Electrical Equipment of Machine Tools

Electrification in machine tools today is very extensive because it helps to simplify their construction, reduce their weight, and develop automatic control.

Many advanced trends in modern machinery are associated with the development of electrical drive systems and electrical control gear. Among the main trends in the development of electric drive (consisting of an electric motor, its control gear and a mechanical transmission from the motor to the operative members of the machine tool) are improvement in electric motor characteristics, simplicity and high quality of control gear and mechanical transmissions, and proximity of the motor to the operative machine-tool members.

The arrangement of the motor nearby the operative member and also the use of variable-speed electric motors make it possible to simplify mechanical transmissions as well as the construction of the machine. The use of electrical instead of mechanical controls helps to improve machine-tool design and considerably reduce the physical force required to handle the machine.

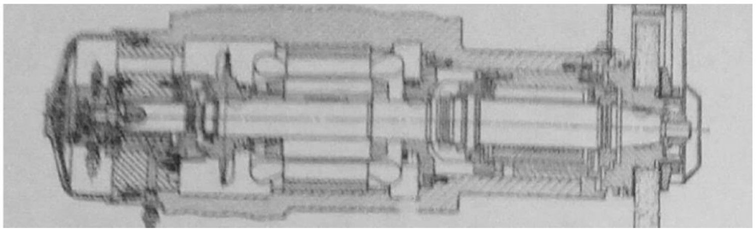
One or more electric motors driving the operative members of the machine tool make up the machine's essential components. The great majority of machine tools are driven by alternating-current three-phase induction motors. These motors are simple, reliable and inexpensive. Direct-current motors are not so common and are used mainly to drive heavy, machine tools.

Induction Motors

Induction motor arrangements are classified with reference to the method of their mounting and environmental influence protection. A conventional foot-mounted motor is shown in (Fig.a) , Flange-type motors (Fig.b) for horizontal and vertical positioning are extensively used. An example of a built-in motor is given in Fig. c. Here one of the shafts of the machine (commonly the spindle) serves as the motor shaft.

Fig. **a**

Fig. **b**



(c)

Electric motors used in machine tools are equipped with various devices for protection against environment effects. To provide for safety of operation and prevent alien objects from getting into motors, the latter have protective guards. Some motors have vent holes, either downward-directed or located in vertical planes, as protection against liquid drops. Some motors are fully enclosed and have no vent holes, but because of inadequate cooling, their power is much smaller than that of ventilated motors of the same size. There are enclosed self-ventilated motors with a fan mounted on the rear end of the motor shaft and covered with a lid. The fan cools down the motor during operation. Motors of this type are most widely used in machine tools.

Electric motors are designed to operate at the standard voltages of 127, 380 and 500 V. A motor can be connected to the mains with two voltages differing from each other by $\sqrt{3}$ times, for instance, 127 and 220 V or 220 and 380 V. The motor stator is delta-connected for the lower voltage of each of the two values, and star-connected for the upper one; this results in equal current intensity in stator windings for the both connections. With motors used for 500 V, the stator winding is invariably star-connected.

The A02 series of electric motors includes nine sizes of enclosed self-ventilated motors with cage rotors from 0.6 up to 100 kW, having rotational (synchronous) speeds of 600, 750, 1000, 1500, and 3000 rpm. The speed of an induction motor can be increased by increasing the alternating current frequency. When grinding small-diameter bores, very high spindle speeds are necessary to provide the required cutting speeds, e.g. for grinding with a 3 mm-diameter abrasive wheel at the peripheral speed of 30 m/s, the rotational spindle speed should be 200,000 rpm. For this purpose units known as high-frequency direct-drive wheel-heads are often used. Such a unit comprises a grinding wheel spindle with a built-in high-frequency cage-rotor induction motor. Wheel heads with mist lubricated bearings are often used.

