SOME THEORETICAL QUESTIONS OF THE THERMAL PROTECTION BY SIMULATION

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Introduction

Electrical machines are protected against overheating, and the damage resulting from it, by means of various protective devices. Overheating may arise either from overload or from improper operation (e.g. shortcircuit, major phase asymmetry).

Whenever improper operation is detected, it is generally justified to switch off the machine at once. The protective units serving for this purpose are not considered here, the paper deals only with protection against overheating.

Theoretically, no overheating must occur in an adequately dimensioned and properly selected machine, provided the technological discipline is strictly observed. In many cases, however, exceptional operational conditions or load combinations dependent also on the work of the operating personnel develop that may lead to damage or immediate breakdown.

Principles and applicability of thermal protection

The devices protecting from overheating are based either on direct or on indirect sensing.

Protective devices with *direct sensing* follow the operational temperature by means of a built-in temperature sensor, e.g. a thermistor [8, 10, 13]. When the machine reaches the critical temperature, a comparator unit gives the magnetic contactor K an instruction to switch off the motor from the mains (Fig. 1). It follows from the

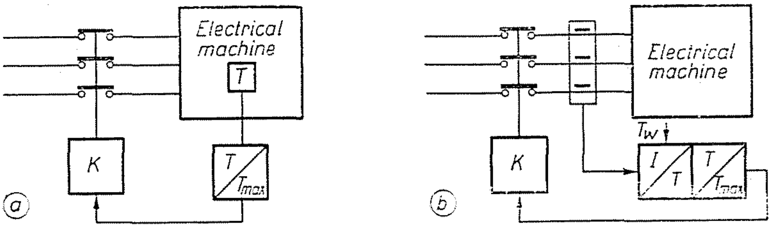

Fig. 1. Block scheme of motor protections with direct sensing (a) and indirect sensing (b)

operation principle that protective devices with direct sensing protect the machine both from overload and improper operation, thus giving complete motor protection. A basic condition is that the temperature sensor be built in the hottest place of the machine so as to ensure good heat transfer and little delay. The uncertainty in this regard, the difficulties in dismounting the machine for the elimination of possible defects, further the problem arising when the sensors have to be built into ready-mounted machines ultimately, as well as the well-known difficulties of their application to the protection of high-voltage machines and rotors, have inhibited the direct temperature protection from being generally used [11, ... 14, 20].

Protective devices with *indirect sensing* follow the parameters influencing the temperature of the hottest point (e.g. current consumption I, ambient temperature T_w) and form a protection signal on the basis of the parameters observed. A basic requirement is that the protective device be able to draw a conclusion from the protection signal to the thermal conditions of the decisive point, and to give a switch-off instruction if necessary (Fig. 1/b).

The cheapest and most usual solution of the protections with indirect sensing is the "bimetal thermal relay", the sensor of which is a bimetal heated by a current proportional to the current consumption of the motor. The protection signal in this case is the deformation of the bimetal in proportion to its heating up.

The heated bimetal as a signal-forming sensor is completely uncapable of giving by its deflection any conclusion to the temperature of any point of an electrical machine. In spite of this fact, its very small time constant makes it suitable for certain protection tasks. The driving motors of machines working in a practically steady-state operation (such as pumps, ventilators, mixers, conveyors, etc.) can satisfactorily be protected by devices with bimetal sensors, since in steady-state operation the current consumption furnishes sufficient information on the temperature conditions of the motor (see relationship (2) below).

The instantaneous current consumption does not give sufficient information on the thermal conditions of electrical machines in cases of varying load and intermittent operation — particularly of frequent restart or reversion, — and thus machines operating in this manner cannot be protected by means of bimetal thermal relays which, by their too early intervention, inhibit the accomplishment of technological processes involving complicated load combinations.

