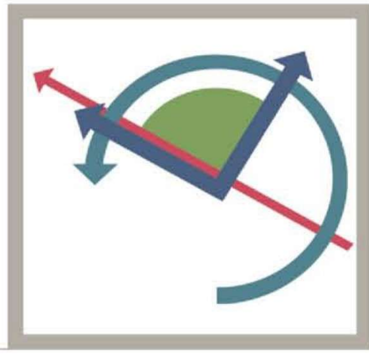
本书主要内容包括：直流电动机机械特性；直流电动机启动、调整和制动；三相异步电动机机械特性；三相异步电动机启动、调整和制动；电系统瞬态行为的基本原理；电动机的选择；电机拖动系统的两个实例以及电力拖动控制技术。



ELECTRICAL POWER DRIVES AND CONTROL

电力拖动与控制

高　心　夏丽萍　主编

电子科技大学出版社

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图书在版编目（CIP）数据

电力拖动与控制/高心 夏丽萍主编. —成都：电子科技大学出版社，2005. 2

ISBN 7-81094-764-8

Ⅰ. 电 … Ⅱ. 高… Ⅲ. 电力传动—自动控制—高等学校—教材 Ⅳ. TM921.5

中国版本图书馆CIP数据核字（2005）第014354号

内 容 简 介

本书在《ELECTRICAL MACHINE AND DRIVES》（讲义）的基础上编写而成。

本书主要内容包括：直流电动机机械特性；直流电动机起动、调速和制动；三相异步电动机机械特性；三相异步电动机启动、调速和制动；电系统瞬态行为的基本原理；电动机的选择；电机拖动系统的两个实例以及电力拖动控制技术。

本书适合于普通高等学校、职工大学和夜大学的非电机专业作为双语教材使用，亦可作为工科大专院校电气工程及其自动化专业的双语教材，也可供有关科研人员阅读。

电力拖动与控制

主 编 高 心 夏丽萍

出　　版：电子科技大学出版社（成都市建设北路二段四号）
责任编辑：汤云辉
发　　行：电子科技大学出版社
印　　刷：四川文瑞印务有限责任公司
开　　本：787mm×1092mm 1/16　印张 7.25　字数 180千字
版　　次：2005年2月第一版
印　　次：2005年2月第一次印刷
书　　号：ISBN 7-81094-764-8/H·28
印　　数：1—2000册
定　　价：11.80元

前　　言

双语教学是采用英文教材进行英文或中英文授课的方式。该教学方式是新形势下高校教学改革进一步深化的结果，有利于高校与国际间的接轨。培养学生创新能力，关键是要让学生即时了解和掌握国外最新的科研动态和信息；而进一步提高学生外语水平，尤其是提高专业外语水平以及文献资料的查阅和正确理解，是了解掌握科技信息的有效途径。

编者经过两年多的双语教学实践，深深地体会到双语教学仍有一个循序渐进的过程，学生虽然有一定的基础英语水平，但对于学习专业性较强的英文教材或文献而言，有一定的难度。具体表现为：要么根本不能读懂；要么不能理解文献的含义，甚至完全误解。为了逐步提高双语教学水平，编者在《ELECTRICAL MACHINE AND DRIVES 》（讲义）的基础上，结合学生的基础和特点以及多年教学经验，编写完成了这本《ELECTRICAL POWER DRIVES AND CONTROL》双语教材。目的是使学生在掌握基本概念、本原理和解决问题的基本方法的基础上，努力扩大学生专业词汇量，克服词汇障碍；尤其是帮助学生掌握英文教材的语篇特点及句子结构，提高其理解能力。

本书是按照学分制要求的学时数（50～60 学时）编写而成。其先修课程为自动控制原理、电机学。

本书的主要特点是：本书侧重于基本原理和基本概念的英文阐述，并始终强调基本理论的实际应用，着重分析了电动机的机械特性，电动机的起动、制动和调速的方法和控制，并给出了适量的例题；各章还附有词汇和阅读理解，以及适量的习题，便于教学或自学使用；为了使学生了解国外的科研动态和信息，培养他们阅读外国文献的能力和创新能力，提高学习双语课的有效性，书中还给出了英文科技文献阅读材料，以及利用 MATLAB 语言编写的有关电力拖动系统的程序和仿真分析；书中还介绍了目前电力拖动系统中有关现代控制技术等方面的基本原理和知识。本书文字阐述清楚、概念准确、通俗易懂、深入浅出。内容阐述循序渐进、富于启发性，便于自学。

