TECHNICAL SOLUTION PROPOSAL **Reference: G2013-012**

Title: **Prediction of the service life of accumulators**

Corporate entity: **Diehl Aerospace GmbH**

Description:

This proposed technical solution is a method or algorithm for predicting the service life of accumulators.

Motivation

The importance of electrical energy storage has increased rapidly in recent years. This results from the increasing demand in a wide range of application areas. These include, for example, the storage of electricity from renewable energy sources, the development of increasingly powerful portable devices and research in the field of electric vehicles. In this context, the accumulator - also referred to as "battery" in the following - which was invented almost 200 years ago, is also experiencing a major surge in development. One of the best-known and technically most interesting types of rechargeable batteries is a lithium-based accumulator. This is characterised by a high degree of efficiency, a high energy density and a short charging time. Unfortunately, these charge storage devices do not only have advantages: Constant monitoring of voltage and current is necessary to prevent overcharging or deep discharging, which can destroy individual cells. Incorrect handling of the charge accumulator can endanger the environment due to its high flammability. The ageing of the cells is also a problem.

To get a grip on these difficulties, many companies produce charge management systems for lithium accumulators that measure current, voltage, temperature, etc. and can switch off the accumulator in an emergency. One product of this kind is the IC "bq20z65" from the company Texas Instruments (TI). This is a complete accumulator management system which, in addition to the above-mentioned variables, can measure the

internal resistance, the existing capacity, the remaining capacity and much more on the respective accumulator. Together with the actual accumulator, this creates a complete accumulator "pack".

In the aviation industry, lithium-ion accumulator packs are also used for the emergency power supply of aircraft. For this purpose, the company DIEHL Aerospace produces so-called "Emergency Power Supply Units" (EPSU). Their task is to supply energy for the emergency lighting in the aircraft in an emergency. According to the specifications, the supply must be guaranteed for 12 minutes, which is why the accumulator must not fall below a minimum capacity. In addition, the accumulator is required to deliver a power of 72W during this period, which means that there are also maximum limits for a permissible internal resistance of the accumulator. In order to comply with the above-mentioned requirements, all relevant accumulators of an aircraft must currently be removed and checked by maintenance personnel every 6 months. After 36 months, the accumulator is replaced and disposed of as a precaution.

This procedure obviously entails a very high level of battery wear. For this reason, DIEHL Aerospace is striving to develop a procedure within the CleanSky project that can predict the service life condition of an accumulator. This makes it possible to replace the accumulators only according to actual need and not according to rigid intervals. This saves costs for maintenance, new equipment and disposal of old equipment.

In order to be able to make a prediction for the service life of an accumulator, it is necessary to develop an algorithm that can predict future events from existing data.

The algorithm

The aim is to predict how many charging and discharging cycles remain for an accumulator - here also representing an accumulator pack - until it no longer meets the above-mentioned specifications and must be replaced. For this purpose, an algorithm must be implemented that can determine the presumably remaining cycles as precisely as possible or can indicate in which of the cycles the battery is likely to fail. The presented algorithm is based on respective measurements of the internal resistance Ri of the accumulator, since the remaining number of cycles decreases with increasing internal resistance.

The calculations of the algorithm can be divided into several steps:

1.) Calculation of the reference slope mref of the internal resistance Ri

In the following, the respective values or curves of the internal resistance Ri of the accumulator over its number of cycles n are considered. A certain cycle is always completed when the accumulator has been charged to 100% and then discharged to 100%. An actual charge and discharge of this kind hardly ever occurs in practice. As a rule, the accumulator is partly charged and then partly discharged again. For the present procedure, therefore, actual successive partial charges and partial discharges are added up. A cycle is considered complete when the sum of the partial charges and discharges reaches 100%. If, for example, the accumulator is charged and discharged by 20%, 30%, 10% and 40% respectively in four consecutive actual partial cycles, the sum is 100%, so that the four actual partial cycles are counted as one "full" or "nominal" cycle of the number of cycles n.

In the following, a slope m always denotes a change ΔRi of the internal resistance Ri over a change Δn of the number of cycles n, i.e. $m = \Delta Ri / \Delta n$.

To calculate the reference slope mref, the following specific data of the accumulator are required:

- Internal resistance at the first cycle n=0: Ri(0)

- Maximum permissible internal resistance Ri, after which the accumulator may no longer be operated, i.e. fails: Ri(nmax)

- Expected maximum number of cycles after which the battery reaches or exceeds the permitted internal resistance Ri(nmax): nmax

The value Ri(0) is measured as the internal resistance after completion of the first (n=0) charge and discharge cycle after its manufacture or commissioning. The value Ri(nmax) results from the intended use of the accumulator or from the system design of the system in which the accumulator is used. In particular, the value is given by the electrical circuit that the accumulator has to feed. The value Ri(nmax) is the value of the internal resistance of the accumulator at which the overall system of accumulator and circuit just functions.

The value nmax designates the presumed number of cycles of complete, i.e. 100% charging and discharging processes, after which the accumulator fails, i.e. presumably assumes or exceeds the internal resistance Ri(nmax). The number nmax is usually specified or supplied by the manufacturer of the accumulator and is, for example, in the order of nmax=1000.um nmax=1000.

The reference slope mref describes the presumed linear increase of the internal resistance over the number of cycles starting from cycle n=0 to cycle n=nmax. The value increases linearly over the number of cycles n from the value Ri(0) to the value Ri(nmax). The reference slope mref of the internal resistance is an important component for calculating the number of remaining cycles and serves as an orientation value for the increase of the internal resistance. The slope mref results in

$$mref = \frac{Ri(nmax) - Ri(0)}{nmax}.$$

There are two alternatives for calculating the actual slope of the curve of the internal resistance Ri according to the following process steps 2a or 2b.

2a.) Calculation of the actual slope m(n) of the internal resistance Ri with the same interval length i/2

In order to determine the actual slope m(n) of the internal resistance Ri over the number of cycles n for the cycles n=1,2,.... the last i cycles before cycle na are considered at the time or place of a current cycle na in order to make a statement about the future course of the internal resistance for cycles na+1, na+2, ... to predict the future course of the internal resistance for cycles na+1, na+2, ... For example, the battery is currently in cycle na+1, i.e. the measurement of the internal resistance Ri(na) for cycle na is already available. However, the measurement of the internal resistance Ri(na+1) etc. for cycles greater than na is not yet known.

The value i is predetermined, e.g. determined empirically, obtained from empirical values or through tests or simulations. Preferably, the value i is chosen as an integer, in particular an even integer. i is chosen specifically for each battery type.

The last i cycles before cycle na are also divided into two equal sections of i/2 cycles each. The two sections can therefore be described as follows:

1. range from cycle na-i to cycle na-(i/2),

2. range from cycle na-(i/2) to cycle na.

In both subranges, mean values Rm1 and Rm2 of the resistance values Ri are formed. For this purpose, the respective resistance values Ri are summed and divided by their number - i.e. (i/2)+1 values in both ranges. Then the difference of the mean values is divided by their distance - i/2 cycles - to arrive at the current gradient m(na) at cycle na. This results in the following general formula:

$$m(n) = \frac{Rm2 - Rm1}{\left(\frac{i}{2}\right)} = \frac{\sum_{j=n-\frac{i}{2}}^{n} Ri(j) - \sum_{j=n-i}^{j=n-\frac{i}{2}} Ri(j)}{\left(\frac{i}{2}\right)\left(\frac{i}{2}+1\right)},$$

with

$Rm2 = \frac{\sum_{j=n-\frac{i}{2}}^{n} Ri(j)}{\left(\frac{i}{2}+1\right)}$ for the second area and $Rm1 = \frac{\sum_{j=n-i}^{j=n-\frac{i}{2}} Ri(j)}{\left(\frac{i}{2}+1\right)}$ for the first area.

