THE SIMPLIFIED THEORY AND DESIGN OF A CURRENT SOURCE INVERTER FOR AC MOTOR DRIVES

By

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Received February 21, 1977
Presented by Prof. DR. GY. RETTER

The schematic of the discussed Current Source Inverter known from technical literature is shown in Fig. 1. The controlling and regulating circuits are not indicated in this Figure, as the present paper does not desire to analyse their problems. The advantages of Current Source Inverter over the conventional voltage source type inverters will not be discussed either as they are treated in the technical literature.

A simplified theory of the inverter circuit shown in Fig. 1 using the Park-vectors is presented for the periodic steady-state. The analysis leads to simple expressions, by means of which the rating of the inverter and selection of the proper main elements of the inverter can be carried out by a relatively simple method and with an accuracy satisfying the practical demands.

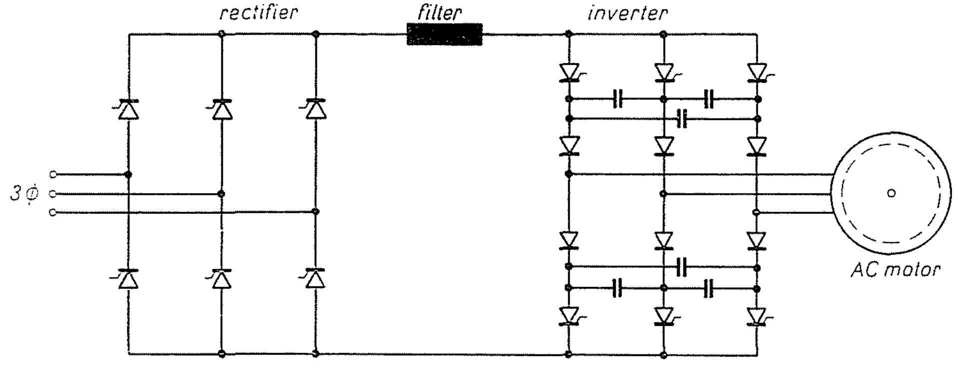

Fig. 1. Principled schematic of the Current Source Inverter drive system

1. Operation of the inverter

Although the physical mode of operation of the Current Source Inverter (henceforth only Inverter) is known from literature (see, e.g. [2]); however for a better understanding and introduction of the symbols, it will be useful to discuss briefly the mode of operation of the Inverter.

As mentioned above, the Park-vectors are used for analysing the operational characteristics, because in this way the simplest and most concise results will be obtained. According to [5], the motor is substituted for by the equivalent circuit of Fig. 2. Here $\bar{u}_s$ is the stator supply voltage, $\bar{i}_s$ the stator current, and L' the transient inductance of the motor. Finally, $\bar{u}'$ is a fundamental harmonic voltage of constant amplitude, which must be chosen in a way, that the equivalent circuit yields a correct fundamental harmonic current in the operating point. The minuscules with the dash designate Park-vectors, and the capital letters without a dash usually stand for constant quantities. The small letters without dash over them mean real instantaneous values.

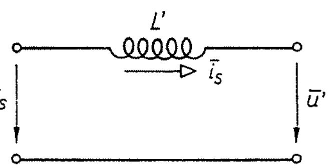

Fig. 2. Transient equivalent circuit of the motor

In the equivalent circuit — which is valid for both the Park-vectors and their harmonic components separately, too, — the resistance of the motor with respect to the harmonics is neglected. The effect of resistances on the fundamental harmonics can be exactly considered by voltage $\bar{u}'$; practically this may be necessary only at quite low frequencies, e.g. below 10 c/s. From Fig. 2, the differential equation of the motor with the Park-vectors:

$$\bar{u}_s = L' \frac{d\bar{i}_s}{dt} + \bar{u}'. \tag{1}$$

It is assumed that both the stator and the commutating capacitors are star-connected, otherwise an equivalent star-connection is considered. Therefore the circuit of Fig. 3 is obtained for the system consisting of the motor and the inverter.

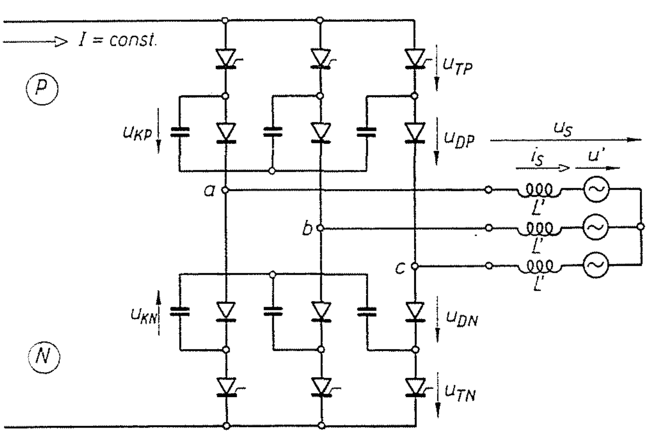

Fig. 3. The inverter and motor circuits with the positive directions

The two sides of the bridge circuit forming the inverter are marked with P and N, the three phases by a, b and c, respectively. The positive directions of the voltages and currents of each component are indicated by arrows placed beside these components. The subscripts T, D and K refer to the thyristors, diodes and capacitors. The direct current I is assumed to be ideally smooth, and the speed of the motor is considered to be constant.

In the periodic steady state during a single period of the output fundamental frequency, the processes take place or recur six times in a similar way, so due to periodicity it is sufficient to analyse an interval lasting only for one sixth of a period, In the most frequently occurring operating mode such an interval should be considered, where a commutating process takes place on side N between the phases b and c. This is shown in Fig. 4, where dashed lines stand for the paths of the currents in the various circuit modes. The basic state is shown in Fig. 4/a, this develops at the end of the previous interval; on side P, the thyristor and diode of phase a, and on side N those of phase b are conducting, the direct current I assumed to be constant flows in phase-windings a and b of the motor.

The investigated next interval starts when on side N the thyristor of the successive c-phase receives a firing impulse; this time capacitors b and c with appropriate charge will stop the conducting state of the thyristor b. The term of current commutation from thyristor b to thyristor c is very short compared with the other processes, so it can be neglected.