Properly dimensioned and well selected electrical machines operating under varying load are capable of standing a multiple of the rated current without being overheated over a period depending on the thermic prehistory of the machine. Thus, their protection based on indirect sensing requires a signal-forming unit whose transient character satisfactorily agrees with that of the motor to be protected; in other words: the protection is capable of continuously following, i.e. simulating the temperature changes of the hottest point.

Earlier attempts to solve the problem started from bimetal thermal relays. Various thermal and electronic relays with a delay accomplished by different means were designed [8, 9]. Due partly to the lack of characteristic truth and partly to the complicated and expensive construction and to other reasons, these suggestions did not lead to a satisfactory solution of the problem. Considerable difficulties arose also from the fact that no sufficient knowledge of the transient thermal processes of electrical machines was available, and the methods of describing complex thermic structural systems had not been elaborated either.

To accomplish simulation it is necessary to know the temperature-time functions, the so-called transient thermic characteristics in the critical points of the electrical machine to be protected [1, 2, 3, 6]. A practical requirement is also that the simulation protection be "tunable", i.e. can be applied to the protection of various types of machines with different dimensions and power.

Theoretical preconditions and possibilities of the solution by thermal simulation

In the solution of the thermal simulation of an electrical machine to be protected, the transient temperature field of the machine is the starting information basis. Its computation can be achieved by means of the concept of heat and mass flow modelling [1]. The measurements of thermal transients requiring large apparatus comes into account first of all for checking purposes.

When designing the heat flow network model of electrical machines, the structural system is lumped into discrete parts, then the individual parts described by concentrated parameters and coupled properly to each, other, with due consideration to the geometry, the peculiarities in structure, in material and in the distribution of heat sources [1, 15, …, 23]. When refining the parts, reasonable limits must be determined depending on the nature of the task and on the requirements of accuracy.

The individual parts are, in accordance with their thermal function, represented by concentrated heat capacity and by heat flow generators. Thermal coupling of the elements to each other is solved by means of heat conduction resistors, and the coupling to the cooling environment by means of heat transfer resistors and possibly by thermal voltage generators.

Fig. 2 shows the heat flow network model of an asynchronous motor type A 100 as an example. The numbers in the Figure denote the actual values of the network elements.

When building the model serving for simulation, it is advisable to choose, if possible, the points decisive for the protection as nodes of the network.

Writing the equation system for the network model of the electrical machine, its solution will give the transient temperature vector [1, 2, 4]:

$$\mathbf{T}(\tau)=\mathbf{T}(0)+(\mathbf{E}-e^{-\mathbf{D}^{-1}\tau})[\mathbf{T}(\infty)\pm\mathbf{T}(0)] \tag{1}$$