The slope m(na) over the last i cycles before the current or last cycle na is used to predict the further course of the internal resistance in subsequent cycles na+1, na+2, etc. The prediction of the course of future values of Ri for cycles after cycle na is done by extending the slope line through the mean values Rm1 and Rm2 with the slope m(na) beyond cycle na to cycles na+1, na+2,

2b.) Calculation of the actual slope of the internal resistance Ri with two subintervals of different sizes $I_1 und\ I_2$

An extension of the previously described method 2a.) for determining the internal resistance by means of two equally sized subintervals of the respective length i/2 is the subdivision into two differently sized subintervals I1 and I2 according to the method variant 2b.). This is based on the following considerations: In the normal case, i.e. with linearly increasing Ri, it makes sense to average over as many values as possible in order to be able to make a straight line for the mean slope m and thus an exact prediction for the course of Ri. However, there are also cases in which the values of the internal resistance Ri increase differently over time or over the number of cycles, i.e. the rate of increase changes. In this case, the more recent values of e.g. a steeper increase should be weighted more than e.g. values from longer ago with a slower increase. To calculate the more recent predicted slope - which differs from the earlier slope - past values should rather be neglected. To solve this problem, the calculation of the slope m(n) is made variable by two subintervals of different sizes I1 and I2. The ratio of the two subintervals is selected depending on the current, i.e. last measured value of the internal resistance Ri(na). The two sub-ranges can be described as follows:

1. range from cycle na-I1-I2 to cycle na-I2,

2. range from cycle na-I2 to cycle na.

First, the interval values I1 and I2 must be determined. For this purpose, a current resistance gradient a(na) is determined for the value Ri(na) in cycle na. For this purpose, the current

or last measured internal resistance value Ri(na) is subtracted from the mean value Rma of the last I2 cycles before cycle na - excluding it - and then divided by the distance between the two values, which is (I2+1)/2. The value I2 is again predefined, e.g. determined empirically, obtained from empirical values or through tests or simulations. I2 is chosen specifically for each battery type.

The slope a(n) is therefore calculated as follows:

$$a(n) = \frac{Ri(n) - Rma}{\frac{I2+1}{2}} = \frac{Ri(n) - \frac{\sum_{j=n-I2}^{n-1} Ri(j)}{I2}}{\frac{I2+1}{2}},$$

mit

$$Rma = \frac{\sum_{j=n-I2}^{n-1} Ri(j)}{I2}.$$

The slope a(n) is only used to determine the interval length I1 and must never be confused with the slope m(n), which is used to predict the number of remaining cycles. A factor k(n) is calculated from the value a(n), which determines the interval length I1 depending on the current slope a(n). The factor k(n) and I1 are calculated by:

$k(n) = \frac{kmax * mref}{a(n)}$ und $I1 \approx k(n) * I2$.

Since k(n) is not necessarily an integer, the result k(n)*I2 is rounded to the nearest integer I1.

kmax can be set as a variable factor and must be determined by testing.

Only now is the actual slope of the resistance values calculated: The slope m(n) results again as follows: In both subranges I1 and I2, mean values RmI1 and RmI2 are again formed over in each case I1+1 and I2+1 values of Ri, the mean values are subtracted from each other and divided by their distance - which is (I1+I2)/2. The result is

$$m(n) = \frac{RmI2 - RmI1}{\frac{I_1+I_2}{2}} = \frac{\frac{\sum_{j=n-I2}^{n} Ri(j)}{I2+1} - \frac{\sum_{j=n-I1-I2}^{n-I2} Ri(j)}{I1+1}}{\frac{I_1+I_2}{2}},$$

mit $RmI1 = \frac{\sum_{j=n-I1-I2}^{n-I2} Ri(j)}{I1+1}$ und $RmI2 = \frac{\sum_{j=n-I2}^{n} Ri(j)}{I2+1}$.

3.) Calculation of the number of remaining cycles V(n)

The actual goal of the algorithm is to determine the remaining number of cycles V(n), which indicates the remaining cycles as a function of the cycles already completed. For this purpose, the assumption is first made that with a new battery, i.e. in cycle n=0, the remaining number of cycles V is equal to the originally assumed total number of cycles nmax, i.e. V(0)=nmax. It is also assumed that the remaining number of cycles V(n) decreases by the value one per cycle. This results in a reference line Gr in a diagram in which the residual cycle number V(n) is plotted against the cycle number n. The slope of the reference line Gr is 1.

In order to include the values m(n) for the current slope of the internal resistance Ri, which are currently determined according to the above, in the calculation of the number of remaining cycles V, and in order to provide a forecast of the remaining cycles that is as accurate as possible, the currently determined slope m(n) is set in relation to the reference slope mref. This ratio is called the factor Km(n), with

$$Km(n) = \frac{m(n)}{mref}.$$

To determine the actual remaining cycles V, a new value for V(n) must be determined iteratively after each cycle n or each determination of the gradient m(n). For this purpose, the following equation for calculating the outstanding remaining cycles V is applied after each cycle has elapsed:

$$V(n) - V(n-1) - Km(n).$$

Optionally, it must be ensured that the factor Km may not assume a negative value, since it does not make sense to let the residual cycle number V increase or become larger as the number of cycles n increases. The smallest value that Km may assume is then Km=0. This means that the residual cycle number V(na) stagnates at the previous value V(na-1) of the previous cycle na-1 for a given cycle na.

Furthermore, for each cycle n a straight line equation with the variable x for the new predicted number of residual cycles V can be set up. x=0 describes the last cycle n-1, x=1 the current cycle n, x=2 the next expected cycle n+1, etc. The straight line equation is determined as follows:

$$V(n, x) = V(n-1) - Km(n) * x.$$

Now the intersection of the straight line V(na,x) with the abscissa can be determined for a cycle na. The point of intersection indicates at which number of cycles n a failure of the battery is to be expected.

Smoothing the values

To improve and optimise the display of the values V(n), there is alternatively or additionally the possibility to smooth the determined and displayed values or their course in a display. Furthermore, the prediction or display of the presumably remaining cycles V(n) can be further improved. In this case, the calculated number of cycles V(n) is continued unchanged as a value in the above-mentioned calculations. Only a possibly deviating display value A(n) is displayed or used for display. For this purpose, it is queried after each cycle whether the previously displayed number of cycles A(n-1) is smaller than the current or actually determined number of remaining cycles V(n). The value V(n) is then corrected, if necessary, into another (different) display value A(n) and this is displayed. There are two correction methods for this purpose:

- Constant forecast
- Decreasing forecast

Constant forecast

This procedure queries whether the actually determined remaining cycles V(n) have increased compared to the previous display A(n-1) or not. If they have not increased, the new value V(n) is to be adopted as the current value to be displayed A(n) = V(n). If they have increased, the new increased number V(n) should not be displayed, but the previously displayed number A(n-1). This ensures that the number of remaining cycles V(n) never increases in the display as A(n), but at most remains constant or falls as the number of cycles n increases. This is expressed as a programmatic query:

If (V(n) > A(n-1)), then (A(n) = A(n-1)), otherwise (A(n) = V(n)).