The speed-torque characteristic of the motor is the relationship between the motor speed n and the torque M it develops, and is expressed as $n = f(M)$

There are electric motors with speed-torque characteristics known as drooping, rigid and absolutely rigid. With drooping speed motors, change of torque (i.e., load) results in substantial motor-speed change. It change of torque does not markedly affect the motor speed, such a motor is said to have a rigid characteristic. A motor possesses an absolutely rigid characteristic if its speed does not depend on load changes.

The speed-torque characteristic features a special factor called slippage, denoted by s, which represents the ratio between the fail in motor speed under critical (maximum0 load (M-M_c) as compared with the speed of idling (when M = 0), the speed of idling being

$$S = \frac{n_o - n}{n_o}$$

Where n_o = speed of rotating magnetic field (synchronous speed of electric motor), rpm and 1/s

n= rotor speed (asynchronous), rpm

Slippage s is expressed as a percentage or decimal fraction,

The torque developed by the induction motor can be roughly estimated by means of the following formula:

$$M = \frac{2M_c}{\frac{s}{s_o} + \frac{s_c}{s}}$$

Where M_c = critical torque (maximum load) of motor

S_c = critical slippage corresponding to M_c

Figure 53 depicts the induction motor speed-torque characteristics constructed by means of the torque M formula. With *n* being equal to n_o, M=0 which corresponds to the idling of the motor. When the motor is started and the rotor is still immovable (s=1), the motor develops striating torque M_s which is higher than the rated (or nominal) torque M_r. The values of M_c and S_c determine the critical point (or the maximum) of the characteristic. The interval between the idling point and the critical point of the characteristic is called the working interval. It is this interval that is suitable for stable operation with the motor speed not depending on the torque change (as is the case with induction motors used in machine tools). The rated value of slippage depends on the type of motor and its rated power, and is within the limits of 0.02-0.12; the higher the motor power, the lower the spillage.

In addition to plain induction motors, there are motors with higher starting torque and slippage (0.07-0.16). While motors with normal slippage have a rigid speed-torque characteristic and are used in most machine tools, motors with higher spillage have a drooping characteristic and are used in machine-tool drives with frequent motor starts and considerable starting loads. Curve *1* shown in fig 53 is for a rigid characteristics motor, and curve 2-for a drooping characteristic motor. It is evident from the Figure that, all other things being equal, the drooping characteristic motor has lower rated speed and higher starting torque M_s. Point A represents the rated value of load.

The following induction motor specifications are usually given in catalogues: rated power N_r, kW; rated speed n, rpm; synchronous speed n_o, rpm; ratios $\frac{M_c}{M_r}$ and $\frac{M_s}{M_r}$ (where M_r and M_s are rated and starting torques, respectively). The value of M_r is determined from the formula.

$$M_r = 9550\frac{N_r}{n} \ N.m \ (kgf.m)$$

Ratio $\frac{M_c}{M_r}$ defines the value of permissible mechanical overload of the motor.

$$\frac{M_c}{M_r} = 1.7\text{-}2.5$$

The value of M_c depends on mains voltage. As the voltage value may change, the maximum permissible value of overload is assumed to be 0.85 M_c.

With general-purpose induction motors having cage rotors, ratio $\frac{M_s}{M_r}$ = 0.8-2

Principal movement drive motors are started up under no load, so the starting torque $M_s < \frac{M_s}{M_r}$ is sufficient. Motors started up under load should develop higher starting torques.

Starting up induction motors. When a motor with cage rotor is started up, the intensity of the starting current exceeds its rated value 4 to 8 times. This rise in the current causes the voltage in the mains to drop. When a higher-power motor is being started up and the voltage in the mains drops, its starting torque also drops, while other motors operated under overload from the same mains may stop (change to a short-circuit regime). So it is only where the rated motor power comes to not more than 25 percent of the power of shop mains transformers that such a motor can be started up without protective devices limiting the starting current intensity. Would-rotor induction motors are started up by means of a rheostat connected to the rotor circuit.