本书的出版工作，得到了西南民族大学教材建设基金的大力资助。在编写的过程中西南民族大学教学指导委员会和电气信息学院教学指导分委员会的专家和老师对本书提出了许多的宝贵意见，在此表示衷心的感谢！

由于作者学识和时间所限，书中难免有错漏不足之处，恳请广大读者批评指正。

编　者

2004 年 10 月于西南民族大学

CONTENTS

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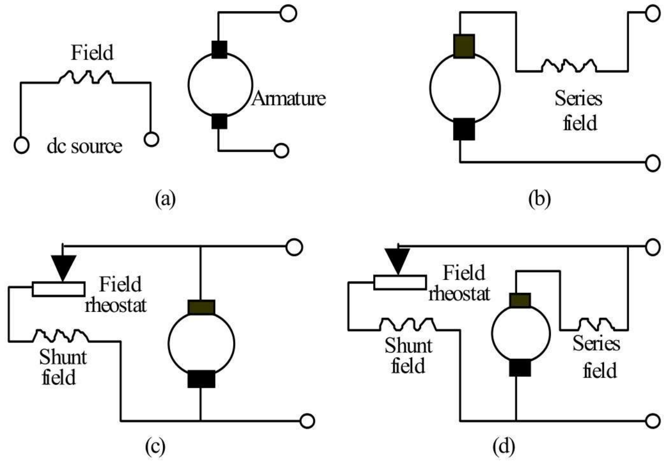
CHAPTER 1
Direct-Current Motors Drives

1.1 Introduction to DC machines

DC machines are characterized by their versoatility. By means of various combinations of shunt-, series-, and separately-excited field windings they can be designed to display a wide variety of volt-ampere or speed-torque characteristics for both dynamic and steady-state operation. The outstanding advantages of DC machines arise from the wide variety of operating characteristics which can be obtained by selection of the method of excitation of the field windings. The method of excitation profoundly influences both the steady-state characteristics and the dynamic behavior of the machine in control systems.

Consider first DC generators. The connection diagram of a separately-excited generator is given in Fig. 1.1(a). The required of field current is a very small fraction of the rated armature current; on the order of 1 to 3 percent in the average generator. A small amount of power in the field circuit may control a relatively large amount of power in the armature circuit; i.e., the generator is a power amplifier. Separately-excited generators are often used in feedback control systems when control of the armature over a wide range is required. The field windings of self-excited generators may be supplied in three different ways. The field may be connected in series with the armature (Fig. 1.1(b)), resulting in a series generators. The field may be connected in shunt with the armature (Fig. 1.1(c)), resulting in a shunt generators, or the field may be in two sections (Fig. 1.1(d)), one of which is connected in series and the other in shunt with the armature, resulting in a compound generator. With self-excited generators, residual magnetism must be present in the machine iron to get the self-excitation process started.



(a) separate excitation (b) series (c) shunt (d) compound

Fig. 1.1 Field-circuit connections of DC machines

Any of the methods of excitation used for generators can also be used for motors. Direct-current motors transform electrical energy into mechanical energy. They drive devices such as hoists, fans, pumps, calendars, punch-presses, and cars. These devices may have a definite torque-speed characteristic (such as a pump or fan) or a highly variable one (such as a hoist or automobile). The torque speed characteristic of the motor must be adapted to the type of the load it has to drive, and this requirement has given rise to three basic types of motors: Shunt motors, Series motors, Compound motors.

A series motor is identical on construction with a shunt motor except for the field. The field is connected in series with armature current (Fig.1.2). This series field is composed of a few turns of wire having a cross section sufficiently large to carry the current.

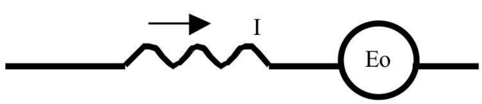


Fig. 1.2 Schematic diagram of a series motor

Although the construction is similar, the properties of a series motor are completely different from those of a shunt motor. In a shunt motor, the flux F per pole is constant at all loads because the shunt field is connected to the line. But in a series motor the flux per pole depends upon the armature current and, hence, upon the load. When the current is large, the flux is large and vice versa. Despite these differences, the same basic principles and equations apply to both machines.