Decreasing forecast

With this alternative procedure, it is queried whether the current number of remaining cycles V(n) is smaller than the previously displayed number A(n-1). If this is the case, the new determined value V(n) is taken over as the current display value A(n), otherwise the display is decreased by the value "one", i.e. A(n) is selected as A(n-1) - 1. The query for this looks as follows:

If (V(n) < A(n-1)), then (A(n) = V(n)), otherwise (A(n) = A(n-1)-1).

Trend curve

In the display or representation of the values V(n) or A(n), a trend line or trend curve can also be displayed. Three types of trend curves are available:

- "moving average"
- "Polynomial of higher degree"
- self-calculated "own trend line (straight line)"

For the trend curves "moving average" and "polynomial of higher degree", the values and coefficients of the trend curves are determined from the data of the existing diagram itself, i.e. from the values V(n) or A(n), the trend curve is calculated and finally displayed together with the course of the values V(n) or A(n). This can be done, for example, using a spreadsheet programme. The self-calculated "own trend line (straight line)" is calculated via a gradient for a usual straight line equation as follows:

$$mT(na) = \frac{\Delta V}{\Delta n} = \frac{V(na) - V(na-k)}{k}.$$

Here V(na) is the last value displayed in the diagram, i.e. the value at the current cycle na. k is chosen so that V(na-k) is the previous value displayed in the diagram. This only applies if the previous value V(na-k) is greater than V(na), i.e. the displayed curve V(n) has fallen from the penultimate to the last value. The straight line then runs through the last two displayed values. If both values are equal, k=n is chosen, i.e. V(na-k) is the original value V(n=0)=nmax. The straight line runs with the determined gradient mT(na) through the last displayed value V(na).

Starting from V(na), the straight line equation then results in

V(na) V(x) = V(na) + mT(na) * x.

he variable runs through the range x=0 up to any positive value, which specifies over how many cycles, starting from the current cycle na, the straight line should be shown in the display.

With this formula and the specification for x, it is possible to make a prediction for the next x=100 cycles, for example, and to display this as a continuation of the characteristic curve into the future.

The "moving average" can give a very good approximation to the calculated values, but it is not possible to output a trend of the straight lines beyond the current cycle na because of the missing values for averaging for n>na.

For this purpose, the trend curve "polynomial of higher degree", e.g. 5th degree, was inserted as an alternative. This variant allows, in addition to the approximation to the calculated or displayed curve, also its continuation, i.e. a prediction of the curve for future cycles.

As a range of cycles for the trend curve prediction, an at least approximate value of x=100 in the aircraft range is useful, since aircraft checks are usually carried out every 250 to 650 flight hours, or approx. every two months.

Forecast traffic light

The appropriate parameter for predicting the remaining battery life is the value of the internal resistance Ri. This value is normalised so that the number of remaining cycles at the end of the life is zero. The above formulas of the algorithm are therefore valid for all operating conditions.

In normal operation, the internal resistance Ri is within the expected range. The actual final life of the accumulator pack is then approximately equal to the expected value (e.g. actually 900 to 1100 cycles with nmax = 1000 cycles).

However, if an accumulator pack is operated under exceptional conditions, such as severe temperature or load fluctuations, its service life will be shortened. These operating conditions are reflected in strong changes of the internal resistance Ri.

If, on the other hand, the accumulator pack is operated frequently under ideal conditions, it is to be expected that its service life will be extended.

The display of the remaining service life V(n) as numerical values often conveys an insufficiently tangible impression of the accumulator state.

In this case, the display of a traffic light is preferred to symbolise the remaining life of the accumulator. This makes the recognition of the battery status clearer.

Alternatively or additionally, a traffic light indication of the accumulator status can be given. In this way, a more general statement about the condition of the accumulator is to be made. For this purpose

the scheme of a traffic light is used. A new accumulator starts in a green state. If the accumulator is OK, i.e. can still be used for a "long time", the traffic light should show "green". If the accumulator is in a critical range, i.e. its end of life is only a certain number of vgelb,

z. Finally, when the battery has only a few cycles of Vrot left to live or no longer has sufficient capacity for a specific application, e.g. for the emergency power supply of the emergency lighting of an aircraft, "red" shall be displayed.

If, however, the battery behaves "unusually", there is an additional separate display "n < ngelb" if the internal resistance already becomes critical at a comparatively low number of cycles n below the limit number ngelb, i.e. the remaining number of cycles is below Vgelb. Another separate display "n < nrot" indicates when the battery no longer has the required capacity Vrot for a comparatively short period of use, i.e. below the limit number nrot. Limits are defined for the determined expected remaining cycles V(n), namely Vgelb and Vrot, as well as for the cycles actually completed n, namely ngelb and nrot.

The query formulated for the traffic light display looks as follows:

If (V(n) > Vyellow) AND (n < nyellow), then display = "green

or

If (V(n) > Vred) AND (nyellow < n < nred), then display = "yellow"

or

If (Vyellow > V(n) > Vred) AND (n < nyellow), then display = "yellow" und „n < nyellow“

or

If (V(n) < Vred) AND (n < nred), then display = "red" and "n < nred"

Otherwise

Display = „red“

Level indicator

The remaining life of the battery can also be symbolised as a fuel tank, i.e. as a power reserve for cycles that are still available. Here, the battery starts in cycle zero with a "full tank". With each cycle, the tank - as a function of the operating mode of the battery

- emptied by a certain amount. Besides, a stronger increase of the internal resistance should accelerate the emptying of the tank, a weaker increase should slow down the emptying.

Alternatively or additionally, a symbolic display of a "filling level" of the battery can therefore also take place. The fill level symbolises the remaining number of cycles. A display unit with several individual, e.g. ten, displays was designed for the calculation of the filling level display. It is constructed in such a way that the display changes at respective limits that are available for a display, e.g. after each tenth of the original maximum number of cycles nmax. In the case of a new battery with the maximum number nmax of remaining cycles, all - in the example ten - display elements are shown or are active, e.g. light up. During operation, one of the displays goes out after the respective proportion of remaining cycles assigned to the display has passed. In the example, the display always decreases when the remaining number of cycles V(n) has fallen by 10% of the maximum number of cycles, i.e. by nmax/10, until finally, in the last tenth, only the lowest and last, e.g. "red" display "lights up". Here, too, the display stages can be colour-coded, e.g. in groups of green, yellow and red displays.

Design example

Further features, effects and advantages of the algorithm result from the following description of a preferred embodiment of the invention and the accompanying figures. Here, a schematic sketch of the principle shows:

Figure 1 measured values of an internal resistance and a reference slope,

Figure 2 the determination of the current slope with intervals of the same size,

Figure 3a the determination of the first from the second interval size,

Figure 3b he determination of the current slope with intervals of different sizes,

Figure 4 the current prediction of the failure cycle,

Figure 5 display values A(n) for constant prediction,

Figure 6 display values A(n) for decreasing prediction,

Figure 7 display values A(n) with trend curves,

Figure 8 A trend curve V(n) with assignment to a traffic light display,

Figure 9 the progression curve from Fig. 9 with an assignment to a tank indicator.

Fig.1 shows measured values of the internal resistance Ri(n) of a battery for the cycles n=0 to n=6 and the theoretical course of the internal resistance according to the reference slope mref over the entire estimated service life of the battery from n=0 to n=nmax according to the manufacturer's specifications.