Fig. 4/b shows the state occurring when thyristor b stops conducting; this state is the first circuit mode of the interval analysed. There is no change from the point of view of the motor currents, but the charge and voltage of the mentioned commutating capacitors vary because of the direct current flowing through them. This process lasts until voltage changes cause the diode of phase c on side N to come to the boundary of the conducting state. When this diode begins to conduct, the first circuit mode ends, and the second one starts, as shown in Fig. 4/c. This mode is the *overlapping,* during which the stator current changes from phase b to phase c. It ends, when the phase-current b becomes zero, and then the diode of phase b will come out of the conducting state. This is followed by the third, and at the same time the last, circuit mode which is again a two-phase conducting state. This is shown in Fig. 4/d. From this state the next interval follows which is started by the firing of thyristor b on side P.

The Park-vector paths, in the stator coordinate system, for a total output period are shown in Fig. 5 where the loci of the path portions belonging to the above discussed interval are emphasized by thicker lines.

Due to periodicity, the paths must be closed and symmetrical around the zero-point. Fig. 5/a shows the path of the stator Park-vector current $\bar{\imath}_s$, which is a regular hexagon, owing to I=const. The current vector is in position I_0 in the initial instant and the first circuit mode of the examined interval, and during the overlapping it turns by 60 degrees along the side of the hexagon perpendicular to the phase axis of

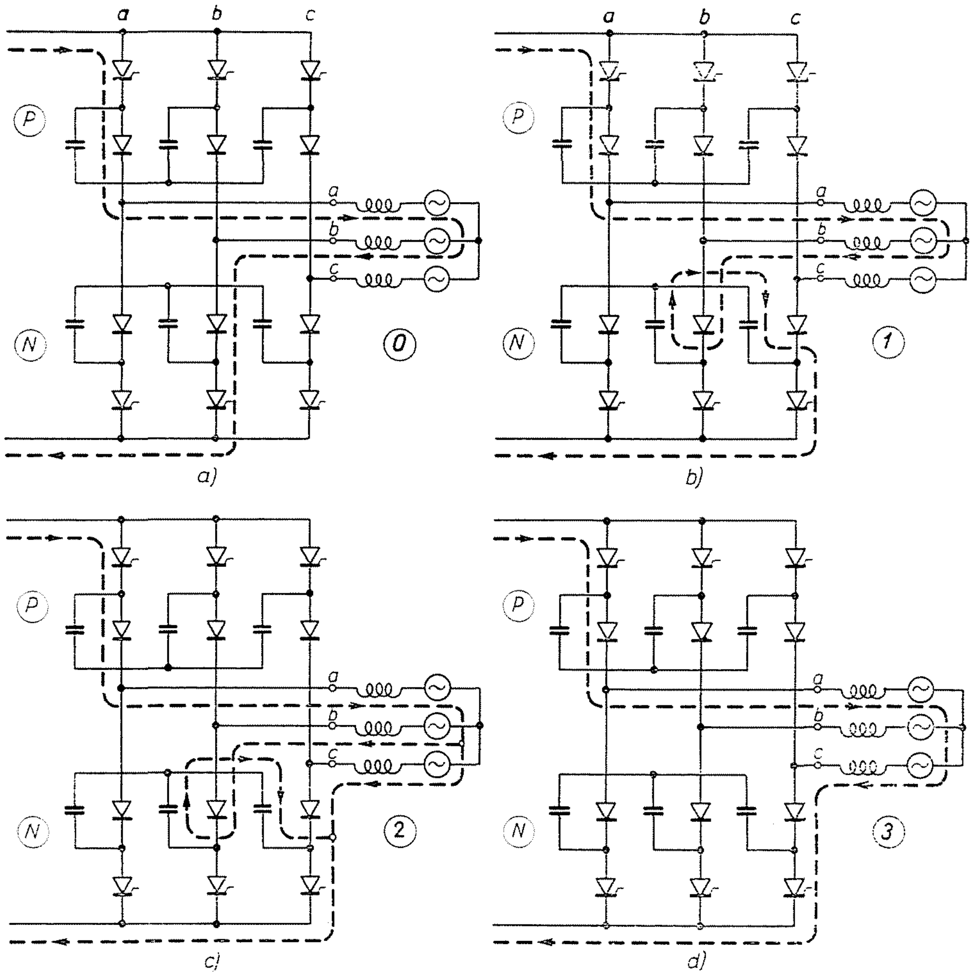

Fig 4. The circuit modes of the inverter in an interval of the periodic operation: a) starting state, b) first mode, c) second mode (overlapping), d) third mode

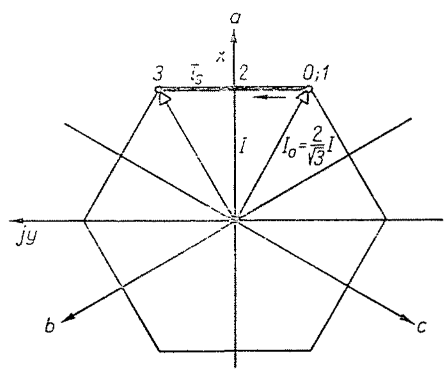

Fig. 5/a. Path of stator-current Park-vector

a and remains in this position in the third circuit mode of the interval until the beginning of the next overlapping.

Fig. 5/b shows the loci of the voltage vectors. As $\bar{u}'$ is a vector of constant amplitude and fundamental harmonic, its path is a circle, and $\bar{u}'$ passes along this circle at an angular speed $\omega_1 = 2\pi f_1 = \text{const.}$, where f_1 is the fundamental stator frequency. At the beginning of the interval examined, the position of $\bar{u}'$ is characterised by angle α.