A compound DC motor carries both a series field and a shunt field. In a cumulative compound motor, the mmf of the two fields add. The shunt field is always stronger than the series field. Fig.1.3 shows the connection schematic diagrams of a compound motor. When the motor runs at no-load, the armature current I in the series winding is low and the mmf of the series field is negligible. However, the shunt field is fully excited by current I_x and so the motor behaves like a shunt machine: it does not tend to run away at no-load.

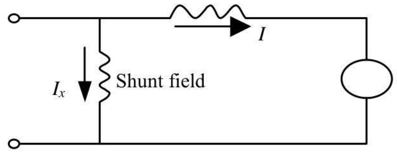


Fig. 1.3 Schematic diagram of the motor

As the load increases, the mmf of the series field increases but the mmf of the shunt field remains constant. The total mmf (and resulting flux per pole) is therefore greater under load than at no-load. The motor speed falls with increasing load and the speed drop from no-load to full-load is generally between 10 percent and 30 percent.

Example 1.1

A shunt motor rotating at 1500r/min is fed by a 120V source. The line current is 51A and the shunt-field resistance is 120Ω. If the armature resistance is 0.1Ω, calculate the following:

a. The current in the armature

b. The counter-emf

c. The mechanical power developed by the motor

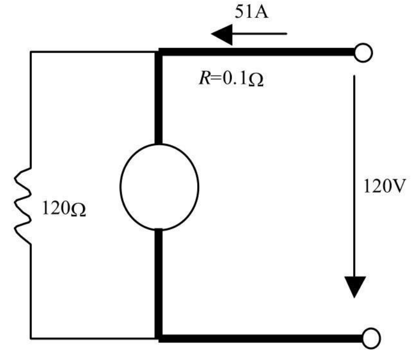


Fig. 1.4 See Example 1.1

Solution

a. The field current is

$$I_m = 120\text{V}/120\Omega = 1\text{A}$$

The armature current is

$$I_a = 51 - 1 = 50\text{A}$$

b. The voltage across the armature is

$$U = 120\text{V}$$

Voltage due to armature resistance is

$$I_aR_a=50\times0.1=5\text{V}$$

The cemf generated by the armature is

$$E_a = 120–5 = 115\text{V}$$

c. The total power supplied to the motor is

$$P_i = U\,I = 120\times51 = 6120\text{W}$$

Power absorbed in the armature is

$$P_a = U\,I_a = 120\times50 = 6000\text{W}$$

Power dissipated in the armature is

$$P_R = I_a\,R_a^{\ 2} = 50^2\times0.1 = 250\text{W}$$

Mechanical power developed by the armature is

$$P_m = 6000–250 = 5750\text{W}$$

(equivalent to 5750/746 = 7.7hp)

The actual mechanical output is slightly less than 5750W because some of the mechanical power is dissipated in bearing friction losses, in windage losses, and in armature iron losses.

1.2 Torque-Speed characteristic

The relationship between speed and torque corresponds to the relationship between voltage and current for a generator, i.e. it is the motor external characteristic. Typical torque-speed characteristic are shown in Fig. 1.5, in which it is assumed that the motor terminals are supplied from a constant-voltage source. In a motor the relation between the emf E_a generated in the armature and the armature terminal voltage V_a is

$$V_a = E_a + I_aR_a \tag{1-1}$$

or

$$I_a = \frac{V_a - E_a}{R_a} \tag{1-2}$$

where I_a is now the armature-current input to the machine. The generated emf E_a is now smaller than the terminal voltage V_a, the armature current is in the opposite direction to that in a generator, and the electromagnetic torque is in the direction to sustain rotation of the armature.