Fig. explains the determination of a current slope m(na) using intervals or ranges of equal size and shows measured values from Ri(na-i) to Ri(na) for i=4 and starting from a current cycle na. The mean values Rm1 and Rm2 (drawn dashed) for first and second range are formed as follows: The respective associated (i/2)+1 = 3 values of Ri contributing to the respective averaging in the first or second range are indicated by respective outlines, are summed and divided by their respective numbers. The current slope is determined as the difference of the mean values Rm2-Rm1 divided by their distance in abscissa direction i/2. The prediction of the course of future values of Ri for cycles after cycle na by extending the slope lines is indicated by a dashed line.

Fig. 3a shows the determination of the interval size I1 from the interval size I2. I2 was chosen here to be I2=3. First, therefore, the I2, i.e. three, values of Ri for na-3 to na-1 are averaged to Rma and the slope a(na) is determined. To do this, the difference between the current value of Ri(na) and the average value Rma is divided by their distance (I2+1)/2. The slope is then put in relation to mref and from this the length I1 is determined using kmax. For the determined slope a(na) the value a(na) = 0.7 results in the example. mref is mref = 0.5 in the example. kmax = 3 was chosen as the value kmax. This results in k(na) = 2.14 and therefore I1 = 6.

Fig. 3b shows the determination of the actual current slope m(na) of the internal resistance Ri. The value curve of Ri is that of Fig. 3a. In the first range, the I1+1, i.e. seven values of Ri from na-I1-I2 = na-9 to na-I2 = na-3 are averaged to RmI1. In the second range, the I2+1, i.e. four values, of Ri from na-I2=na-3 to na are averaged to RmI2. The mean values RmI1 and RmI2 are drawn in dashed lines, the respective contributing values Ri are outlined by contour lines. The slope m(na) is then calculated from the difference between the mean values RmI2 and RmI1 and their distance from (I1+I2)/2. The extended slope line going beyond the current cycle na is again used to predict future values of Ri.

Figur 4 shows the determination of the prediction line V(n,x) for remaining residual cycles for nmax=8.

In the first example, the current cycle is the one with cycle number na = 3. In cycle n = 1, the result was a slope m(1) = 0.8, which is smaller than the reference slope mref = 1. With V(0) = nmax = 8 and Km(1) = 0.8 the result is V(1) = V(0)-0.8 = 7.2. In the second cycle the result was

m(2) = 1 and thus Km(2) = 1 and V(2) = 6.2. In the current third cycle m(3) = 1.3 and thus

Km(3) = 1.3 and V(3) = 4.9.

In the current cycle na=3 the straight line equation V(3,x) is now also set up and results in

$$V(3,x) = V(2) - Km(3) * x = 6{,}2 - 1{,}3x.$$

This straight line intersects the abscissa at about n=6.8, i.e. at the time when the third cycle na=3 has been run, the battery is expected to fail after about 6.8 cycles.

In a second example, starting from the first example, one more cycle has passed: After completion of the fourth cycle, another measurement of the internal resistance Ri(4) is now carried out. Now na=4. m(4) = 0.9 and thus Km(4) = 0.9 and V(4) = 4.0. The now valid straight line V(4,x) results in

$$V(3,x) = V(2) - Km(3) * x = 6{,}2 - 1{,}3x.$$

This straight line intersects the abscissa at about n=8.9, i.e. at the time when the fourth cycle na=4 has been run, the life expectancy of the battery has changed. Now the battery is expected to fail after about 8.9 cycles.

Fig. 5 shows a smoothing of the values with constant prediction in an exemplary display diagram. The display value A(n) is shown. It can be seen that even with a reduction of the internal resistance Ri, and thus an increase of V(n), which would entail a local increase of the number of cycles V(n), the curve A(n) remains constant. If the resistance Ri increases, the curve A(n) shown continues to decrease. In Fig. 5, nmax = 3000. However, due to an unexpectedly strong increase in the internal resistance from approx. cycle n= 1000, the life expectancy of the battery drops to below 1200 cycles.

Fig. 6 shows an alternative representation of A(n) with smoothing of the values with decreasing prediction in an exemplary display diagram for the same data for V(n) on which Fig. 5 is based. In Fig. 6 it can be seen that the displayed number of cycles A(n) always decreases per cycle, even if the internal resistance value and thus the value V(n) remains the same or even decreases.

Fig. 7 shows three trend curves for an alternative course of A(n), namely a respective one to the "moving average", to the "polynomial", in the example of the 5th degree, and to the "own trend line (straight line)" in a diagram. The curves each start at cycle n=1 and extend to the current cycle na. The two curves "polynomial" and "straight line" also extend predictively beyond the current cycle na, in each case starting from the last determined or displayed value V(na), starting at the current cycle na for the next x=100 cycles up to na+100.

Fig. 8 shows a curve for V(n) over the number of cycles n - and thus the condition of the battery - and associated zones for a traffic light display and for the display of the messages "n < nred" and "n < nyellow". Also shown is the traffic light itself with the three displays "green", "yellow" and "red" as well as the two additional displays for messages "n < nred" and "n < nyellow"

Fig. 9 shows again the curve V(n) from Fig. 8. In addition, a "tank" or "filling level" indicator for the battery is shown with ten display segments "1" to "10". Segment "1" indicates a remaining number of cycles between 90% and 100% nmax. Segment "2" indicates a remaining number of cycles between 80% and 90% nmax. The formation continues until segment "1" shows a remaining cycle count between 0% and 10% nmax. The segments are again in the traffic light colours "red", "yellow" and "green".

The query for this was set up as follows as an example: With ten displays, "1" is the display for highest, "10" for lowest "level":"

If V(n) < 0.9 * nmax, then level indicator: "2"
or
If V(n) < 0.8 * nmax, then level indicator: "3"
or
If V(n) < 0.7 * nmax, then level indicator: "4"
or
If V(n) < 0.6 * nmax, then level indicator: "5"
or
If V(n) < 0.5 * nmax, then level indicator: "6"
or
If V(n) < 0.4 * nmax, then level indicator: "7"
or
If V(n) < 0.3 * nmax, then level indicator: "8".
or
If V(n) < 0.2 * nmax, then level indicator: "9"
or
If V(n) < 0.1 * nmax, then level indicator: "10"
otherwise

Level indicator: "1"