where τ is the time

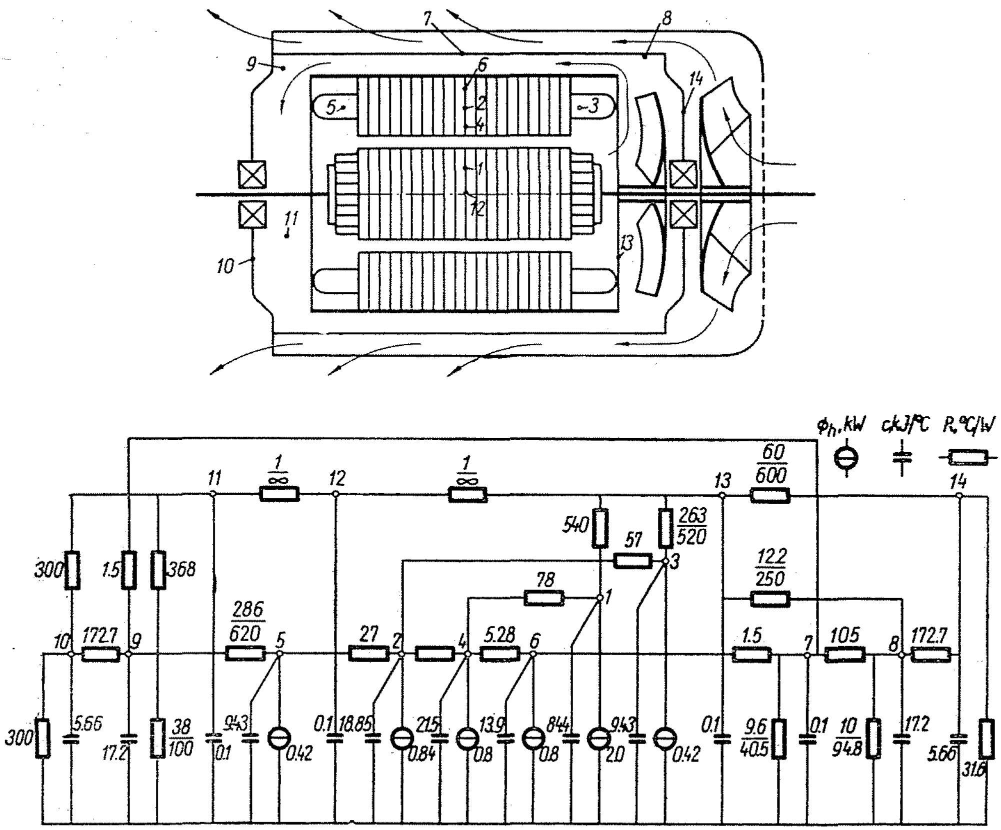

Fig. 2. Scheme of an asynchronous motor (a) and its heat flow network model (b)

T (0) and **T**(∞) the values of the overtemperature vector at the time $\tau=0$ and in the steady-state condition ($\tau \rightarrow \infty$), respectively,

E the unit matrix, and

D the time-constant matrix.

As is well known, in the steady-state ($\tau \rightarrow \infty$)

$$\mathbf{T}(\infty)=\mathbf{K}^{-1}\mathbf{\Phi}_h^{\circ} \tag{2}$$

and

$$\mathbf{D}=\mathbf{K}^{-1}\mathbf{C}. \tag{3}$$

In these equations:

K is the conduction matrix,

$\mathbf{\Phi}^{\circ}$ the source heat flow vector, and

C the diagonal matrix of the concentrated capacitances.

In the case of the motor examined the coil head of the stator is the decisive part to which nodes 3 and 5 of the network correspond. Fig. 3 shows the node characteristics of the heating-up found by computation. For comparison, also the

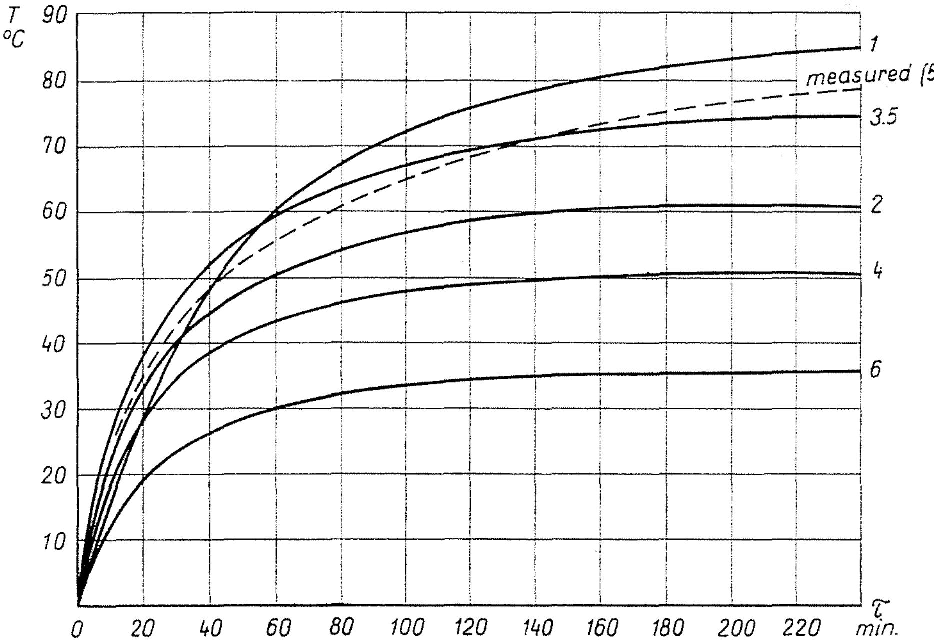

Fig. 3. Computed node characteristics of the network shown in Fig. 2. The curve drawn in dash-line is the characteristic determined by measurements for the coil head 5