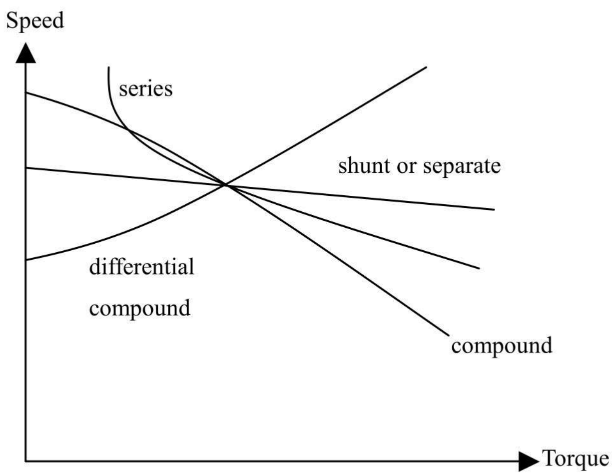


Fig. 1.5 Speed-torque characteristics of DC motor

The speed at which a motor will run depends on the balancing point of the electromagnetically developed torque and the torque arising mechanically. Both torques are functions of speed though they may be approximately constant, as in the case of the shunt motor and the couiomb-friction load; or they may vary considerably with speed, as for the series motor and for the fan-type load. There is some analogy here with the generator external. Characteristic and its load electrical characteristic, which are both functions of current. As an example, the output voltage of a self-excited generator is decided by the intersection of the field-circuit resistance and the armature-circuit terminal characteristics, which are both functions of field current.

The present discussion is concerned primarily with the speed/torque characteristic of the machine itself. The mechanical speed/torque characteristic can then be superimposed on the same graph to obtain the balancing speed. The speed/current and speed/torque equations have already been used and are reproduced in the most convenient forms below,

$$\omega = \frac{V}{k_\phi} - \frac{R}{k_\phi} I_a = \frac{V}{k_\phi} - \frac{R}{k_\phi^2} T_e \tag{1-3}$$

R could include external resistance but if this is zero, there is only the machine armature-circuit resistance R_a, which in the descriptive matter following will be taken to include armature, interpole and comp ensating windings and the brush drop for simplicity. The series winding of present will be considered separately as R_f, which symbol will also be used for the shunt-excited or separately excited field resistance.

The final term in eqn. (1-3), the influence of the load, is normally only a second order effect if $R = R_a$ which is small. The first term V / k_ϕ immediately shows the general effects of voltage and flux on speed as already discussed. To draw the speed/torque or speed/current curves merely requires the substitution of various values of torque (or current) and a knowledge of all the other

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parameters on the right-hand side of the equation will permit the corresponding speed values to be worked out. If field current is being varied, then the values of k_ϕ must first be obtained form the k_ϕ/I_f relationship. K_ϕ is related independently to both the magnetization curve and to the rest of the system, but nevertheless it must satisfy both of these relationships simultaneously for steady-state conditions. Similar considerations apply to the torque $T_e = T_m$, which is related to both the electromagnetic and the mechanical systems.

In shunt- and separately-excited motors are characterized by having control of K_ϕ which is approximately independent of supply voltage or the machine load. For any constant value of K_ϕ, eqn. (1-3) show that the speed/torque curse is a straight line starting from V/K_ϕ at zero torque and falling by an amount proportional to the resistance drop and hence to the torque. Consequently, increased torque must be accompanied by a very nearly proportional increase in armature current and hence by a small decrease in counter emf to allow this increased current through the small armature resistance. Since counter emf is determined by flux and speed, the speed must drop slightly. Like the squirrel-cage induction motor, the shunt motor is substantially a constant-speed motor having about 6 percent drop in speed from no load to full load. If the field current and K_ϕ are reduced, the no-load speed is increased in inverse proportion and the slop of the characteristic becomes steeper.

An outstanding advantage of the shunt motor is ease of speed control. With a rheostat in the shunt-field circuit, the field current and flux per pole can be varied at will, and variation of flux causes the inverse variation of speed to maintain counter emf approximately equal to the impressed terminal voltage. A maximum speed range of about 4 or 6 to 1 can be obtained by this method, the limitation again being commutating conditions. By variation of the impressed armature voltage, very wide speed ranges can be obtained.

In the series motor, increase in load is accompanied by increases in the armature current and mmf and the stator field flux. Because flux increases with load, speed must drop in order to maintain the balance between impressed voltage and counter emf; moreover, the increase in armature current caused by increased torque is smaller than in the shunt motor because of the increased flux. The series motor is therefore a varying-speed motor with a markedly drooping speed-torque characteristic of the type shown in Fig. 1.5. For applications requiring heavy torque overloads, this characteristic particularly advantageous because the corresponding power overloads are hold to more reasonable values by the associated speed drops. Very favorable starting characteristics also result from the increase in flux with increased armature current.