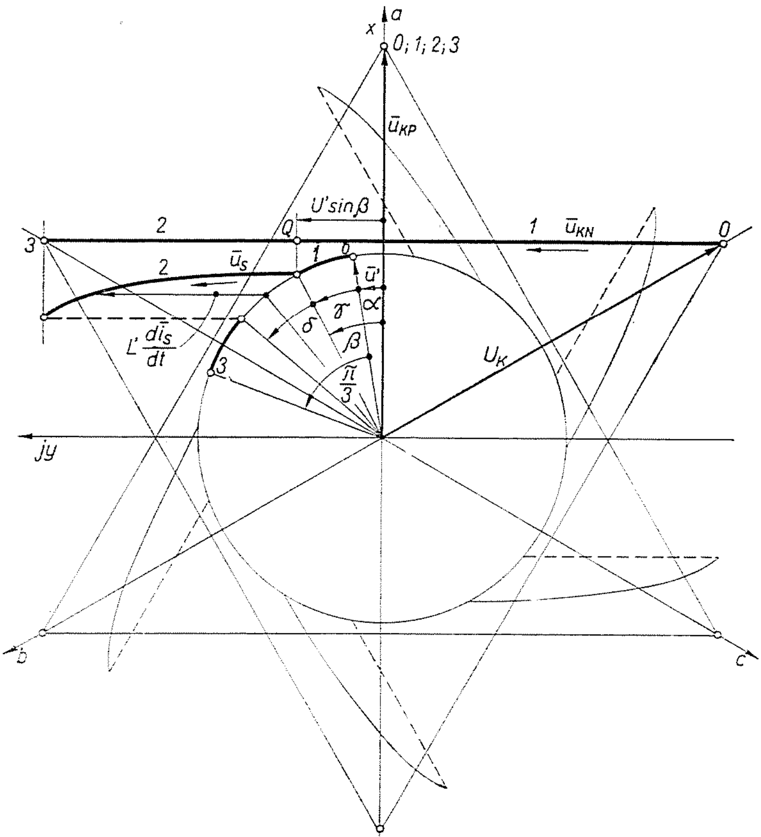

Fig. 5/b. Paths of stator voltage and condenser voltages

The stator terminal voltage differs from $\bar{u}'$ only during the overlapping, by the selfinduction voltage $L' \cdot d\bar{i}_s/dt$; the hexagonally symmetrical path of vector $\bar{u}_s$ is obtained in this way.

The vector loci of the capacitor voltages can be determined from the following considerations. The processes recur on both bridge sides by every 120 degrees, but there is a 60-degree phase displacement between the two bridge sides. It follows from the 120-degree periodicity, that the vector path must be trilateral. As in a 120 degree interval the capacitor voltage of one of the phases — e.g. in the case of Fig. 4, the capacitor voltage of phase a on side N — remains unchanged, in accordance with the projection rule of the Park-vectors the paths must be perpendicular to the phase axis. Considering the foregoing, the required vector paths are finally such equilateral triangles, whose vertices lie in the phase axis. $\bar{u}_{KN}$ and $\bar{u}_{KP}$ in Fig. 5/b show the paths of the N- and P-side capacitor voltages, respectively. The two triangles are congruent, but turned by 60 degrees from each other, owing to the phase displacement of the two bridge sides. U_K means the position of the N-side capacitor voltage at the beginning of the interval examined; as can be seen, U_K is actually the maximum value of the condenser phase voltage. The Park-vector $\bar{u}_{KN}$ runs on the thickened triangle-side in this interval, in the first circuit mode between the points O and Q, then during the overlapping between the points Q and 3. In the third circuit mode the vector remains in point 3, until the firing of the successive thyristor a on side N. In the Figure, the duration of the first circuit mode of the interval is given by angle γ, the second (overlapping) by angle δ. An abbreviation of $\alpha+\gamma=\beta$ is also introduced for later use.

The Park-vector parts of the thyristor voltages are the same as the Park-vectors of the capacitor voltages, but the instantaneous values of the thyristor voltages contain zero sequence components, too.

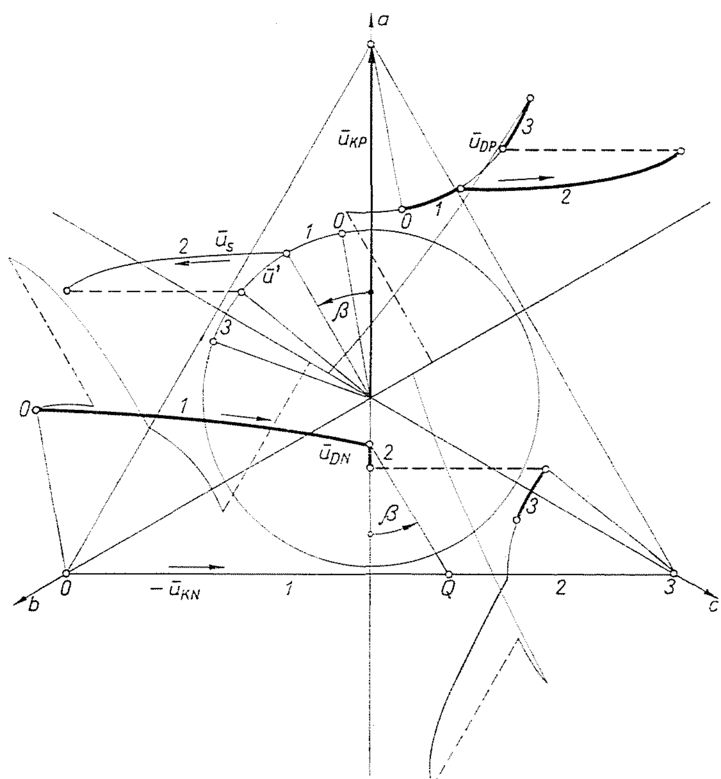

Fig. 5/c. Path of diode-voltage Park-vectors

Finally, Fig. 5/c shows the path of the diode voltage Park-vectors. This path can be constructed by means of the vectors shown in Fig. 5/b, if

$$\bar{u}_{DN}=\bar{u}_s-\bar{u}_{KN} \tag{2}$$

and

$$\bar{u}_{DP}=\bar{u}_{KP}-\bar{u}_s \tag{3}$$

are used, which follow from Fig. 3 directly. Also the instantaneous values of the diode voltages contain zero sequence components, therefore $\bar{u}_{DN}$ and $\bar{u}_{DP}$ mean only the Park-vector parts of the two diode voltages. The diode voltage vectors of the two bridge sides follow the same path, but at a given moment the two vectors are situated on another part of the path, in accordance with the phase displacement of the two bridge-sides. At the beginning of the interval examined, and in the different circuit modes of the interval, the position of $\bar{u}_{DN}$ and $\bar{u}_{DP}$ is designated by the serial numbers used also in the previous Figures.

By means of the Park-vector paths, the starting and end values of the vectors can be determined in each circuit mode of the interval, and the periodicity conditions can be validated with them. Therefore the relationships governing the behaviour of the system can be derived, and they give directions for the rating of the inverter.