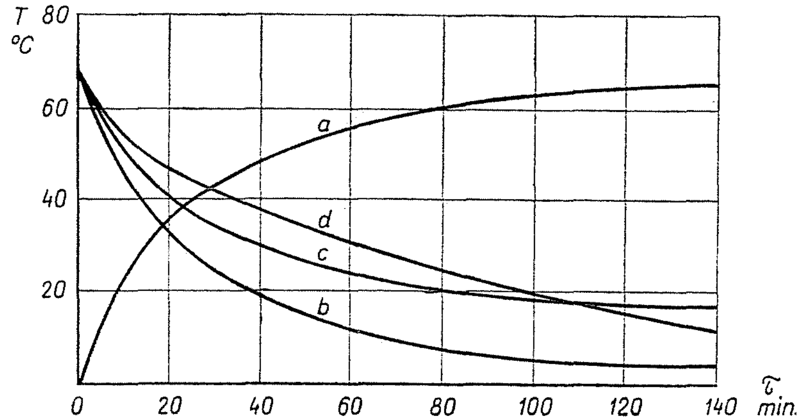

Fig. 4. Transient characteristics of the stator windings of an asynchronous motor a) warming-up, b) mirror image of the warming-up characteristic, c) cooling in idle run, d) cooling in standstill

characteristics determined by measurement for the coil head corresponding to node 5 are plotted (in the Figure: dash-line).

The warming characteristics obtained from measurements and computation exhibit fairly good agreement both in shape and in conformity, and thus the heat flow network modelling can be accepted as an information basis for the simulation.

With decreasing the load, on switching to idle run or in standstill the temperature of the machine decreases. For the simulation it is of importance that during the decrease of the load to the state of idle run, the ratio of the source heat flows deriving from the copper loss and iron loss is changing, and in stand the heat sources stop existing, further the coupling to the cooling environment alters in the absences of the ventilation. All this is well reflected in Fig. 4. For the above reasons, the coil head of the stator examined does not cool down in accordance with the mirror image of the warming-up curve. From the foregoing it follows also that some elements of the network model must be modified when cooling down is examined [2, 5, 6].

Principles of the simulator design

Based on the foregoing, it can be stated that the simulator of the protection has to produce a fairly approximative temperature-time function of the point decisive for the protection, or its analog equivalent, by sensing the current-consumption/time function and the operation mode of the machine, as well as the ambient temperature conditions.

Considering the design of the simulator, it appears reasonable to start from the heat flow network model of the machine. After choosing suitable scaling, the heat flow network model can be mapped into an analogous electrical network which then can be built from active and passive circuit elements. In this case the temperature field of the electrical machine can be reproduced on the basis of the node potentials of the analog electrical network, and the permissible temperature of the hottest point on the basis of the comparation voltage level.

The protection signal will be produced by the analog simulator built in this way like an analog computer and the switch-off signal will be provided by a comparator unit.

The experience concerning the follow-up capability of analog simulators is favourable [3, 6, 24]. However, analog simulators are too much complicated and expensive for practical application in motor protection. The complexity of the construction is due to the fineness of the lumping of the network and to the complicated design of the analog current generators of the heat sources.

