of positioning of the short-circuit switch before the rectifier is that the strongest short-circuit can be made because there is no voltage drop over the rectifier diodes.

For the bigger VIRYA windmills the rectifier and the short-circuit switch are placed in a box positioned at the tower foot. So DC current is flowing through the cables in between the rectifier and the batteries. This has as advantage that the cable losses are minimal and this is especially important for a windmill which can supply large currents.

In figure 7 it can be seen that a current is flowing in phase U only for 2/3 of the time. So if the rectifier is mounted far from the generator, a long cable with three wires is needed to connect the generator with the rectifier. Also in these cables the current will flow only for 2/3 of the time. If the rectifier is mounted close to the generator and if the batteries are positioned far from the rectifier a long cable with two wires is needed to connect the rectifier with the batteries. But the current in this cable will flow always. Now suppose that in both cases, cables are used with the same length and with the same copper area per wire. This means that the same total heat loss is produced for both situations.

However, the price of a cable with three wires of a certain size is about a factor 1.5 higher than for a cable with two wires. If the windmill can produce large currents, like it is the case for the biggest VIRYA windmills, it is therefore decided to position the rectifier in a box at the tower foot. But the rectifier is not positioned in the generator for the following reason.

The larger VIRYA windmills have a rather high design tip speed ratio and the starting torque coefficient of the rotor is therefore rather low. The generator is rectified in star because the increase of the unloaded sticking torque for star rectification is less than for delta rectification. This is because higher harmonic currents can't circulate in the winding for star rectification. So the rotor will start at a lower wind speed for star rectification than for delta rectification. However, the maximum short-circuit torque for star connection is also lower than for delta connection. So to be able to stop the rotor at very high wind speeds, it is better to make short-circuit if the winding is connected in delta. Short-circuit in delta is the same as short-circuit in star if the star point is short-circuited too. So if the generator is connected in star, one extra wire is needed which connects the star point of the generator with the short-circuit switch. For the bigger VIRYA windmills no swivel is used to prevent cable twist. So a flexible cable with four wires is needed from the generator to the short-circuit switch. The specified cable can make about 50 turns in one direction. This cable has to be disconnected and turned back if the cable twist becomes too large. Another way is turning back of the head.

The head can make a 360° turn if the wind direction is turning 360°. This will happen only some times a year and the turn will not always have the same direction. However, the head can also turn 360° if high wind speeds are suddenly followed by no wind at all. In this case, the rotor thrust will became negative because the rotor is working as a propeller. Because of this negative thrust, the rotor pulls itself in the front direction and this means that the head can make a 360° turn. This turn, because of the propeller effect, is always right hand seen from above. This is the main cause for cable twist and it happens especially on sites with very fluctuating wind speeds.

The cable losses are calculated with formula 3. For the wire resistance R one has to take the resistance for the double length of the cable in between rectifier and battery because the current I is going forwards and backwards. The resistance of a copper wire with a length L (m) and a cross sectional area A (mm^2) is given by:

$$R = \mu * L / A \qquad (\Omega) \tag{16}$$

The specific resistance μ for copper is 0.0175 $\Omega\ mm^2/m$.

Because of the cable losses, there is a certain voltage drop over the cable. This voltage drop depends on the chosen cable and on the current (see formula 1). The voltage at the rectifier is therefore somewhat higher than the charging voltage at the battery.

The maximum charging voltage is limited by the battery charge controller which consists of a voltage controller and a dump load. The battery charge controller has to be placed close to the batteries to prevent a voltage drop in between the dump load and the batteries.

6 Rectification of 2-phase alternating current

3-phase PM-generators are most common if the 3-phase current is rectified to get a DC current. However, for some situations it is logic to design a 2-phase generator. This is the case if a 6-pole radial flux armature is used in combination with a stator stamping with 24 grooves. A 6-pole generator normally needs a stator stamping with 18, 36 or 54 grooves. So a stator stamping with 24 grooves gives problems for a 3-phase winding. However, a 2-phase, 6-pole winding can easily be laid in 24 grooves as it contains six coils of phase U and six coils of phase V. A 2-phase winding is also a logic choice for a 6-pole axial flux generator with two coils of phase U and two coils of phase V.