2. Calculation of the inverter

For the calculations it is useful to decompose the Park-vectors to x, y (real and imaginary) components in the coordinate system of Fig. 5, as e.g. $\bar{u}_{KN}=u_{KNx}+$ $+ju_{KNy}$, $\bar{i}_{KN}=i_{KNx}+ji_{KNy}$, etc. It follows from the foregoing that in the first circuit mode of the examined interval, only the capacitors b and c will be charged with direct current $I=$const., which accomplish the next current-commutation on side N of the inverter-bridge. According to the known definition of the Park-vector (e.g. [6]), using Fig. 4/b, we obtain that $i_{KNx}=i_{KNa}=0$ and $i_{KNy}=2I/\sqrt{3}=I_0=$const. during the mentioned process. As an effect of this charging current, $u_{KNx}=U_K/2=$const. will hold, only u_{KNy} will change from the starting value $-\sqrt{3}\,U_K/2$ shown in Fig. 5/b to the value of $U'\sin\beta$ (point Q) during the period $t=\gamma/\omega_1$. Considering all this, from the differential equation $i_{KNy}=C\cdot du_{KNy}/dt$ we obtain for the first circuit mode of the interval examined the following equation:

$$\frac{I_0}{\omega_1 C}\,\gamma=\frac{\sqrt{3}}{2}\,U_K+U'\sin\beta \tag{4}$$

where C is the capacitance of a commutating capacitor in star-connection.

Point Q in Fig. 5/b designates the moment, when the b—c line voltage of the commutating capacitors become equal to the stator line voltage b—c. In this case, the c-phase diode of side N, which has received a cutoff voltage, will come to the boundary of the conducting state and will be connected to the stator terminals b—c.

So the second curcuit mode of the interval, i.e. the overlapping, will start. As the line values b—c are proportional to the y-components of the Park-vectors, $u_{sy}=u_{KNy}$ during the total time of overlapping. (The initial value of these is $U'\sin\beta$). As can be seen in Fig. 4/c, in this circuit mode the two phase-windings of the stator and the commutating capacitors from an oscillating circuit, whose natural frequency is

$$\Omega=\frac{1}{\sqrt{L'C}}\,. \tag{5}$$

More exact calculations show (see [4]) that the natural frequency of circuit L'—C practically determines the period of overlapping, which is approximately $\Omega t=\pi/2$ if measured in eigen-periodic angle, that is one quarter of a period. The overlapping angle expressed in terms of the fundamental stator frequency period is

$$\delta=\frac{\omega_1}{\Omega}\,\frac{\pi}{2}=\varepsilon\,\frac{\pi}{2} \tag{6}$$

where — as will be seen later — the definition

$$\varepsilon=\frac{\omega_1}{\Omega}=\omega_1\sqrt{L'C} \tag{7}$$

proves to be very useful, as it gives the ratio of the existing fundamental stator frequency to the eigenfrequency.

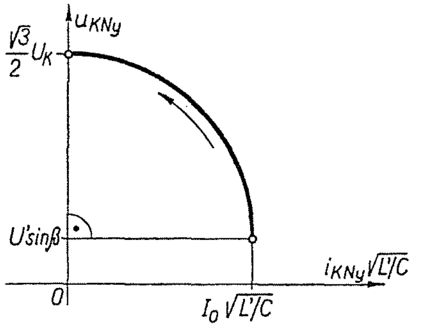

Fig. 6. Process of commutation of the stator current

The mentioned oscillation which is of one quarter wave-length, — during which the current commutation takes place from one of the stator phase-windings to the other — is represented by the quarter circular arc shown in Fig. 6. During commutation, u_{KNy} varies within the boundaries shown in Fig. 5/b, and i_{KNy} decreases from I_0 to zero, and the second circuit mode of the examined interval ends. In accordance with Fig. 6, the following expression can readily be derived:

$$I_0\sqrt{\frac{L'}{C}}=\frac{\sqrt{3}}{2}\,U_K-U'\sin\beta \tag{8}$$

If the motor is given and the capacitance of the commutating condenser has been chosen, the condenser voltage U_K and the charging time γ could be calculated at an arbitrary frequency for a load $I=\sqrt{3}I_0/2$, if angle β and voltage U' were known.

As was mentioned, voltage U' must be chosen in such a way, that the fundamental harmonic current calculated from the equivalent circuit of Fig. 2 should be equal to the actual fundamental harmonic stator current of the motor. To satisfy this condition, let us express the fundamental harmonic component $\bar{I}_1$ of Park-vector $\bar{i}_s$.

For this, Fig. 7 shows the path of the stator current Park-vector in a coordinate system rotating together with the fundamental harmonic. The path is a closed folium, and the end point of vector $\bar{i}_s$ runs along it six times during one period. The end point of the fundamental harmonic current component $\bar{I}_1$ is in the weighted centre of the folium according to the general equation

$$I_1=\frac{3}{\pi}\int_0^{\pi/3}\bar{i}_s(\xi)e^{-j\xi}\,d\xi. \tag{9}$$

If the overlapping were neglected, or in other terms an instantaneous commutation were assumed, then $\delta=0$, as from (9) the relationship $I_1=3I_0/\pi$ and $\varphi_1=\beta$ would be obtained. This is only a first, rough approximation; however, this is sufficient at low frequencies.

As $\delta\neq 0$, therefore phase angle φ_1, i.e. the angle between voltage $\bar{U}'$ and fundamental harmonic current $\bar{I}_1$, and angle β differ by the relatively small value of Θ. If the overlapping process is considered in a way, that integration in (9) is carried out only for the period $\pi/3-\delta$ of the two-phase conducting-state, but δ is not considered, $\Theta=\delta/2$ will result. This is a good approximation at all frequencies. The period of overlapping slightly increases this value Θ, and so the calculation is more accurate if $(0.6\sim 0.65)\ \delta$ is considered; therefore, considering (6), $\Theta\approx\varepsilon$, i.e. $\varphi_1=\beta+\varepsilon$. Amplitude I_1 depends on δ only slightly, thus it can be calculated with the previous value

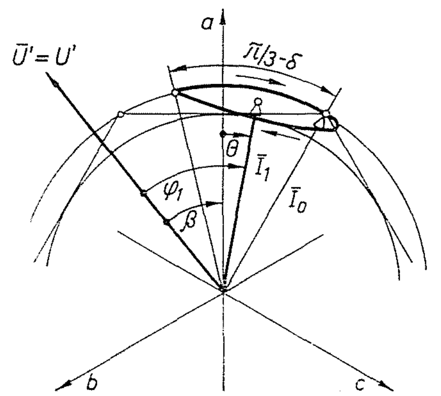

Fig. 7. Vector diagram of the stator current in the synchronous coordinate system

obtained with $\delta=0$. Finally, the fundamental harmonic of the stator current can be calculated by means of the following simple and practically exact equations, expressed in terms of the inverter parameters:

$$\bar{I}_1=I_1 e^{-j\varphi_1}=\frac{3}{\pi} I_0 e^{-j(\beta+\varepsilon)}. \tag{10}$$

This formula is written in the coordinate system rotating together with the fundamental harmonic, where $\bar{U}'$ points to the direction of the real axis.