Changing motor speed. The rotor speed of a cage-rotor induction motor is found from the formula.

$$n = \frac{60f}{\rho}\left(1-s\right) rpm$$

Where f = alternating current frequency, Hz

p = number of pole pairs

s = slippage of rotor

It is evident from the formula that motor speed can be changed by changing current frequency, slippage or the number of pole pairs.

With the frequency of alternating current in the mains being constant, the first method can be applied only if there is a separate a.c. generator to feed the electric motor.

The second method of speed changing – by change of slippage – is accomplished by introducing effective resistance into the rotor circuit, which can be done only with wound-rotor induction motors.

The third method of speed changing – by changing the number of pole pairs-is the most widely used in machine tools. It involves the use of multi-speed pole-change motors.

Motor braking can be accomplished mechanically or electrically. Electrical methods of braking include regenerative braking, injection braking, reverse-current braking etc.

Regenerative braking is possible only with multi-speed motors. Its principle consists in that the motor, while still connected to the mains, is switched over to a lower speed step and so starts working as a generator returning electrical energy into the mains. This results in the motor slowing down to the speed of the changed step. Further braking is accomplished mechanically or otherwise.

Injection braking is carried out by injecting direct current into the stator winding, thus forming a constant magnetic field therein. This field retards the rotating field of the motor and stops the later. Once being fully stopped, the motor is automatically disconnected from the mains by a special devices.

Reverse-current braking is carried out by interchanging two phases in the stator winding. Here, the direction of the rotating magnetic field is reversed, which retards the initially rotating rotor. When the braking ends, the motor is automatically disconnected from the mains. The drawback of this method is that it is attended with load peaks and produces impacts in machine transmissions. However, this method is widely used in machine tools due to its simplicity and reliability.

Motor reversal is accomplished by changing any two external terminals (phases) of the motor.

Direct Current Motors

Direct current motors with shunted excitation (shunt-wound motors) are extensively used in heavy machine-tool drives. They are connected according to the circuit diagram shown in Fig. d. The armature winding A is connected to the mains through starting rheostat 1, exciting (shunt) winding SW – through rheostat 2 used for speed variation.

The torque and speed values for the d.c. motor are determined by means of the following formulas:

$$M = kI_a\ \phi,\ N.m\ (kgf.cm);\ n = \frac{v - 1_a r_a}{{}_c\phi}\ rpm$$

Where M = torque developed by motor, N.m

n= motor speed, rpm

V == mains voltage, V

F_a = current intensity in armature winding A

r_a = armature circuit resistance, ohm

c = constant of given motor

k = 0.05 - 0.12 – proportionality factor

ϕ=magnetic flux of motor, Wb.s

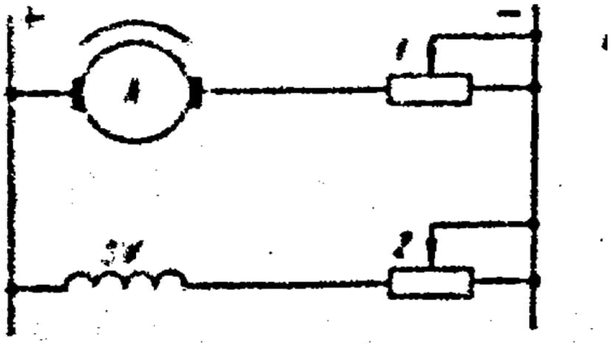


Fig. d

The speed torque characteristics of the motor are given in Fig. d. Numeral f denotes the line corresponding to the rated speed-torque characteristic. The relatively small value of armature winding resistance determines a sufficiently rigid rated characteristic of the shunt-wound motor, which is expressed graphically by the modest slope of line 1.

With the motor in operation, the resistance the resistance of rheostat 1' can be increased; this will result in an increase of the total armature circuit resistance and the slope of the characteristic's line. In this way, a number of modified rheostat-produced characteristics 2,3,4 is obtained.

Power losses in the exciting circuit depend on the motor power and are within the limits of 1-8 per cent; the lower the power, the higher the losses.