The two phases U and V of a normal 2-phase winding are making a phase angle α of 90° with each other. The voltage variation of the phases U and V of a 2-phase winding is given in figure 13. A 2-phase winding can be seen as a 3-phase winding of which the third phase W contains no coils and generates a voltage which is always zero. So the voltage variation of phase W coincides with the α-axis.

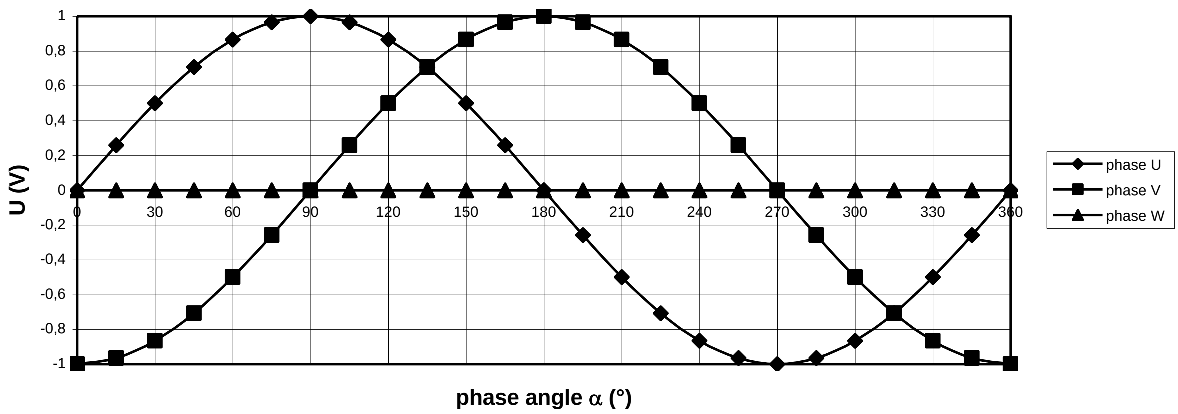

fig. 13 Voltage variation for phases U, V and W as a function of α for a 2-phase winding

A 2-phase winding is rectified in star. Rectification is done with a 3-phase rectifier in the same way as given in figure 5 for a real 3-phase winding. The only difference is that phase W contains no coils which means that the star point is directly connected to the point of the rectifier which lies in between the diodes D3 and D6.

Also for a 2-phase winding, only those phases are guiding current which have the highest or the lowest voltage. In figure 13 it can be seen that phase U has the highest voltage and that phase V has the lowest voltage for $0° < \alpha < 90°$. The voltage difference is minimal for $\alpha = 0°$ and for $\alpha = 90°$ for which it is 1. The voltage difference is also calculated for $\alpha = 15°$, 30°, 45°, 60° and 75° and it was found that the differences are respectively 1.2247, 1.3660, 1.4142, 1.3660 and 1.2247. So the voltage difference is maximal for $\alpha = 45°$ and the maximum voltage difference is 1.4142 V which is equal to $\sqrt{2}$ times the peak value of one phase.

In figure 13 it can be seen that phase U has the highest voltage and that phase W has the lowest voltage for $90° < \alpha < 135°$. The voltage difference is minimal for $\alpha = 135°$. The voltage difference is maximal for $\alpha = 90°$ for which it is 1. The voltage difference is also calculated for $\alpha = 105°$, 120° and 135° and it was found that the differences are respectively 0.9659, 0.8660 and 0.7071.

In figure 13 it can be seen that phase V has the highest voltage and that phase W has the lowest voltage for $135° < \alpha < 180°$. The voltage difference is minimal for $\alpha = 135°$. The voltage difference is maximal for $\alpha = 180°$ for which it is 1. The voltage difference is also calculated for $\alpha = 135°$, 150° and 165° and it was found that the differences are respectively 0.7071, 0.8660 and 0.9659.