A possible way of simplifying the simulator is to simplify the analog network. A solution to this is offered by simplifying model assumptions (cylindrical symmetry, neglection of the heat loss of the shields, etc.) and by simplification of the lumping. As shown in Fig. 5, the deviations in the characteristics are moderate if 3-storage heat flow networks are used instead of 4-storage ones. However, even with the simplest network, difficulties arise from the complicated circuit of the analog current generators [6]. Giving up the pure analogy offers a possibility of avoiding the difficulties: a voltage signal proportional to the motor current can be used as actuating signal (hybrid-analog simulation).

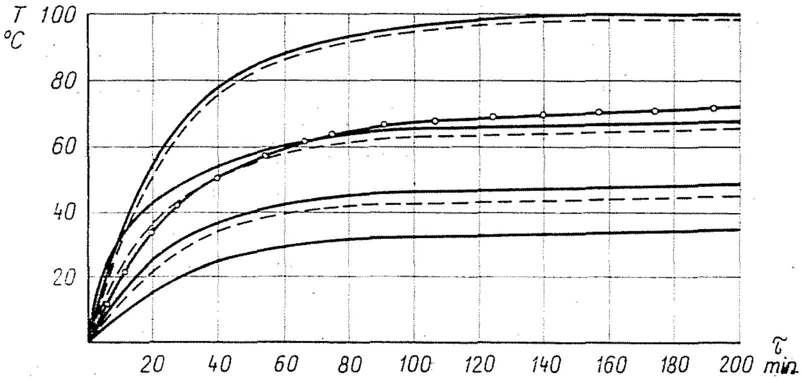

Fig. 5. Transient thermal characteristics of the stator coil head of an asynchronous motor in the case of a four-storage model network (continuous curve) and of a 3-storage model network (dash-line curve). The measured characteristic is plotted in dashed line

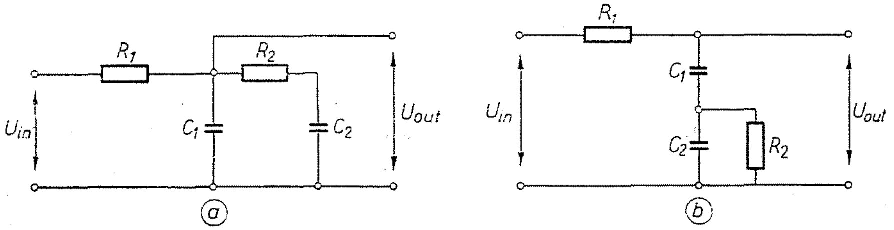

Fig. 6. Examples for the circuitry of a two-storage hybrid-analog (a) and of an abstract (b) simulator

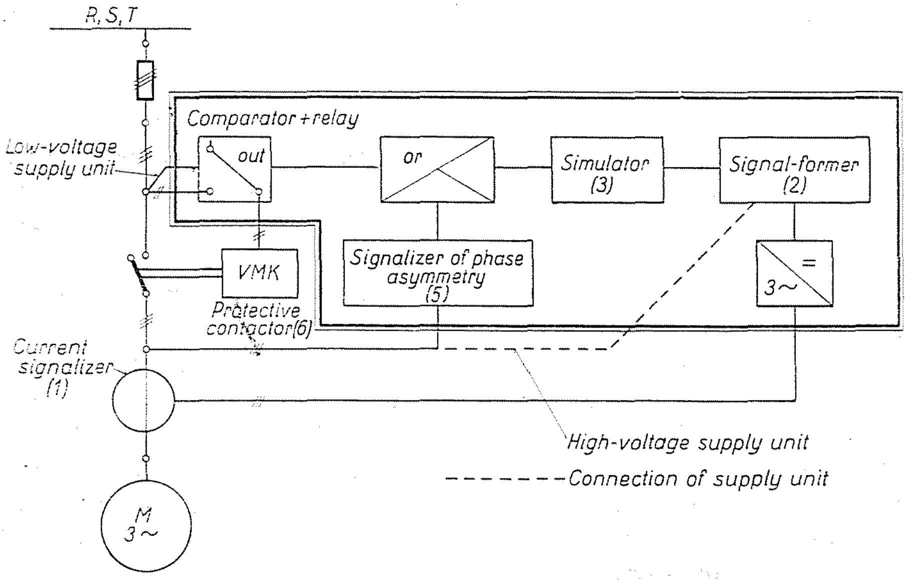

Fig. 7. Circuitry of a complex motor protection device furnished with an abstract simulator. 1: current signalizer, 2: signal-former, 3: simulator, 4: comparator+relay, 5: unit protecting against phase-asymmetry, 6: magnetic contactor, M: motor