In the compound motor, the series field may be connected either cumulatively, so that its mmf adds to that of the shunt field, or differentially, so that it opposes, The differential connection is rarely used. As shown by the broken-dash curve in Fig. 1.5, a cumulatively-compounded motor has speed-load characteristics intermediate between those of a shunt and a series motor, with the drop of speed with load depending on the relative number of ampere-turns in the shunt and series fields. It does not have the disadvantage of very high light-load speed associated with a series motor, but it retains to a considerable degree the advantages of series excitation.

The application advantages of DC machines lie in the variety of performance characteristics offered by the possibilities of shunt, series, and compound excitation. Some of these characteristics have been touched upon briefly in this section. Still greater possibilities exist if additional sets of brushes are added so that other voltages can be obtained from the commutator. Thus the versatility of DC-machine systems and their adaptability to control, both manual and automatic, are their outstanding features.

Example 1.2

A 25-hp, 500-rev/min, DC shunt-wound motor operates from a constant supply voltage of 500V. The full-load armature current is 42A. The field resistance is 500Ω, the armature resistance is 0.6Ω and the brush drop may be neglected.

Calculate

(a) the field current required to operate at full-load torque when running at 500 rev/min. What would be the no-load speed with this field current?

(b) Calculate the speed, with this field current, at which the machine must be driven in order to regenerate with full-load armature current.

(c) Calculate the extra field-circuit resistance required to run at 600 rev/min; (i) on no load, (ii) at full-load torque.

(d) Calculate the external armature circuit resistance required to operate at 300 rev/min with full-load torque.

The magnetic characteristic was taken at 400 rev/min.

The problem will be solved in mechanical engineers' units so that $E = k_N N$ and T_e=7.04 k_N I_a. N is the speed in rev/min and k_N is the generated e.m.f. per rev/min. From the data given below, k_N is calculated immediately.

Field current	0.4	0.6	0.8	1.0	1.2	A
Generated e.m.f.	236	300	356	400	432	V
k_N = e.m.f. / 400	0.59	0.75	0.89	1.0	1.08	V per rev/min

(a) E at full load = $V–I_aR_a$ = 500–42×0.6 = 474.8V

∴ k_N required = 474–8 / 500 = 0.9496

From the k_N / I_t curve this requires 0.9A and the field circuit resistance must be 500/0.9=555Ω, i.e. an external 55Ω.

On no load, E = 500V neglecting the small voltage drop.

∴ $N = E/kN$ = 500/0.9496 =527 rev/min.

(b) when regenerating $E = V + I_aR_a$ = 525.2V

∴ N = 525.2/0.9496=554 rev/min

(c) (i) On no load, E = 500V ∴ k_N required = 500/600 = 0.833

From k_N/ I_t curve this requires 0.7 A as the field current.

The extra field circuit resistance is 500/0.7–555 = 159Ω

(ii) Full-load electromagnetic torque $T_e = 7.04 \times 0.9496 \times 42 = 280$ lbf ft.

Useful torque at full load, form the rating particulars given:

$$T_{\text{coupling}} = 25 \times \frac{33000}{2\pi \times 500} = 262.5 \quad \text{lbf ft}$$

i.e. there is a mechanical loss torque of 17.5 lbf ft due to the iron and mechanical losses. Assuming this varies as speed, the total torque developed at 600 rev/min must be 262.5+17.5×600/500=283.5 lbf ft.

(This is only a nominal allowance for the change of loss torque and no great error would follow form assuming it to be constant).

Hence, $T_e = 7.04\ k_N I_a = 283.5$, from which $k_N = 40.2 / I_a$.

Further, $E = 500 - 0.6I_a = k_N N = (40.2I_a) \times 600$, from which a quadratic equation in I_a can be obtained.

The lower and only practicable value of I_a is found to be 51.5 A and this gives

$k_N = 40.2/51.5 = 0.78$, and $E = 500 - 0.6 \times 51.5 = 468.8$V.

I_f form the curve is 0.625 A, and the extra field circuit resistance is 500/0.625-555=245Ω

Note that k_N is very nearly 0.9496×500/600 = 0.79. This neglects the small change in E due to the additional $I_a R_a$ drop necessary to maintain the torque at full load with reduced flux.

(d) The developed torque must be 262.5 + 17.5×300/500 = 273 lbf ft.