The rated value of armature current is determined as the difference between the rated value of motor current and the value of exciting current. However, the exciting current value in the shunt-wound motor is small, so it is often not taken into account in design.

Shunt-wound motors can endure short-term operation under overload with permissible overload factor λ =2-2.5. This value is limited by the appearance of considerable brush sparking.

Shown in Fig. 55 by dotted line 9 is the speed-torque characteristic of motor with reversed armature polarity, in which the direction of motor rotation is reversed.

Starting up the shunt-wound motor is carried out only with the aid of a starting rheostat 1' is connected to the circuit with all its steps and the motor begins speeding up in accordance with characteristic 4. The resistance of the rheostat steps is determined in such a way that on being started up the motor should develop predetermined torque M_1 (usually $m_1 \approx 2M_r$). as the motor accelerates, its torque drops and when it reaches the predetermined value M_2 ($M_2 \approx 1.1\ M_r$), one rheostat step is disconnected. The motor then changes over to run in accordance with characteristic 3. Gradually the steps of the rheostat are all disconnected until the motor runs according to its rated speed-torque characteristic.

In machine tools this operation is accomplished automatically.

Changing the speed of d.c. motors can be effected by changing the armature circuit resistance, by changing the armature circuit resistance, by changing the magnetic flux, and by changing the input voltage.

The first method is rarely used because it involves energy losses. The second method – by changing the magnetic flux – is the most commonly used. The magnetic flux value is changed by rheostat 2' (Fig. e). The rheostat resistance being increased, the exciting current and magnetic flux are reduced, which results in an increase in idling motor speed and slope of motor speed-torque characteristics, represented by a number of straight lines (5,6,7,8). These lines are not parallel to the rated characteristic 1 of the motor and have the greater inclination, the lower values of magnetic fluxes they correspond to. The number of these characteristics depends on the number of steps on rheostat 2'. Where the number of rheostat steps is large, motor speed changing becomes practically stepless.

The third method of speed changing- by changing the input voltage-involves the use of special circuitry and is employed in generator-motor systems.

The braking of d.c. motors is carried out by methods similar to those used for braking induction motors. Regenerative braking is accomplished by means of a shunt circuit rheostat, whose operation causes the armature speed to drop to a minimum. Here, the motor begins operating as a generator returning electric energy into the mains. The motor is brought to a full stop by being disconnected from the mains.

Dynamic braking, the most common method of braking, consists in the armature being disconnected from the mains, while the exciting current is on, and closed through the ballast resistor (o rheostat).

Reverse-current braking is done by changing over the direction of current in the armature circuit.

The Generator-Motor System

This system known also as the Ward-Leonard system, is used in heavy and high-power machine tools with frequent motor reversal or where infinitely variable speed or feed are required. This system also facilitates the starting of the machine tool.

The system (Fig. f) consists of induction a.c. motor 2; d.c. generator 3 driven by motor 2; self-excited direct-current generator 1 for the excitation of generator 3 and motor 4; d.c. motor 4 as the drive motor of the machine tool. Motor 4 is started up by means of shunt-circuit rheostat 6 connected to the exciting winding of generator 3, whose excitation magnetic flux it reduces. This gives a very small value of voltage on the generator brushes, which is then gradually increased. As motor 4 is sped up, it develops a back electromotive force (emf) and the shunt-circuit rheostat is gradually switched off, increasing the generator voltage.