Fig. 1

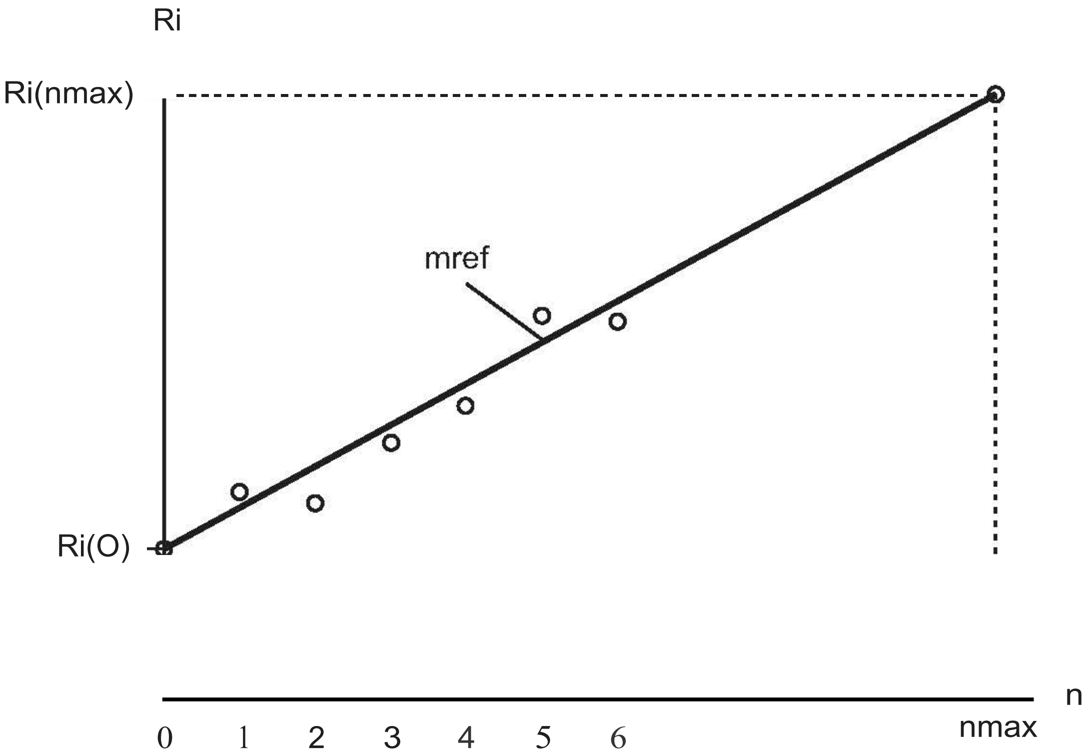

Ri
Ri(nmax)
mref
Ri(O)
n
0 1 2 3 4 5 6
nmax

Fig. 2

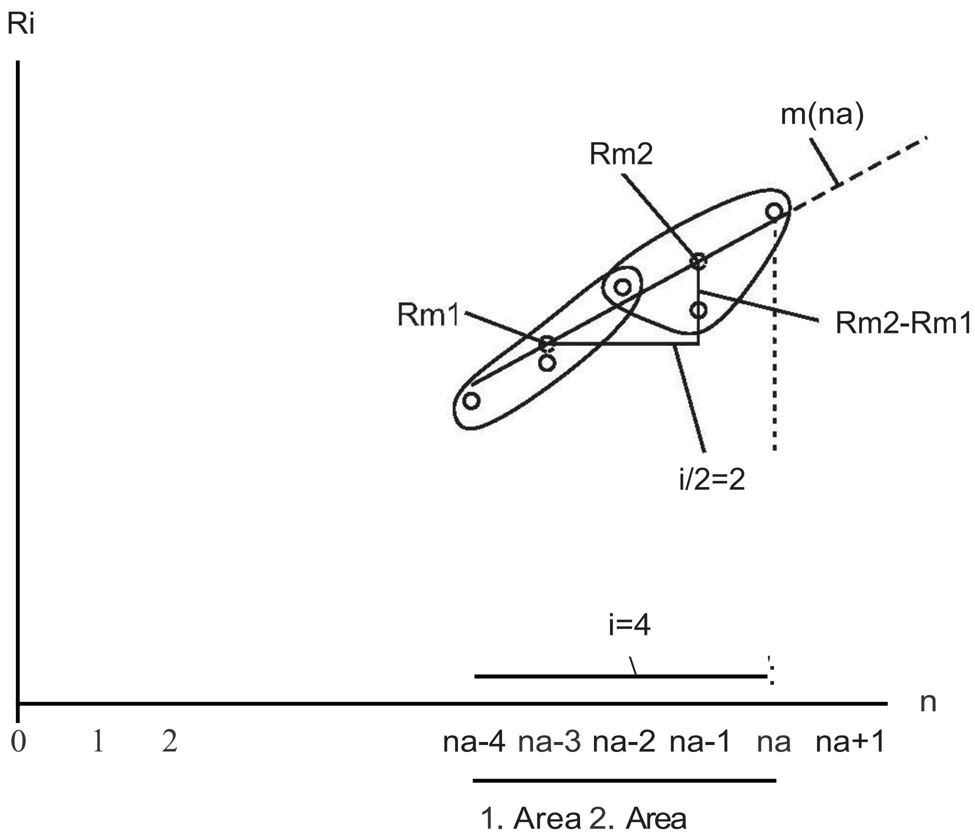
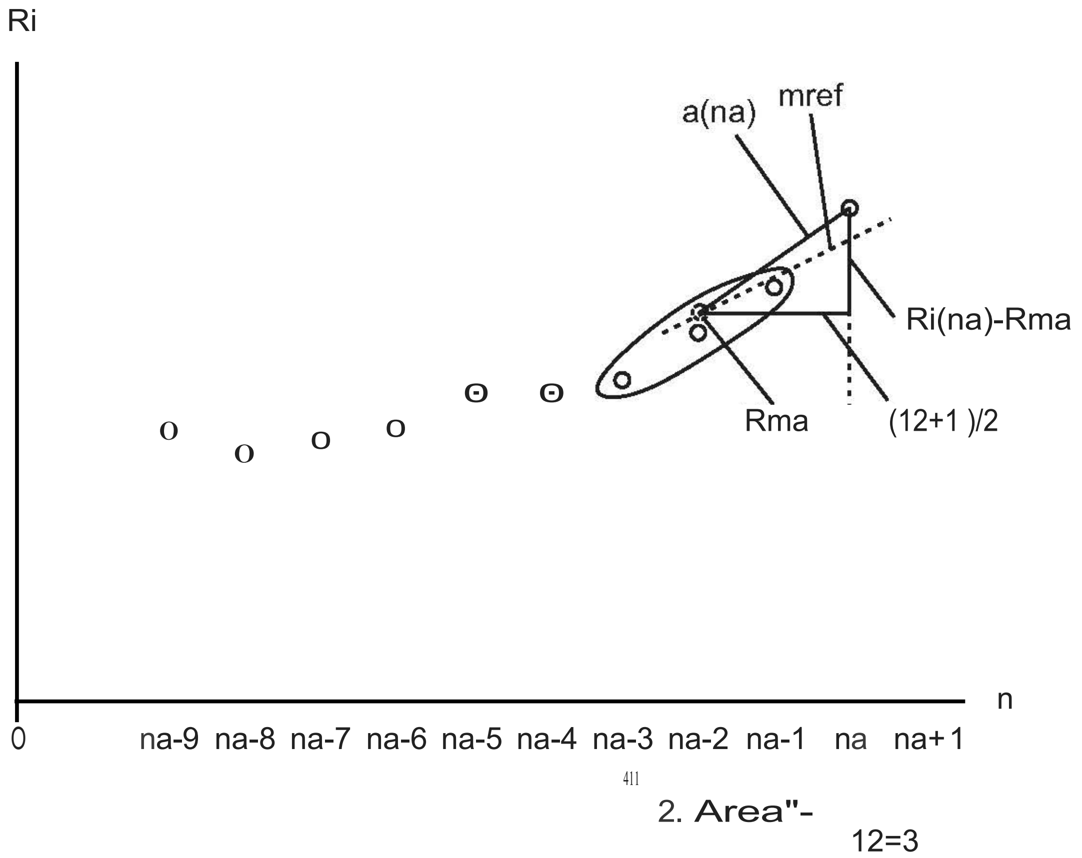
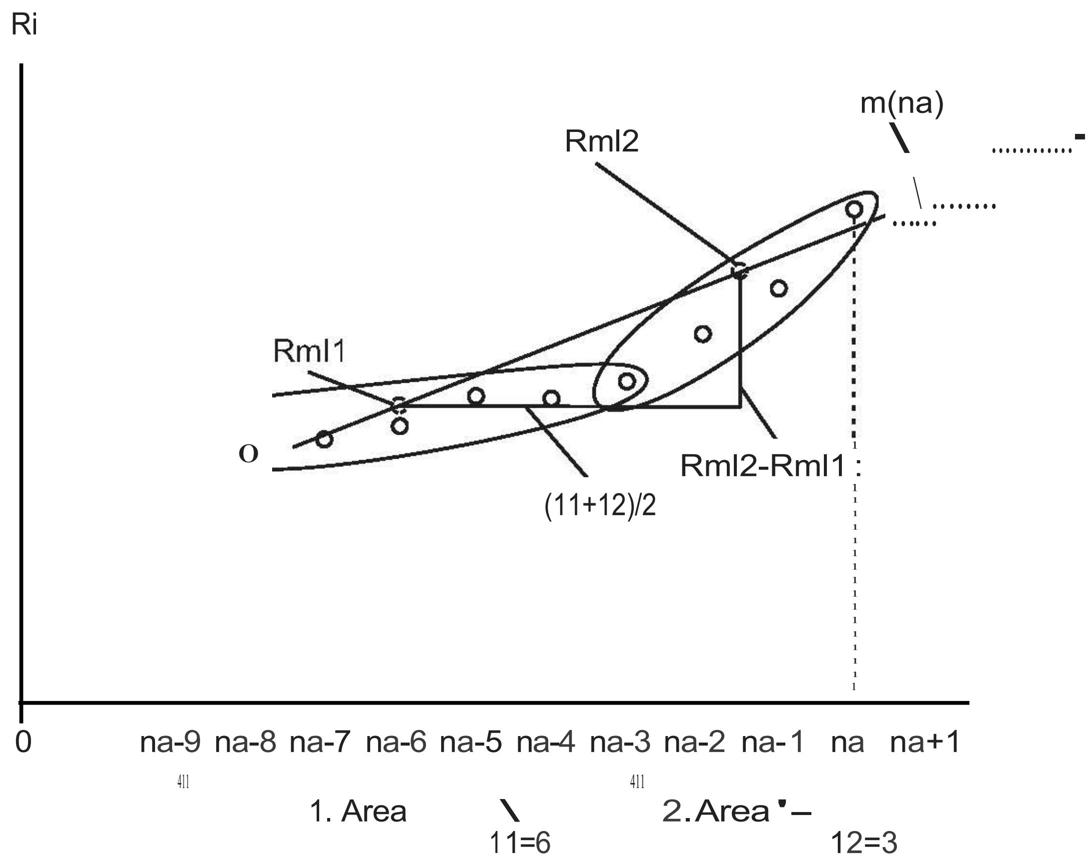