With the flux maintained as is usual for speed reductions, the current becomes 42×273/280=41A

The generated e.m.f. will be $k_N N = 0.9496 \times 300 = 284$V.

The total resistance drop in the armature circuit must be 216V.

∴ the external resistance must be 216/41–0.6 = 4.66Ω

1.3 Starting of DC motors

To bring a motor rest up to speed from a constant supply voltage is a special case of speed control in which the armature-circuit resistance is varied. At standstill the e.m.f. is zero so the armature resistance alone limits the stating current and torque. With a value of say 0.05 p.u., the starting current at full voltage would be 1/0.05=20 p.u. Extra resistance is therefore required, and is connected in series with the armature.

Referring first to the shunt motor, eqn. (1.3) shows that the downwards slope of the speed/torque curve directly proportional to the armature resistance with constant flux and voltage. By increasing the resistance, the characteristic will cut the zero-speed axis to give a lower, though adequate starting torque and a reasonable starting current. Usually a figure of 50%～100% more than the full-load value torque of the motor and load, the speed will rise along the curve R_1, Fig. 1.6(a). At some point, the resistance is changed over quickly to give the curve R_2, such that the current again rises to the starting value, and the speed continues to build up along this new characteristic. The process is continued through perhaps 2 to 10 steps until the balancing speed on the natural characteristic is reached.

For a series motor, the effects of the additional circuit resistance can easily be calculated using the tabular method and a typical set of curves is shown on Fig. 1.6b. Father fewer steps of starting resistance are necessary due to the shape of the characteristics. As already explained, a given overload torque on a series motor is obtained with less overload current than on a shunt motor. This is a useful feature for loads where a high stiction torque is present, e.g. traction applications.

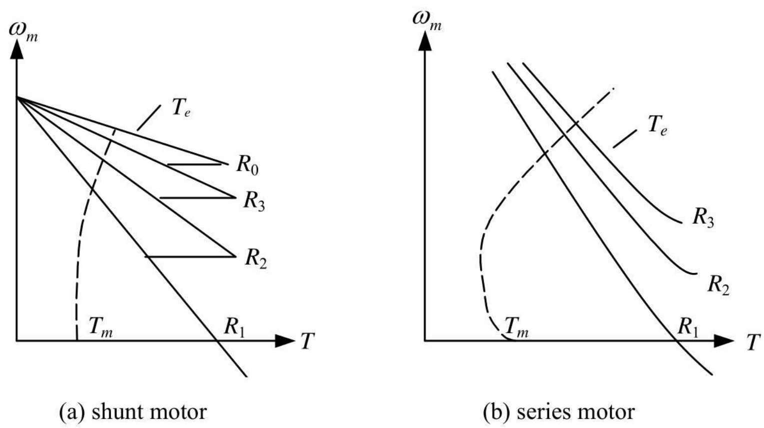

Fig. 1.6. Starting and resistance control

In the case of both the series and the shunt motor, it can be seen that series resistance could be used for speed control, as illustrated by the intersections of the typical T_m curves with the machine characteristics. Limited speed control by this means is sometimes employed but it is wasteful in power. Further, as resistance is increased, the greater sensitivity of speed to load changes is a drawback and eventually it becomes impossible to hold the speed steady at all.

1.4 Speed control of DC motors

Four methods of controlling the speed of a de motor will be discussed in the early part of this chapter. The four methods are:

1. Changing the field flux, Φ, by means of a variable series or shunt rheostat. This method is known as "field control".

2. Changing the voltage V_a across the armature by using a variable resistance in series with the armature. This method is called "armature resistance control".

3. Changing the voltage V_a across the armature, and the current I_a in the in series with the armature. This method is called "series and shunt armature resistance control".

4. Using a controlled source of variable DC voltage to change the voltage V_a across the armature of a separately excited motor. This method is known as “armature voltage control”.

Field control

When the rated or line voltage is applied to the armature of a DC motor and the field flux is manually or automatically varied by means of a field rheostat in series or in parallel with the field excitation winding, the method of speed control is called “field control”, when the motor is started and the variable armature resistance is shorted out so that V_a equals supply voltage, control of the speed may be achieved by varying the field rheostat form no added field resistance or full field current to maximum field resistance or minimum field current.