In every operating point the current defined by (10) must be equal to the fundamental current of the motor calculated from the well-known equivalent circuit or circle diagram. If the stator resistance can be neglected from the point of view of the fundamental harmonics, too, — which is a sufficient approximation at higher frequencies, e.g. above 10 c/s, — then the fundamental current can be expressed relatively simply also with the parameters of the motor. As from the point of view of dimensioning the desired highest frequency is decisive, only the range of higher frequencies will be discussed in the following and the resistance of the stator will be neglected. In this case the expression of $\bar{I}_1$ in the previously mentioned coordinate system—neglecting the calculations detailed in [4] — will be

$$\bar{I}_1=\frac{U'}{\omega_1 L'}\frac{1}{1-\sigma}\left(\frac{s'}{s_{bn}}-j\sigma\right). \tag{11}$$

Here $\sigma=L'/(L_m+L_{sl})$ is the resultant leakage coefficient, s_{bn} is the natural slip at maximum torque of the motor and $s'=(\omega_1-\omega_r)/\omega_{1n}$, the usual slip, where $\omega_{1n}=$ $=2\pi f_{1n}$ is the rated synchronous speed and ω_r the mechanical speed of the rotor (in electrical angle).

It is useful to carry out the calculations in the p.u. system, as the equations will be simpler and will not contain any dimensioned quantities. The basic units should be the rated parameters of the motor. So, e.g., the fundamental stator frequency in the p.u. system is

$$\mu=\frac{f_1}{f_{1n}}=\frac{\omega_1}{\omega_{1n}}. \tag{12}$$

To characterize the condenser voltage let us define a dimensionless parameter

$$K=\frac{\sqrt{3}}{2}\frac{U_K}{U'} \tag{13}$$

and for the fundamental harmonic of the stator current

$$y_1=\frac{I_1 X'}{(U'/\mu)}. \tag{14}$$

Here $X'=\omega_{1n}L'$ is the transient reactance of the machine, and U'/μ is proportional to the rotor flux (as the resistance of the stator was neglected) whose amplitude is formed by the control circuits in each operational point. E.g. if the rotor flux is kept on a constant value by the control circuits, U'/μ is constant and is about 1 in the p.u.

system. Control can be accomplished also to keep the fundamental harmonic of the stator flux constant. In this case U_{s1}/μ is constant and about 1 and, according to Fig. 2, U'/μ can be calculated from

$$\frac{\overline{U}_{s1}}{\mu}=jX'\overline{I}_1+\frac{U'}{\mu} \tag{15}$$

for any stator current $\overline{I}_1$. If some other control is used, the equations holding for the given solution should also be considered when calculating U'/μ.

With the foregoing symbols, from the equivalence of (10) and (11)

$$\sin(\beta+\varepsilon)=\frac{y_{1,0}}{y_1} \tag{16}$$

is obtained, where

$$y_{1,0}=\frac{\sigma}{1-\sigma} \tag{17}$$

is the no-load current of the machine interpreted in accordance with (14). Finally, from (4) and (8),

$$K=\frac{\pi}{3}\,\frac{y_1}{\varepsilon}+\sin\beta \tag{18}$$

$$\gamma=\varepsilon+\varepsilon^2\frac{6}{\pi}\,\frac{\sin\beta}{y_1}\,. \tag{19}$$

All equations necessary for the calculation of the periodic steady state have now been obtained. From these relatively simple equations, the parameters necessary for constructing the Park-vectors of the state variables can easily be determined, with any load of the drive in such a frequency range where the neglection of the stator-resistance is permitted. By means of the Park-vectors, the instantaneous values of the state variables can simply be obtained, and from these the maximum values, etc. For example, from Fig. 7, the projection of direction $\overline{U}'$ of the current vector running along the folium is proportional to the torque of the motor, and so the pulsating torque can also easily be determined.

Assuming an inverter without losses, the powers on the direct and alternating current sides must be equal; from this the mean value of the input d.c. inverter voltage U_{dc} can be calculated. Therefore

$$U_{dc}I=\frac{3}{2}\,U'I_1\cos\varphi_1$$

from which, considering $I_1=3I_0/\pi=3\cdot 2I/\sqrt{3}\pi$ and $\varphi_1=\beta+\varepsilon$:

$$U_{dc}=\frac{3}{\pi}\sqrt{3}U'\cos(\beta+\varepsilon). \tag{20}$$

This equation shows that the inverter operates as a symmetrically controlled, three-phase bridge-connected rectifier, whose firing angle is $\beta+\varepsilon$. The value of the d.c. voltage calculated with Eq. (20) gives a basis for rating the network rectifier of the system.

3. The operating range of the inverter

In the first part of the paper, an interval of the steady state was chosen to illustrate the operation of the inverter, and the circuit modes for this interval were shown in Fig. 4. A careful investigation of the figures leads to two important facts:

1. On side P of the inverter-bridge, only the diode of phase a conducts during the full interval, the other two diodes are not conducting, so there must be back voltages on them.
2. On side N, the diode of phase a does not conduct during the period, so there must be back-voltage on it.

It is clear that these circumstances are the necessary conditions for the fact, that the discussed circuit modes shown in Fig. 4, and the periodic state achieved with them, may take place. Apparently these conditions lay specific claims in respect of the diode voltages during the period.