Ri
m(na)
Rm2
Rm1
Rm2-Rm1
i/2=2
i=4
n
0 1 2
na-4 na-3 na-2 na-1 na na+1
1. Area 2. Area

Fig. 3a



Ri
a(na)
mref
Ri(na)-Rma
Rma
(12+1)/2
n
0
na-9 na-8 na-7 na-6 na-5 na-4 na-3 na-2 na-1 na na+1
2. Area
12=3

Fig. 3b



Ri
m(na)
Rml2
Rml1
Rml2-Rml1
(11+12)/2
0
na-9 na-8 na-7 na-6 na-5 na-4 na-3 na-2 na-1 na na+1
1. Area
11=6
2.Area
12=3

Fig. 4

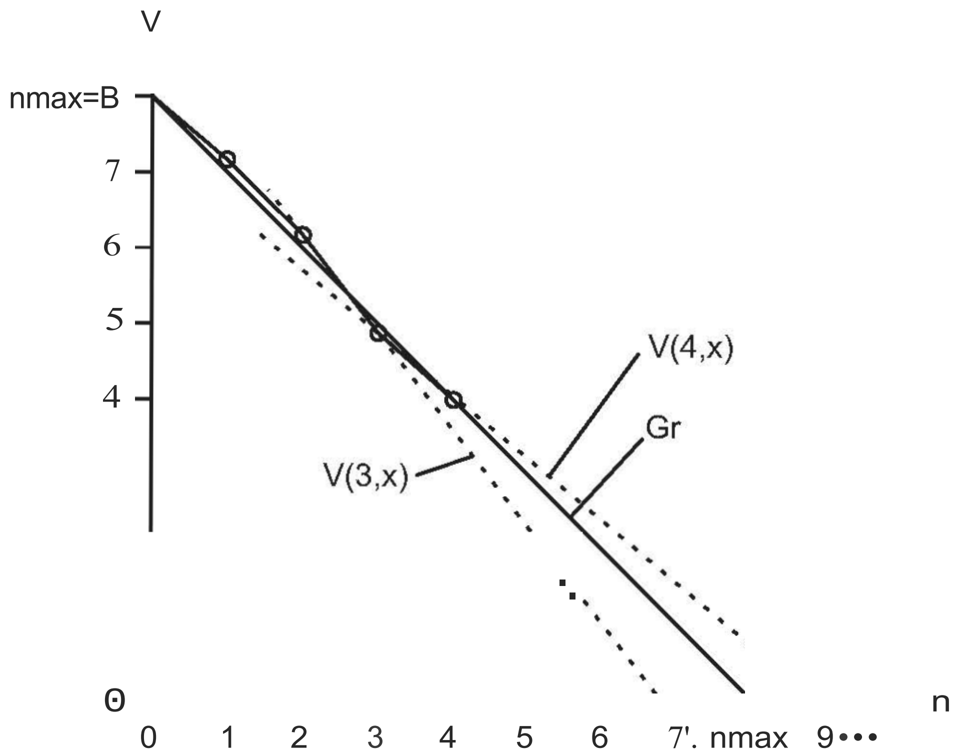

V
nmax=B
7
6
5
4
V(4,x)
Gr
V(3,x)
0
n
0
1
2
3
4
5
6
7'. nmax
9•••

Fig. 5

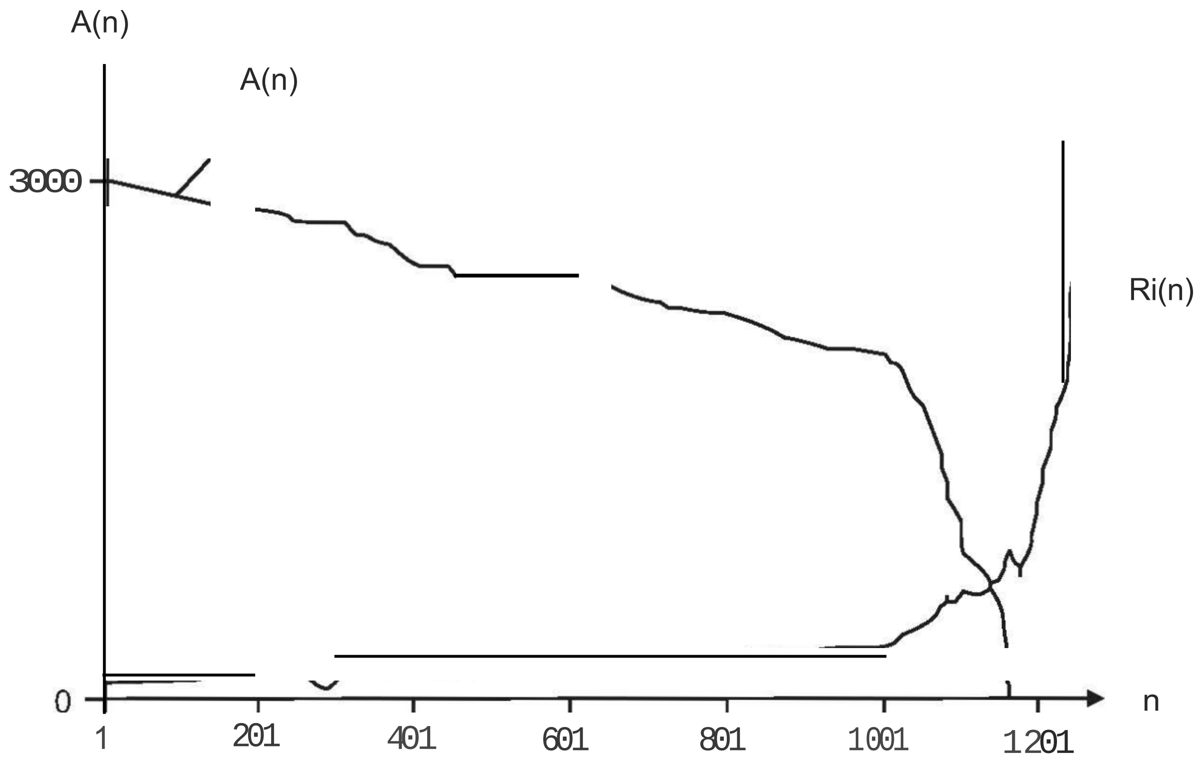

A(n)
A(n)
3000
Ri(n)
0
n
1
201
401
601
801
1001
1201

Fig. 6

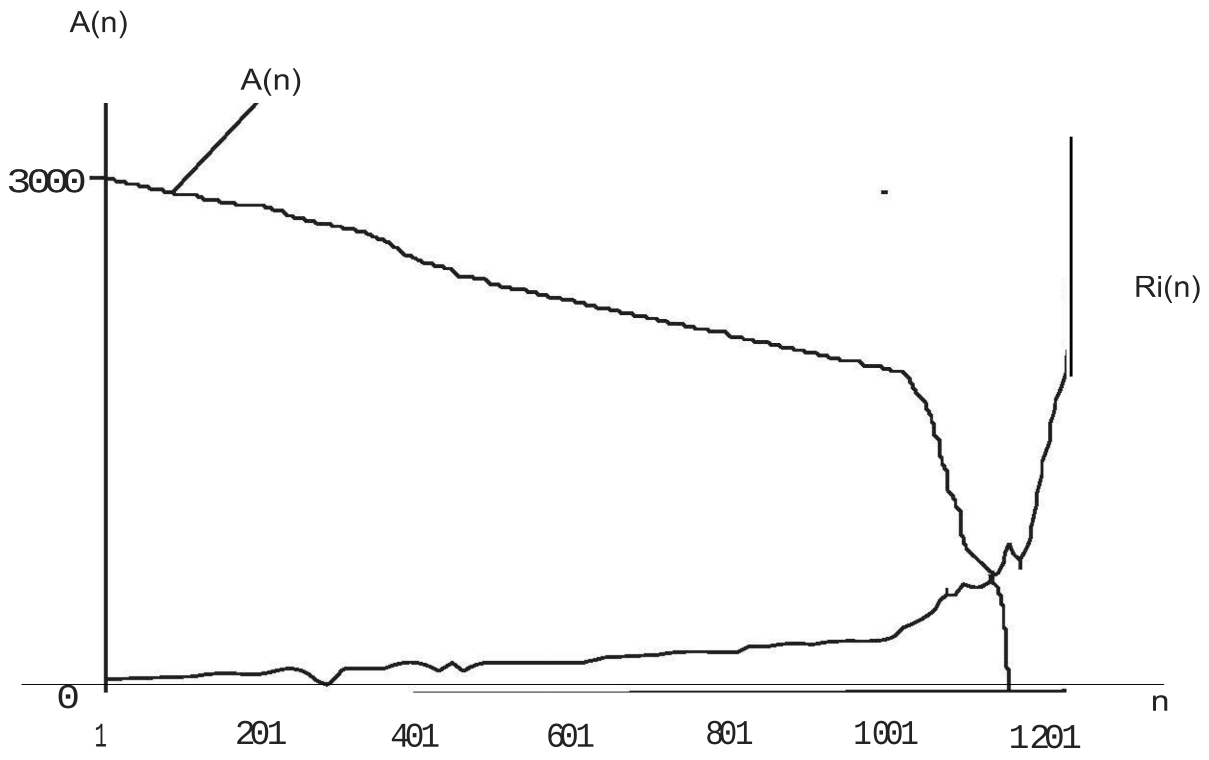

A(n)
A(n)
3000
Ri(n)
0
n
1
201
401
601
801
1001
1201

Fig. 7

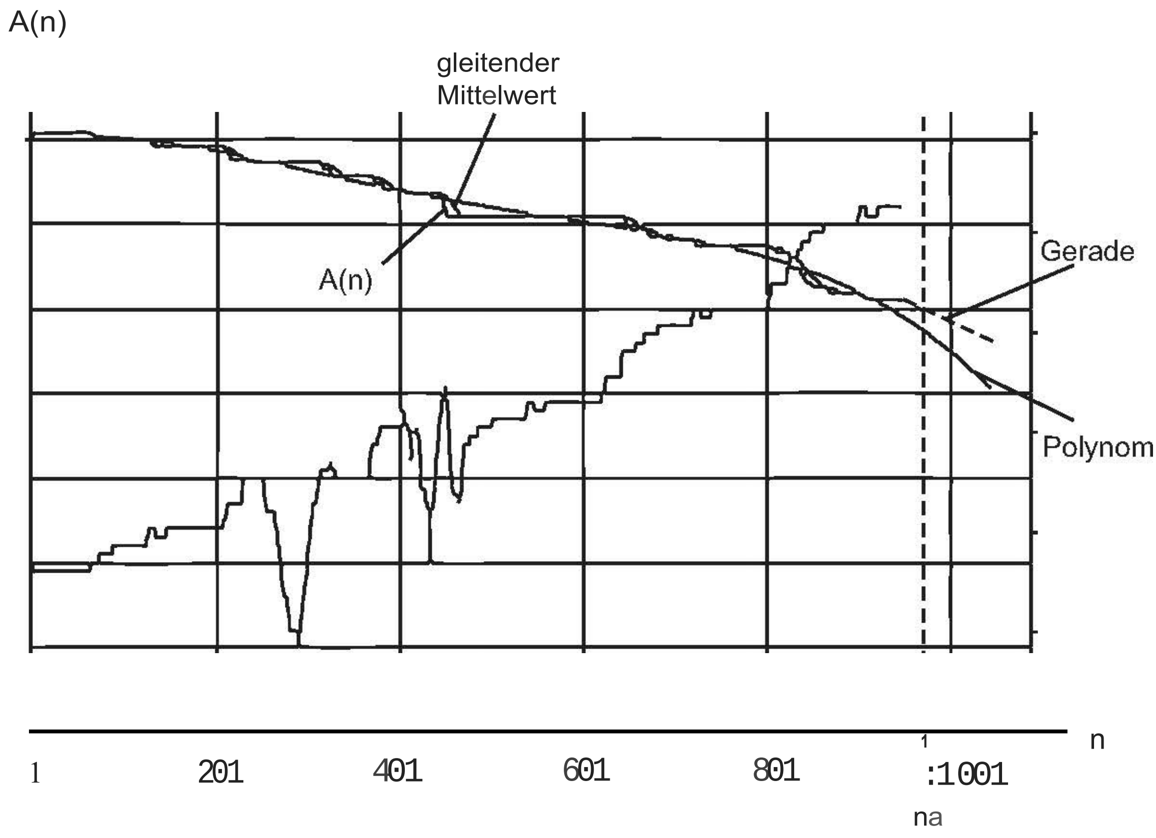