The speed achieved with the full armature voltage and full field current (no added field resistance) is called the basic speed of the motor. Increasing the field resistance, therefore, will decrease the field current and field flux in the fundamental speed equation, causing the speed to rise. It may be said, therefore, that field control can produce only speed above the basic speed.

Field control as a method of speed control to obtain speed above basic speed has the following advantages over other speed-control methods: (1) field control is relatively inexpensive and simple to accomplish, both manually and automatically; (2) it is relatively efficient in terms of motor performance, since the field circuit loss is only 3 to 5 per cent of the total power drawn by the motor; (3)within limits, field control does not affect speed regulation in the cases of shunt, compound, and series motors; and (4) it provides relatively smooth, stepless control of speed .

The third advantage, however, carries with it a warning that this method of speed control is achieved by weakening the field flux within limits. If the field is weakened considerably, dangerously high speeds are produced. Since an increase in speed (created by flux reduction) results in an increase in the load and armature current, the increase in torque ($T = k\Phi I_a$) is produced by a considerable increase in the armature current.

With a weak field and a high armature current, the DC shunt motor is particularly susceptible to the effects of armature reaction instability and may run away in the same manner as a differential compound motor it is precisely for this reason, moreover, that DC motors are started with full field current, With a high speed and high armature current, moreover, commutation difficulties are increased, as the high armature currents are reversed more rapidly and serious damage to the commutator may be produced in arcing.

Armature resistance control

When the field rheostat is set so that normal field excitation (in the saturation)is produced, and the voltage across the armature is reduced, by means of a variable resistance in series with the armature, the method of speed control is called “armature resistance control”, the field rheostat is adjusted to provide normal excitation, and the series armature resistance is adjusted so that the armature voltage, V_a , is varied below the line voltage, V_a Control of the speed is obtained by varying the resistance in series with the armature. Increasing the series armature resistance reduces the voltage across the armature (at any given load) in the fundamental speed equation, $S = k\ (V_a = I_aR_a)/\Phi$, causing the speed to drop. It may be said, therefore, that armature resistance control can produce only speed below the basic speed.

The armature current in the fundamental speed equation is a function of the load. At any given setting of the series armature resistance, an increase in load will produce an increased voltage drop across the series-connected. Armature resistor, which produces a drop in speed. For any no-load speed setting below the basic speed, armature resistance control will produce a sharp drop in speed with the application of load, resulting in poor speed regulation. The greater the value of the series armature resistance, the poorer the speed regulation of the motor. Furthermore the armature current flowing through the series-connected armature resistance will produce an appreciable power loss ($I_a^2 R_a$) which reduces the overall motor efficiency. While this power loss, fortunately, does not produce heat within the motor, it does require a larger continuously rated externally connected, variable resistor may be used both for motor starting as well as for speed control by armature resistance control.

The advantages of armature resistance control are: (1) the ability to achieve speeds below the basic-speed, (2) simplicity and ease of connection, and (3) the possibility of combining the functions of motor starting with speed control.

The disadvantages of armature resistance control the (1) the relatively high cost of large, continuously rated, variable resistors capable of dissipating large amounts of power (particularly in higher horsepower ratings), (2) poor speed regulation for any given no-load speed setting, (3) low efficiency resulting in high operating costs, and (4) difficulty in obtaining stepless control of speed in higher power ratings.

Armature voltage control

The relative efficiency of the smaller motors is not a serious consideration, whereas relative torque, speed regulation, and stepless control are of some importance in small motor applications. In the case of motors of higher horsepower, however, efficiency, torque, good speed regulation, and smooth, stepless speed control are all extremely important considerations. Heavy loads with high inertia require smooth acceleration over a wide speed range. All these criteria may be achieved by using a variable DC voltage from a source of sufficient capacity to supply the required armature voltage and current to a DC motor. The field is always separately excited from a constant-current or constant-voltage source. This method of speed control also eliminates the need for series armature starting resistance.

If the armature voltage supplied from the variable DC source is zero, the motor develops zero torque ($T{=}k\Phi I_a$) and is at a standstill. If the armature voltage is increased slightly, in accordance with the fundamental speed equation $S = k\ (V_a – I_aR_a)/\ \Phi$, the motor starts and turns at a slow speed with a minimum of acceleration. The armature current is limited because of the low voltage across the armature. Reducing the armature voltage to zero, and reversing the polarity of the variable voltage source, will stop and reverse the motor in accordance with the left-hand

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