The generator-motor system allows the speed of motor 4 to be varied in two ways: (a) by changing the input voltage fed into motor 4 with the aid of rheostat 6 (by changing the

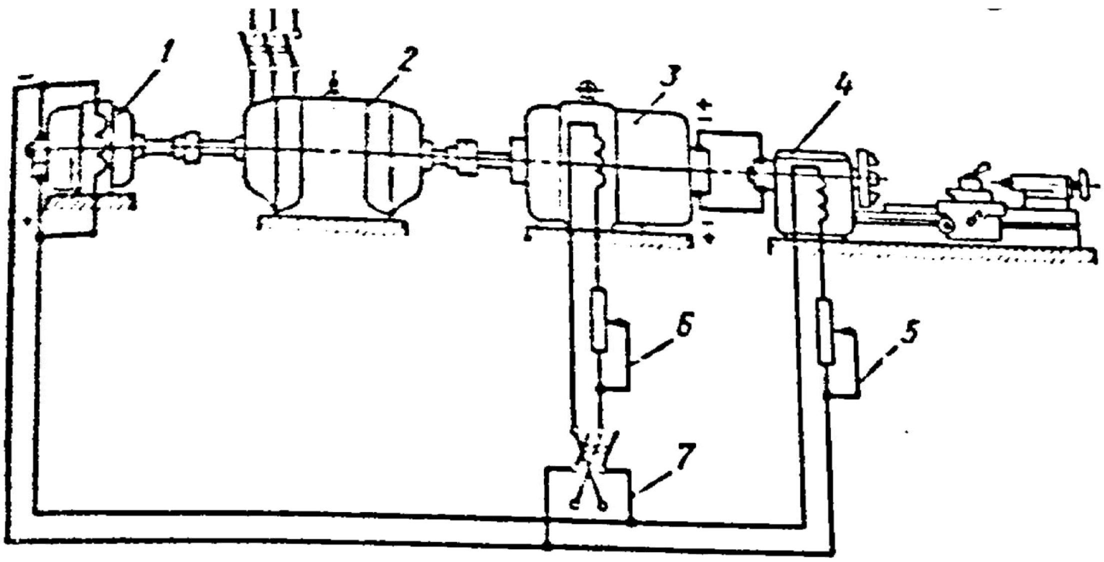


Fig. **f**

magnetic flux of generator 3); and (b) by changing the excitation magnetic flux of motor 4 by means of rheostat 5.

The reversal of motor 4 is accomplished by changing over the direction of current in the exciting winding of generator 3 with the aid of switch 7.

The braking of motor 4 is accomplished by the regenerative method by means of rheostat 5. Here, the magnetic flux of motor 4 increases, the motor emf exceeds the input voltage and the motor begins operating as a generator. Low efficiency (about 0.65), large size, and high cost are among the important disadvantages of the generator-motor system.

Selection of the Power Rating of Machine-Tool Motor

It is highly important to make a correct estimation of the motor power. With insufficient motor power, the machine tool will be underloaded, while the motor itself will be vulnerable to overloads, redundant motor power will result in its being systematically underloaded, which means operation at low efficiency and with low power factor (a.c. induction motors).

In operation, the electric motor tends to heat up. The eat is generated during the transformation of electrical into mechanical energy. Some of input electrical energy is wasted on the heating of the electric-motor windings and magnetic circuit, and to a lesser degree-on friction in motor bearings. The loss of power is the difference between the input (the power of feeding) and output (the useful power) of the electric motor. The power losses on the heating of the motor windings are proportional to the square of the current intensity and are called variable losses. Other losses are conventionally called constant losses.

The acceptable value of motor beating is limited by the thermal stability of the winding insulation material, USSR-made electric motors are mostly equipped with class A insulation (cotton fabric impregnated with insulating compound). This insulation allow a maximum heat temperature of up to 105°C, but due to the difficulty in measuring maximum temperature, marginal temperature for motor windings is limited to 95°C, when measured by means of a plain thermometer, and to 100°C when measured by means of a resistance thermometer.

Estimation of power for motors operating under constant long term load. In long-term operation under constant load, there is enough time for the temperature of the motor to be stabilized. This happens with motors in heavy lathes, vertical lathes, boring machines, gear cutters, etc., with long duration of separate machining operations.

The rated power or output of an electric motor operating under such conditions should be equal to the machine-tool power consumption. Since it is practically impossible to find in any catalogue a motor with rated power matching its power consumption, the motor with the nearest higher value of rated power is chosen.