Let us examine more closely, for instance, what requirements must be fulfilled in accordance with condition 1. in order that, during the current conducting period of diode a on side P, the diodes b and c get back-voltages. According to the transformational relationship existing between the coordinates x, y of the Park-vectors and the instantaneous values of phase-quantities a, b, c (see [6]), with the positive directions of Fig. 3, the following equation and inequalities result for the condition discussed:

$$u_{DPa} = u_{DPx} + u_{DP0} = 0$$

$$u_{DPb} = -\frac{1}{2} u_{DPx} + \frac{\sqrt{3}}{2} u_{DPy} + u_{DP0} < 0$$

$$u_{DPc} = -\frac{1}{2} u_{DPx} - \frac{\sqrt{3}}{2} u_{DPy} + u_{DP0} < 0.$$

Expressing the zero sequence component from the first equation and substituting it into the two inequalities

$$-\sqrt{3} < \frac{u_{DPy}}{u_{DPx}} < \sqrt{3}$$

is obtained. This result is due to the fact that for the fulfilment of condition 1. the Park-vector $\bar{u}_{DP} = u_{DPx} + ju_{DPy}$ must remain in the range of 120° closed by the negative b and c phase axes, during the whole period. This is because u_{DPy}/u_{DPx} is the tangent of vector u_{DP} and thus from the above inequality this angle can vary between $\pm 60°$.

A similar investigation of condition 2. shows that diode a of the bridge-side N gets back-voltage — while diode b alone conducts — only if the Park-vector $\bar{u}_{DN}$ remains in the 120°-range closed by the negative phase axes c and a. The results of the quantitative investigations not detailed here show that from the two conditions the second one is more strict, i.e. condition 2. is decisive. Therefore the periodic operation of the inverter discussed in the first part is possible up to a range determined

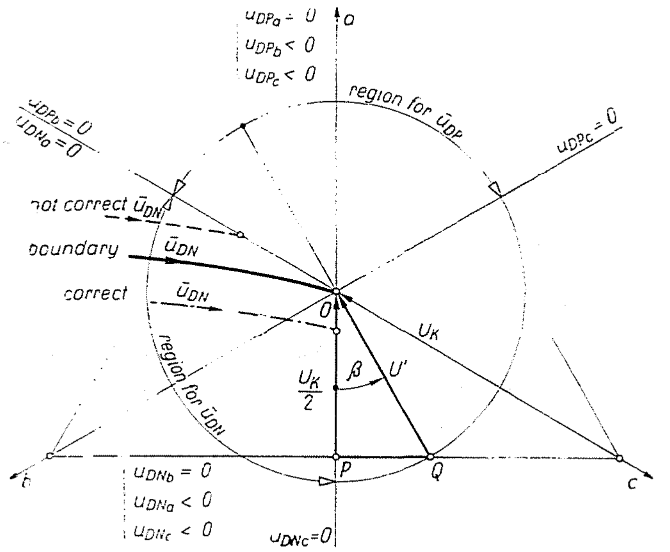

Fig. 8. Finding the operational boundary of the inverter

by the diode voltages of that bridge-side where the commutation is present; this is side N in the discussed interval. Let us investigate the operational characteristics of this side from this point of view.

For demonstration, Fig. 8 shows a portion of the path of Park-vector $\bar{u}_{DN}$ for some specific cases. In normal operation — as discussed — the vector path intersects the negative phase-axis a, when diode c starts to conduct and overlapping begins. This case is shown by the curve in dotted line. The curve in dashed line refers to a case, when the path intersects the negative phase-axis c; this means that not diode c, which is necessary for correct operation, but diode a starts to conduct. According to condition 2. this is evidently not permissible, as in this way the periodic state adequate to the operational mode discussed in the first part will not develop. It is clear from Fig. 8 that in limit case the path of $\bar{u}_{DN}$ must run into the zero-point of the coordinate system; this is the boundary of the intersection with the negative phase-axis a. This case is shown by the curve in heavy line. Plotting the limit point 0 of vector $\bar{u}_{DN}$ by the method discussed in Fig. 5/c will give the rectangular triangle $O-P-Q$. From this a simple equation can be written which characterizes the limitation case:

$$\frac{U_K}{2} = U' \cos \beta .$$

Introducing the dimensionless quantities stated in the previous part:

$$K = \sqrt{3} \cos \beta$$

Finally, using (16) and (18):

$$\frac{\pi}{6} y_{1,0} = \varepsilon \sin(\beta+\varepsilon) \cos\left(\beta+\frac{\pi}{6}\right). \tag{21}$$

This is represented by the curves of Fig. 9. They show the frequency ratio ε defined by Eq. (7) as a function of the fundamental stator-current harmonics interpreted according to (14), in the boundary operational region of the inverter, for motors with different no-load currents. With a given load, the condition of periodic operation for the inverter is that the frequency ratio should be smaller than the value read from the boundary curve for the given motor. From the view-point of the voltage-load of the inverter, as Eq. (18) shows, the greatest possible frequency ratio would be required; however, the operational range of the inverter limits its increase.

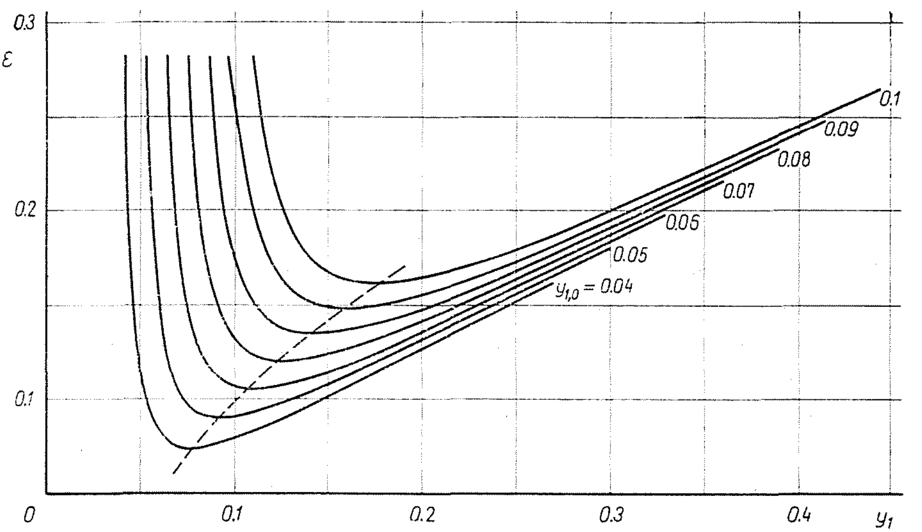

Fig. 9. Frequency ratio as a function of the fundamental harmonic stator current on the boundary of operation

As the drive has to operate everywhere between no-load and a given load, therefore the achievable maximum frequency ratio is determined by the value relative to the minimum-point of the boundary-curves. Fig. 10 shows the boundary curve for the frequency ratio determined in this way as a function of the no-load current. Usually the no-load currents of induction motors are 30~50%, the range for them is plotted in the Figure. It can be seen that the maximum frequency ratio that can be reached is about 0.13 for normal motors. It also follows, that motors with higher no-load currents are more favourable, therefore it is advantageous if the current control saturates a little the airgap magnetic circuit of the motor around the no-load point.