In figure 13 it can be seen that phase V has the highest voltage and that phase U has the lowest voltage for 180° < α < 270°. The voltage difference varies in the same way as for the region 0° < α < 90°. In figure 13 it can be seen that phase W has the highest voltage and that phase U has the lowest voltage for 270° < α < 315°. The voltage difference varies in the same way as for the region 90° < α < 135°. In figure 13 it can be seen that phase W has the highest voltage and that phase V has the lowest voltage for 315° < α < 360°. The voltage difference varies in the same way as for the region 135° < α < 180°.

The current varies in the same way as the voltage if the load is a resistance. So the rectified current is proportional to the voltage difference. The rectified current is given in figure 14 if the current at α = 0° is taken 1.

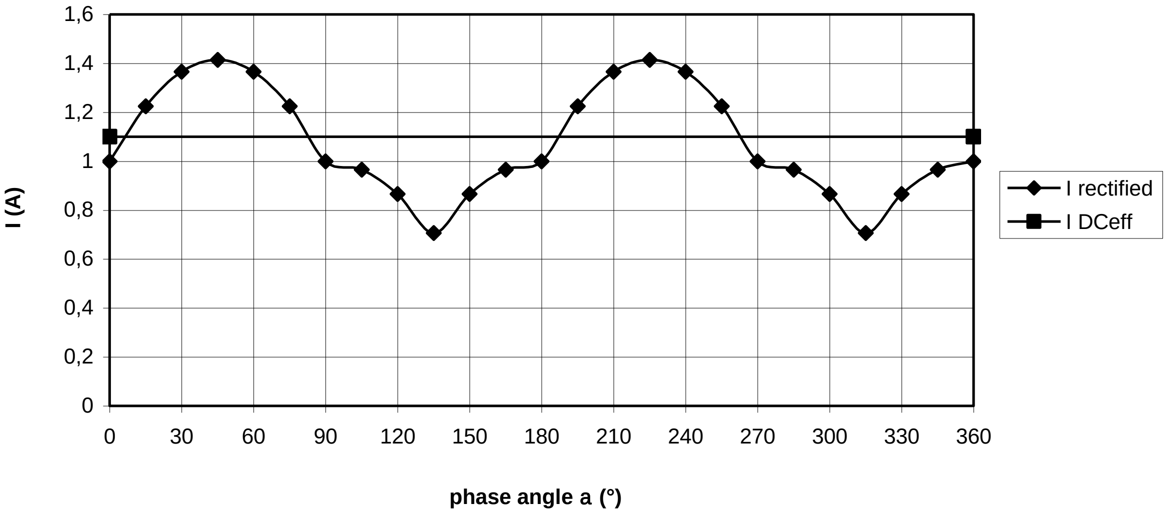

fig. 14 Variation of the rectified current in the load resistance R for a 2-phase winding

Figure 14 shows that the current is fluctuating in a rather strange way. The effective DC current is larger than 1 because the positive effect of the bulges in between 0° < α < 90° and 180° < α < 270° is stronger than the negative effect of the hollows in between 90° < α < 180° and 270° < α < 360°. I could find no exact formula for the effective current for a 2-phase winding but looking at figure 14 it was estimated that the effective current is about a factor 1.1 times the peak value of the phase current. The line for the effective DC current is also given in figure 14.

The fluctuation as given in figure 14 is also valid for the voltage if the load is a resistor. So the effective DC voltage U_{DCeff} is a factor 1.1 higher than the maximum phase voltage U_{max}. The maximum phase voltage U_{max} is a factor √2 times the effective AC phase voltage U_{eff}. So it is valid that:

$$U_{DCeff} = 1.1 * \sqrt{2} * U_{eff} \quad \text{(V)} \qquad (17)$$