The cutting power is found from the following formula:

$$N_c = \frac{P_z}{102} \cdot \frac{v}{60} \, kW$$

Where P_z = cutting force, tangential when turning and milling, longitudinal when shaping, broaching etc.

v = cutting speed

Hence, the power consumption of the machine tool, with mechanical transmission losses taken into account, will be

$$N_c = \frac{N_c}{\eta} == \frac{P_z}{102} \cdot \frac{v}{60\eta} \, kW$$

Where η == mechanical efficiency of machine-tool transmissions.

Estimation of power for motors operating under short-term load. In short-term operation, there is not enough time for the motor temperature to be stabilized. The point is that short periods of operation under load are followed by long periods of down time, when the motor temperature, which has risen during operation, drops to the temperature of the environment. This happens in motors used for the auxiliary drives of some machine-tool members, such as rapid traverse drives of carriages, cross rails, spindle heads, drives of clamping devices, etc.

The operational duration of such drives does not normally exceed 5 to 15 s, while in heavy machines it may reach 1 to 1.5 min. With overloads being within the acceptable limits, this time is too short for the motor to become even normally overheated. The power consumption in this case is determined by overload conditions. The formula for calculating power consumption is

$$N_{p.c.} = \frac{G\mu v}{6120\eta\lambda} \, kW$$

Where G == weight of travelling machine-tool member, N

μ== coefficient of friction of motion

v== speed of travel, m/min

η == efficiency of transmission from motor to travelling member

λ == overload factor

The torque of resistance on starting will be

$$M_{res} = 0.16 \frac{G_{\mu ov}}{\eta \lambda_0 \left(1 - \lambda s\right)}$$

Where μ_o= coefficient of static friction

n_o= speed of motor idling rotation, rpm

s = slippage of motor

once $N_{p.c.}$ and M_{res} are calculated, the electric motor is chosen from the catalogue according to the required rated power. Starting torque M_s is then found for this motor and compared with M_{res}. If $M_s > M_{res}$, the choice is correct.

Estimation of power for motors operating under variable long-term load. These working conditions are common in machine tools incorporated starting clutches in the principal movement drives and used for producing parts of the same type, and also in machine tools on automatic transfer line. Here the electric motor rotates continuously. Cutting periods are followed by idling periods when the cutting tool is retracted and the next work piece is loaded. Accordingly, a certain load of the motor corresponds to each stage of the machining cycle.

Since motors used in machine-tool drives are rated on the basis of long-term load, these long-term constant-load conditions, with the heating of the motor equivalent to the heating of the motor under variable long-term load, need to be found so as to estimate the machine power consumption. Without going into the details, let us note among the methods of equivalent current, torque or power.

Estimation of power for motors operating under intermittent load. These working conditions involve short periods of operation under load, which are not long enough for the motor temperature to be stabilized, followed by short periods of motor shut-downs, which are not long enough for the motor to cool down to the environment temperature. This change of motor temperature can be visualized as a broken curve consisting of alternating rise and fall sections which represent the heating-up and cooling-down of the motor. These conditions occur in most machine-tool drives. One such cycle should not last for ore than10 min. The motor power is best estimated by means of the average losses method.

Hand-Operated Control Gear

The hand-operated control gear includes knife switches, rotary switches, controllers, tumbler switches, and hand-operated starters.

There are single, double, and three-pole knife witches according to the number of knives they contain. These switches feature a casing and a side lever handle. To effect an instant break in the electric circuit, the knives of the switch are equipped with a spring-actuated device. A three-pole knife switch with side hand lever, rated for 100 or 200 A, is most commonly used Fig. (ga).

Rotary switches are more compact and easy to operate than knife switches. The rotary switch shown in Fig. (gb) contains a set of stacked sections each section being a single-pole rotary circuit breaker (or change-over switch). All the sections are controlled by one rotary shaft and are arranged in such a way that when the shaft is rotated some circuits are connected and others-disconnected. Rotary switches are used to connect machine tools to the mains, to start up rarely energized motors, etc.