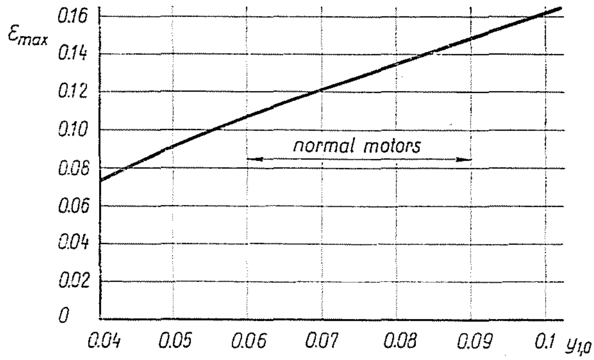

Fig. 10. The diagram of the achievable maximum frequency ratio

From the foregoing it also follows, that the statement concerning the operational range of the inverter in Part 4. of [4], and the boundary curve given therein, only holds for a type of Current Source Inverter, where the commutation is started by auxiliary thyristors and not by diodes (see e.g. [7]).

Finally it is to be noted that the operation limit will exist in the motor mode; such an operation limitation does not exist in the generator mode, as the phase conditions of $\bar{u}'$ in the generator mode are always favourable from the point of view of the diode voltages (Fig. 12).

4. Method of dimensioning

A simple method of dimensioning can be founded on the knowledge of the operational range of the inverter. We start from the requirement that the system must not overstep the operation limit determined in the previous section at the highest frequency with any load. In this case, for a given motor the maximum frequency ratio ε_{max} can be read from the boundary curve of Fig. 10. If also the desired maximum stator frequency $f_{1\,max}$ is given, considering ε_{max} and Eq. (7), the capacitance of the commutating capacitors will be:

$$C=\frac{1}{L'}\left(\frac{\varepsilon_{max}}{2\pi f_{1\,max}}\right)^2. \tag{22}$$

With this and the motor parameters, the operational characteristics at an arbitrary operating point can be calculated with use of the equations derived in the second section. The calculation must be carried out for the operating point giving the greatest voltage and current loads. The greatest voltage load will occur at maximum frequency with the desired maximum stator current, but care should be taken of the fact that with equal currents the voltage load of the diodes is essentially greater in the generator mode than in the motor mode. Thus, from the view-point of diode voltages, the greatest generator-mode load will be decisive.

To illustrate the procedure outlined, the calculation will be shown in brief for an experimental drive under construction. The parameters of the motor are: 5.5 kW, 380/220 V, 12/20. 8 A, 50 c/s, 1445 r.p.m., and the inductances in the p.u. system: $L'=0.16$ and $L_s=L_m+L_{sl}=2.2$.

The desired maximum stator frequency is $f_{1\,max}=f_{1n}=50$ c/s. The control system of the drive will be formed in a way to keep the rotor flux constant and of rated value, and thus $U'/\mu=1$ can be assumed in the approximative calculations. To keep the voltage load of the semiconductors at the possible smallest value, the stator windings of the motor are delta-connected, therefore the rated voltage and current are: $U_n=220$ V and $I_n=20.8$ A.

With the above parameters $\sigma=0.072$, and so $y_{1,0}=0.079$ to which, according to Fig. 10, the maximum frequency ratio 0.13 belongs; for some security, we choose $\varepsilon_{max}=0.12$. Using Eq. (22), the capacitance of the commutating capacitors is $C=48\ \mu F$. (This refers to star-connections; if the condensers are connected in delta, $C_\Delta=16\ \mu F$).

In the motor mode the maximum stator current desired for a short period is 1.5 I_n, in the generator mode it is only I_n; the current limiter is adjusted to these values. For the loading of the inverter-elements the maximum current of the mentioned motor mode is decisive. This motor mode is decisive also for the voltage loads, with the exception of the diodes, since the voltages on the diodes are in spite of the smaller current, higher with maximum load in the generator mode than with a current of 1.5 I_n in the motor mode.

In the following, calculation is presented for the operating point of the above generator mode; in this way the maximum voltage load of the diodes can be determined. Using the equations of Section 2, the parameters necessary for plotting the Park-vectors in this operational point will be: $y_1=0.16$, $\varphi_1=150.6°$, $\beta=143.8°$, $\delta=10.8°$, $\gamma=12.6°$, $\alpha=131.2°$ and $K=1.99$; Fig. 11 and 12 show Park-vector paths.

In Fig. 11, the paths of stator voltage $\bar{u}_s$ and condenser voltage $\bar{u}_{KN}$ are shown. It is not necessary to plot the Park-vectors for the total period, one interval is suffi-

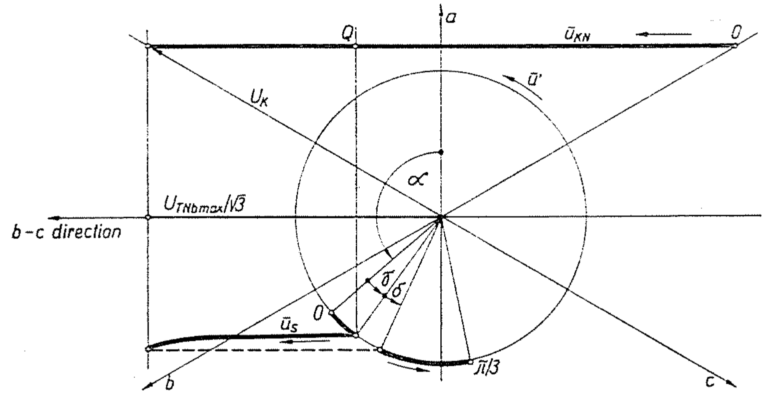

Fig. 11. Park-vectors of the stator and condenser voltages in rated generator mode