A(n)
gleitender
Mittelwert
A(n)
Gerade
Polynom
n
1
201
401
601
801
:1001
na

Fig. 8

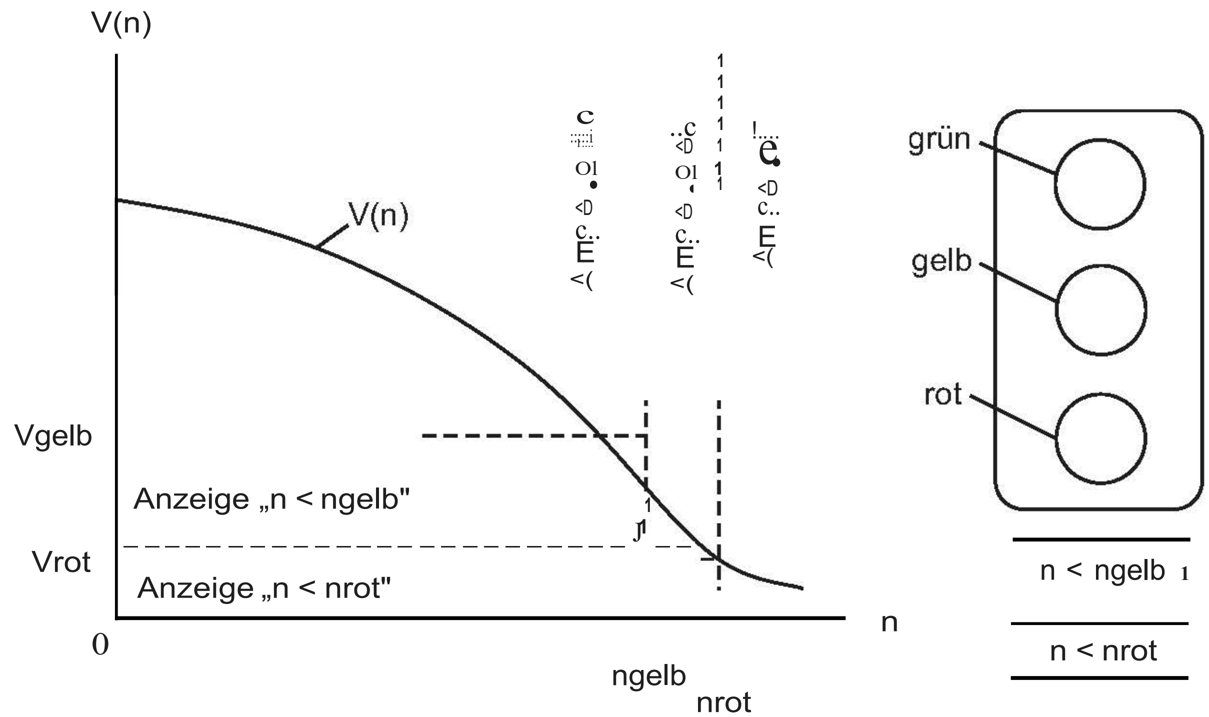
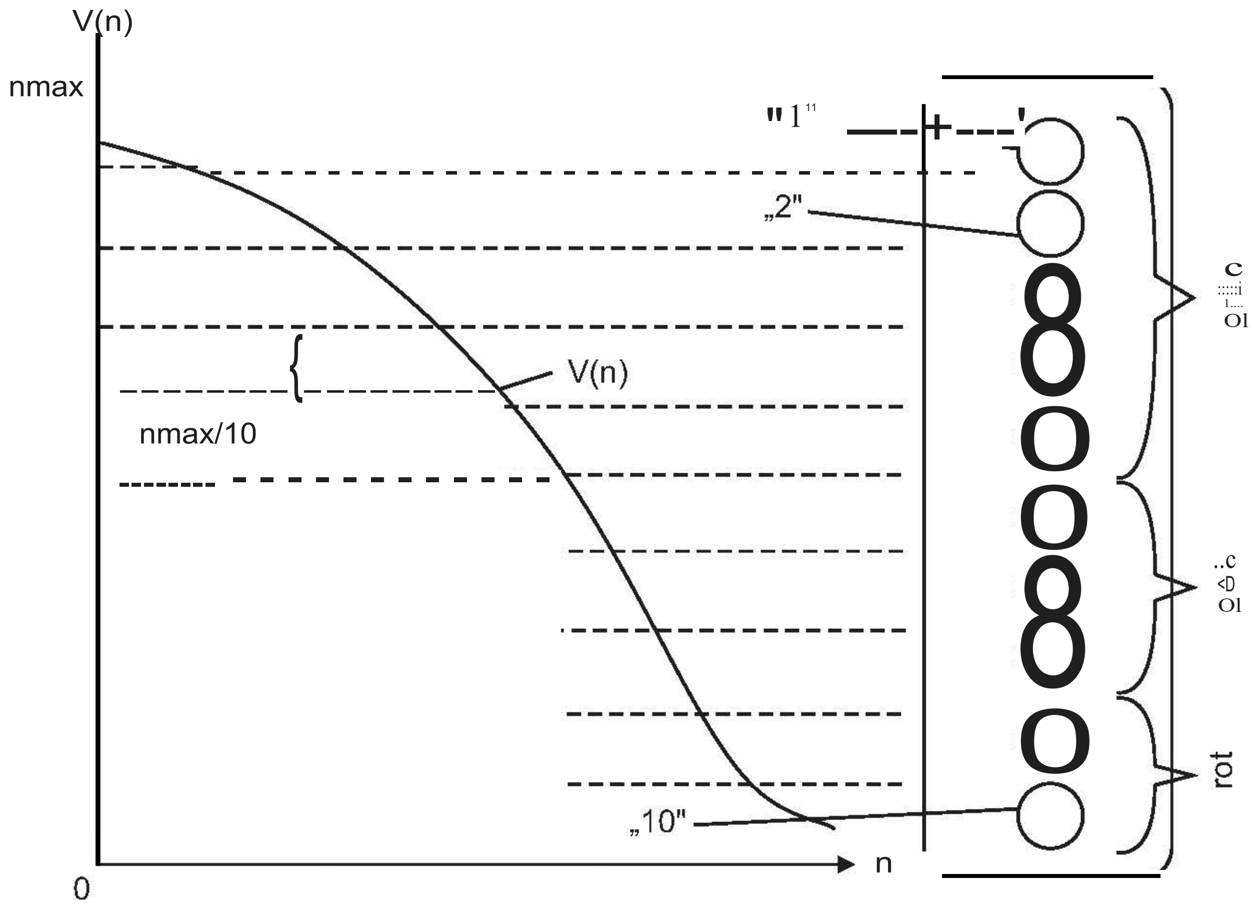

V(n)
V(n)
Vgelb
Anzeige „n < ngelb"
Vrot
Anzeige „n < nrot"
0
n
ngelb
nrot
grün
gelb
rot
n < ngelb
n < nrot

Fig. 9


V(n)
nmax
"1"
„2"
V(n)
nmax/10
„10"
rot
0
n