The question may arise: What is the limit of simplifications? In this respect it is important to know that for the protection it is, in most cases, the thermal transient characteristic of the hottest point that is decisive, thus the simulation can be restricted to the temperature of this single "point".

Theoretical considerations and experiments have demonstrated that the temperature-time characteristic of the hottest point can be simulated with sufficient accuracy by means of a two-storage passive four-pole network [7], for which several solutions are known [5, 25, 26]. It can be demonstrated that, when the fast and slow changes are to be followed, better results can be expected from a four-pole network of the abstract simulator than from the hybrid-analog version (Fig. 6,) [6].

Fig. 7 shows the block scheme of a complex motor-protection device furnished with an abstract simulator [3, 5, 6].

Basic problems of tuning

For practical applications it is mandatory that the simulator be suitable for protecting motors of various dimensions and powers without affecting the truth of characteristics. The various electric motors have different thermal characteristics, and accordingly also the circuit elements of the simulator network destined to protection have different values. As a practical requirement, some elements of the simulator of protection must be variable, and it is also desired that the adjustment and tuning of the simulator can be performed also by persons without theoretical knowledge.

Determination of the tuning values is a problem of identification and synthesis which can be solved only if a relation is found between the transient thermal characteristics of the decisive points (i.e. the heat flow network nodes) of the machines to be protected and the simulator network to be applied. It is obvious that the practical solution of tuning will affect a smaller number of parameters (and thus will be simpler) if the circuitry of the simulator is simple and the simulator is built from few network elements. In this respect, too, the two-storage passive four-poles are advantageous as simulator networks.

The solution of tuning is a crucial question of the protection by simulation. In the practical determination of the tuning values an important role comes to the thermal similarity of electric motors. If a series of motors are thermally similar (homologous), and dimensionless independent and dependent variables are applied, the equation systems describing the heat flow network models go over into a single general equation system, and the solutions into a single generalized solution [3, 6, 27]. Assuming the relative overtemperature

$$\vartheta = \frac{T}{T_\infty} \tag{4}$$

to be a dimensionless dependent variable, and the dimensionless time

$$\mu=\frac{\tau}{\tau_b} \tag{5}$$

relative to the time base τ_b a dimensionless independent variable, the dimensionless equivalent of Eq. (1) will be [7, 27]:

$$\vartheta(\mu)=\vartheta_0+(\mathbf{E}-e^{-\mathbf{D}_x^{-1}\mu})(\vartheta_\infty-\vartheta_0), \tag{6}$$

where $\mathbf{D}_x$ is the dimensionless time-constant matrix calculated from the relative values. According to the foregoing, the dimensionless transient thermal characteristics relative to the hot point of the motors belonging into the homologous series coincide. For practical motor protection it will be satisfactory instead of a full coincidence that the dimensionless characteristics lie within a sufficiently narrow characteristic band. As an illustration, Fig. 8 shows the band of dimensionless characteristics of a type-series of 16 motors [3, 6]. The dash-line in the Figure is the dimensionless characteristic of the simulator.