cient. As is known, the Park-vectors of the phase-quantities give the line quantities, too, if the vector is projected on the resultant (line) direction of the phase axes and the projection multiplied by $\sqrt{3}$. From the inverter circuit it follows that the voltage of any thyristor is equal to a capacitor line voltage, therefore the thyristor voltages can also be determined in the Figure. So, e.g., on side N of the inverter bridge, the voltage of thyristor b — after the forced commutation — is given by the projection b–c of the condenser voltage $\bar{u}_{KN}$. From the Figure the important relation can be read, that the maximum thyristor voltage — both in forward and in reverse directions — is one and a half times as great as U_K:

$$U_{T\,\max}=\frac{3}{2}\,U_K. \tag{23}$$

In the case discussed $U_K=410$ V and $U_{T\,\max}=620$ V will occur, the maximal load of the condensers and thyristors, however, depends on the values of the motor mode with 1.5 I_n. (It is to be noted that, if the delta-connected stator winding is substituted

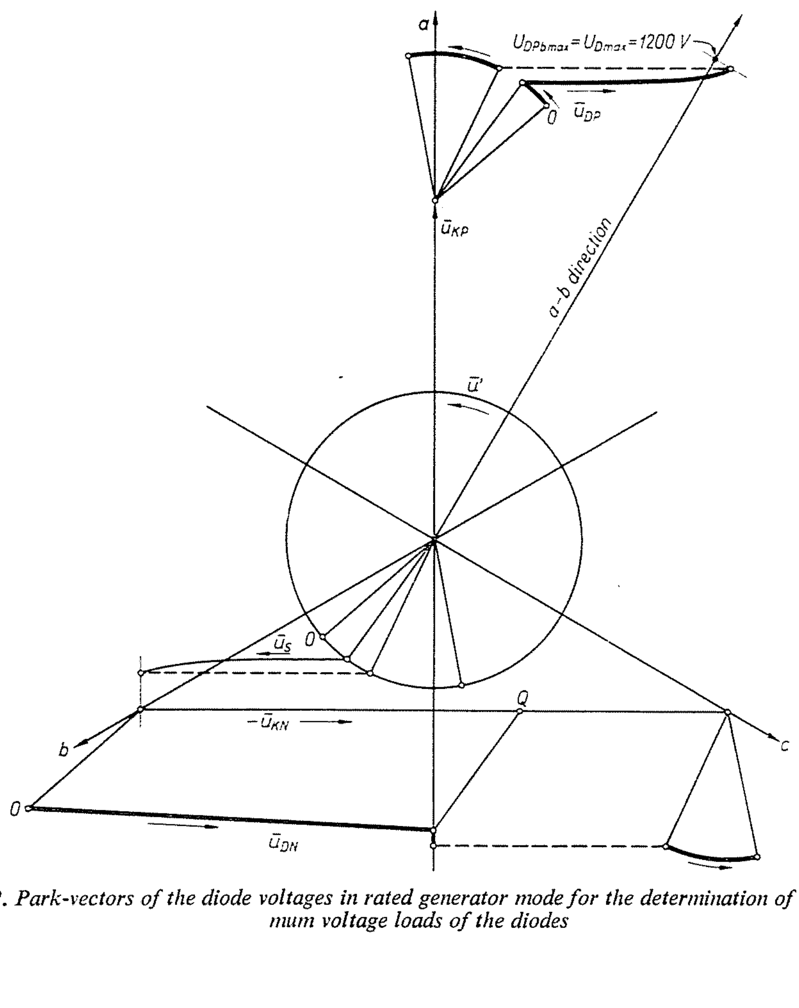

Fig. 12. Park-vectors of the diode voltages in rated generator mode for the determination of the maximum voltage loads of the diodes

by an equivalent star-connection, then — as also the frequency and U'/μ, i.e. the rotor flux, are of rated value, $U' = \sqrt{2}.220/\sqrt{3} \approx 180$ V /phase).

The vector paths of the diode voltages are shown in Fig. 12. The dimensions of the paths compared with U' show how high voltages arise in the generator mode. In the inverter circuit it can be observed that the voltage of any diode is equal to the difference between a stator terminal voltage and a condenser line voltage (see Eq. [2] and [3], too), and thus the instantaneous values of the diode voltages are obtained simply by projecting vectors $\bar{u}_{DN}$ and $\bar{u}_{DP}$ on the resultant (line) direction of the phase axes. The greatest of these projections gives the maximum diode voltage. In the present case it can be found on side P in direction a–b and from this $U_{D\,\max} = 1200$ V. The diodes must be chosen on the basis of this value from the point of view of the cutoff voltage. Otherwise the projection in the direction mentioned means that, in the examined interval, maximum voltage load will occur on the diode of phase b on side P at the end of overlapping, when the N-side diode of the same phase stops conducting. Of course, during the operation of the inverter this load will be present, in accordance with the 60°-periodicity, at the end of the overlapping periods on all diodes.

The calculation and the plotting of the Park-vectors can be carried out similarly also for the operational point of 1.5 I_n in the motor mode. Without detailing, it is only to be mentioned that in this operational point $U_K = 480$ V and $U_{T\,\max} = 720$ V were obtained. These values are of importance when the condensers and thyristors are chosen from the point of wiev of voltage. At the same time, in this operational point $U_{D\,\max} = 830$ V, this is really less than the one obtained in the generator mode.

Summary

The paper presents a simplified analysis of the asynchronous drive fed by a Current Source Inverter, for the periodic steady state. Neglecting the stator resistance of the motor, and assuming perfectly smooth direct current, first the known operation of the system is analysed by the Park-vector method. Then, using the advantages of this method, simple equations are deduced, by which the operational characteristics can be calculated with good approximation for any operating point.

It follows from the analysis that in the operation of the inverter, the ratio of the fundamental stator frequency to the eigenfrequency of the commutating L'C- circuit plays a very important role. The paper shows that, at a given value of this frequency ratio, the system reaches a boundary state, beyond which no periodic state corresponding to the known circuit modes can occur.

The paper gives the limit values of the determined frequency ratio as a function of the motor parameters in a diagram. Finally, starting from this operating range, the paper suggests a relatively simple method of dimensioning, the application of which is shown on a practical numerical problem.

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