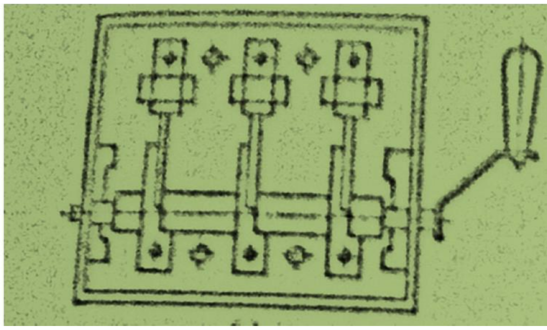


Fig. (ga)

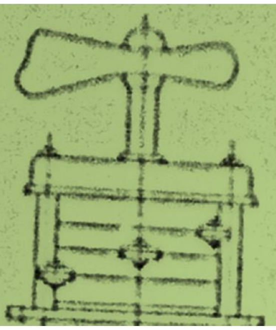


Fig. (gb)

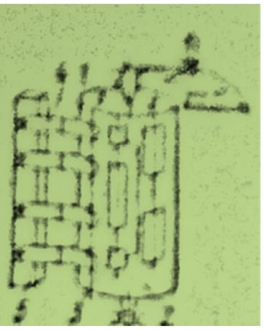


Fig. (gc)

Controllers are used to commutate a large number of circuits. There are cam and drum-type controllers. Shown in fig. (gc) is a drum controller with two working position I and II and one neutral position 0. The controller contains shaft I and, fixed on it, drum 2, which is made of dielectric. The drum accommodates copper lamina 3, while bar 5 also made of dielectric and placed beside the drum, holds contact fingers 4. Each position of the drum corresponds to the commutation of a certain circuit.

Tumbler switches are used in the electric lighting systems of machine tools. In principle and design they are similar to the switches used in lighting mains.

Hand-operated starters are sometimes used to start up one or three-phase electric motors. The operating principle of the starter shown in Fig. h is as follows: when button 5 is pressed contacts 2 and 1 are closed and contact 2 is locked by means of spring-actuated stop 3, thereby connecting the motor to the mains. When button 6 is pressed stop 3 releases the contacts and they break, disconnecting the motor. Casing 4, the buttons and other components of the starter are made as dialectic.

Starting Gear

Contactors are widely used in machine tools to control electric motors. In the circuit shown in Fig. ia , the motor is started by a special device called the contactor. When button 2 is pressed, coil 3 is energized and core 5 attracts armature 4. This results in shaft 6 turning and closing power contacts i. Figure ib shows the scheme of a contactor with straight movement of armature.