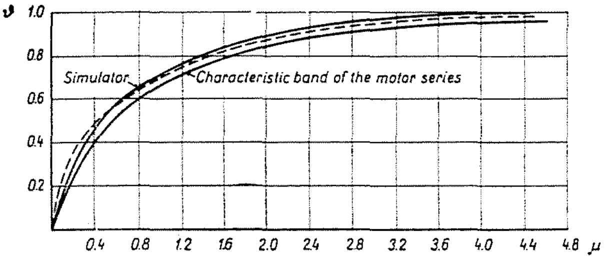

Fig. 8. Dimensionless characteristic band of a full series of asynchronous motors (the band between the continuous lines). The curve in dash-lines is the dimensionless characteristic of the simulator

Tuning the simulator to each motor of the homologous series can be solved in a relatively simple manner. In a possible solution, the continuous tuning is reserved for the adjustment of a single parameter, the signal level of the current signalizer, while the values of the other (variable) parameters are changed in a determined proportion or chosen as fixed values. In the latter case the user may connect the corresponding passive elements to the basic device, e.g., by plugging while the protection is being mounted [6, 27].

The similarity can be judged or recognized by similarity criteria. To derive the similarity criteria one may start from examining the resemblance of the heat flux network models of electric motors [6, 7]. Of course, if the transient thermal characteristics are available, the similarity can be recognized also from the coincidence of the dimensionless characteristics. For electrical machines not belonging in the homologous series, the tuning values can be determined individually, after establishing the transient thermal characteristics, on the basis of the simulator circuitry planned.

The similarity examination must, of course, be extended also to the cooling conditions. In standstill, as mentioned, one of the coupling heat transfer resistances changes. This can be taken into account by correspondingly changing one of the resistor-elements of the simulation network, e.g., by connecting the correction element by means of the auxiliary contacts of the magnetic contactor when the machine is switched off [5, 25].

Follow-up capability

The follow-up capability of a simulation motor-protection device built according to the principles discussed was verified also by measurements on the units of a series of 7.5 kW, 45 kW and 100 kW. To permit due checking, sensors were built into the motors, measuring the temperature in the coil head of the stator of each motor protected. The analog signals of the sensor and the simulator were recorded simultaneously in a common compensograph diagram. Fig. 9 shows the follow-up capability of a 7.5 kW asynchronous motor with the following load-combinations: overload of 1.25 I_n,—partial load of 0.9 I_n,—restarts at a frequency of 480/h, — idle run.

In Fig. 10 the simultaneous-run diagram of a 45 kW asynchronous motor is seen with the following load combination: overload of 1.2 I_n until switch-off, — restart in idle run,—1.2 I_n until switch-off, — restart with I_n,—idle run.

Fig. 11 shows the simultaneous-run diagram for an asynchronous motor of 100 kW. The simulator is seen to keep its follow-up capability after several repetition of the load combination 1.5 I_n — idle run.

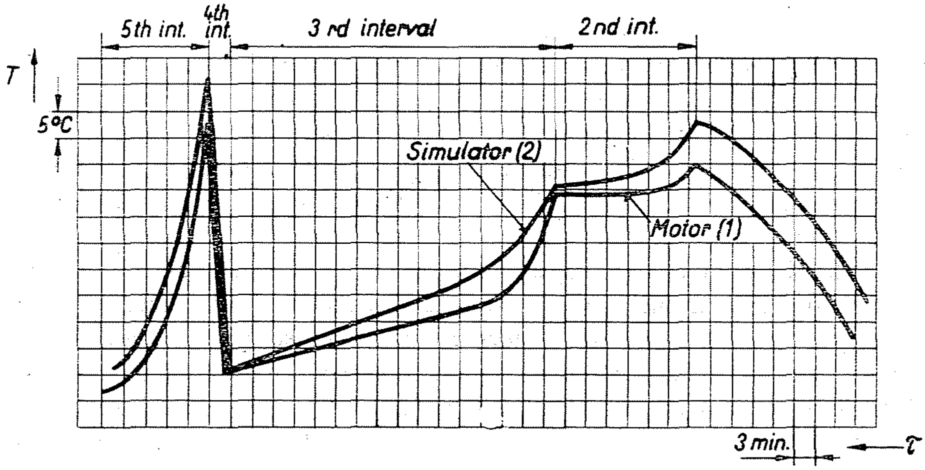

Fig. 9. Diagram of the simulatenous run of simulation, for a 7.5 kW asynchronous motor in operation with varying loads

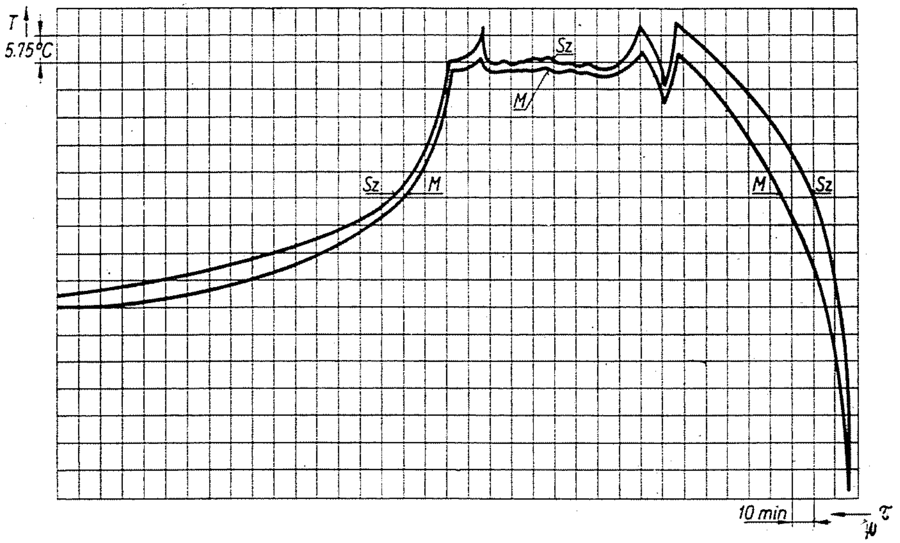

Fig. 10. Diagram of the simultaneous run of simulation for a 45 kW asynchronous motor in operation with varying loads

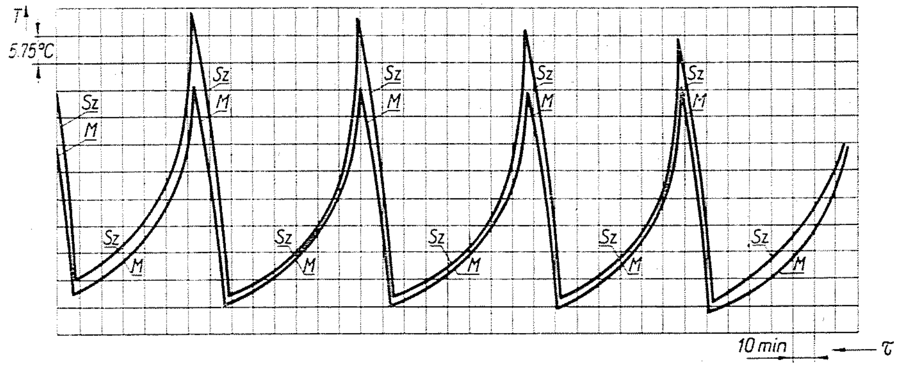

Fig. 11. Diagram of the simultaneous run of simulation for a 100 kW asynchronous motor: repetitions of operation with 1.5 I_n — idle run

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Summary

The most usual types, with bimetal sensors, of motor protections of indirect operation are inadequate for motors working under varying loads, since the actual current consumption does not give any information on the temperature conditions of the motor. Protective devices working on the simulation principle can be applied with good results, as they simulate the temperature conditions of the hottest point continuously. The simulation is based on the transient thermal characteristics of the motor, which can be produced either by measurements or by calculations from heat flow network modelling. The simulator must be designed tunable if electrical machines of different types and dimensions are to be protected. The examination of the thermal similarity of electric motors offers considerable help in the solution of tuning. A fairly good follow-up conformity can be obtained also in cases of complicated load combinations.

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