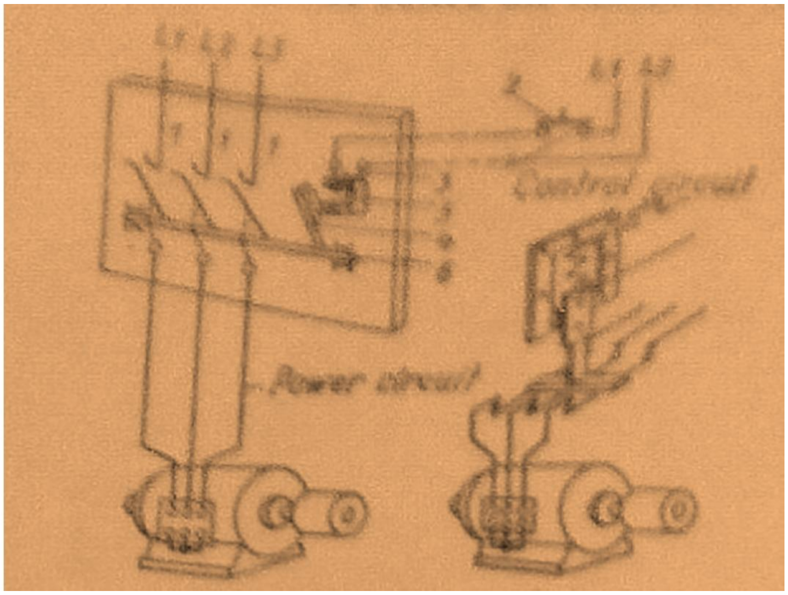


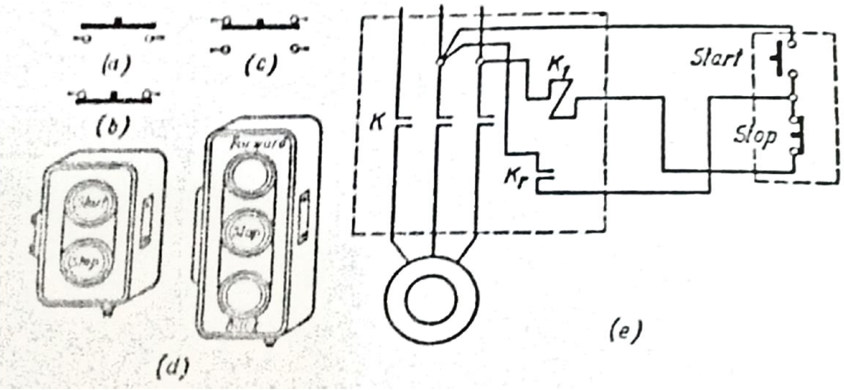
Fig. ja Fig. jb

The devices similar in construction to contactors, but with weak-current contacts to operate in control circuits, are called auxiliary relays.

Buttons to control contactors can have normally open (or front) contacts (Fig ja), and normally closed (or back) contacts (Fig. jb). some buttons have one front and one back contact (Fig. jc). buttons are assembled in blocks, two of which, consisting of two and three buttons, are presented in Fig jd. The blocks are designed for two control commands: “Start” and “Stop”, or for three: “Forward”, “Back” and “Stop”, where there are several “Start” buttons to control one machine-tool member, these are connected in parallel. They have one common retaining contact which is also connected in parallel and is closed when the circuit is energized.

The “Stop” buttons are connected in series.

Combination starters serve to control a.c. cage-rotor induction motors. These starters comprise sets of control gear, such as contactors, button blocks and thermal-overload relays for motor protection. The circuit diagram of such a starter is shown in Fig. je.



The starter contains a double-button block for starting and stopping the motor. To start up the motor, the “Start” button in pushed, closing the circuit of the contactor coil K_1, contacts K are closed and connect the motor to the mains. To prevent coil K_1 from de-energizing when the “Start” button is released, the circuit is provided with retaining contact K_r, connected in parallel with the “Start” button and closed simultaneously with contacts K. The motor is stopped by pressing the “Stop” button which causes coil K_1 to be de-energized, thereby breaking contacts K and disconnecting the motor from the mains.

Combination starters prevent the motor from starting spontaneously when the circuit voltage suddenly fails and then reappears. Subsequent starting can be effected only by pushing the “Start” button.

Depending on purpose, starters come in two versions: plain and reversible.

Automatic Control Gear

Limit switches are used to control the travel of machine-tool mechanisms automatically. They control both reciprocating and rotating movements of machine operative members by closing and breaking the machine-tool control circuit at the required intermediate or terminal points of travel. A limit switch consisting of two back contacts `1 and two front contacts 2, is operated by rod 3 being engaged by the trip dog fixed on a machine’s travelling member.

When released, the rod is returned to its initial position by spring 4.

The microswitch is a small-size version of the limit switch, featuring one independent contact. Microswtiches provide high accuracy of operation with modest operational force (3-7 N, or 0.3-0.7 kgf).

Electromagnetic Devices

Plunger electromagnets (retract solenoids) are used in various control systems of machine tools, e.g. contactors, remote-control begins operating as generator. Low efficiency (about 0.65), large size, and high cost are among the important disadvantages of the generator-motor system.