# CHAPTER 7
# POWER CONVERSION AND LOSSES

The input power to the dc machine under generator action is mechanical conversion to produce the output power; the process yields a number of losses that appear as heat which has harmful effects en the performance of the machine. In this chapter we study the conversion process and the losses associated with it.

## 7.1 Power balance

Most of the input power supplied to a dc machine is converted into useful output power; the remainder of the input power is lost as heat; see fig. 7.1. The principle of conservation of energy requires total power balance

$$P_{in} = P_{out} + LOSSES \qquad (7.1)$$

It is sometimes useful to think of power as ‘flowing’ through the machine, fig.7.2. Power flow is divided into two stages, the borderline being the actual electromechanical energy conversion process $P_c$ is the conversion power.

$$P_c = E_A I_A = \omega_r T_d \qquad (7.2)$$

$E_A$, is the induced emf, $T_d$ the developed torque, $I_A$ the arm current, and $\omega_r$ the angular shaft speed. $P_c$ is also called the <u>internal power</u> because it is defined within the machine; in contrast, $P_{in}$ and $P_{out}$ are <u>external powers</u> that can be measured. $E_A$ and $T_d$ in eqn.7.2 are internal quantities that cannot be measured directly. Power balance in fig. 7.2 requires that

$$P_{in} = P_c + LOSS_1 \text{ and } \qquad P_c = P_{out} + LOSS_2 \qquad (7.3)$$

The total loss is made up of 2 parts :$LOSS_1$ occurs before conversion, and $LOSS_2$ occurs after conversion. Clearly

$$P_{in} > P_c > P_{out} \qquad (7.4)$$

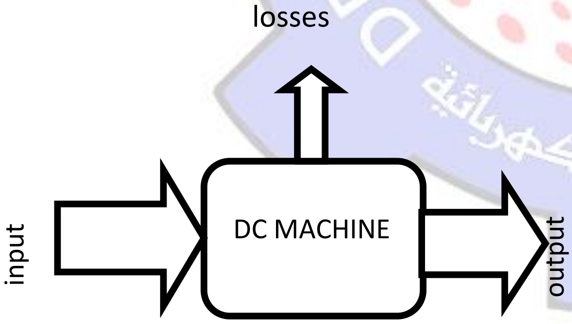

Fig. (7.1) division of power

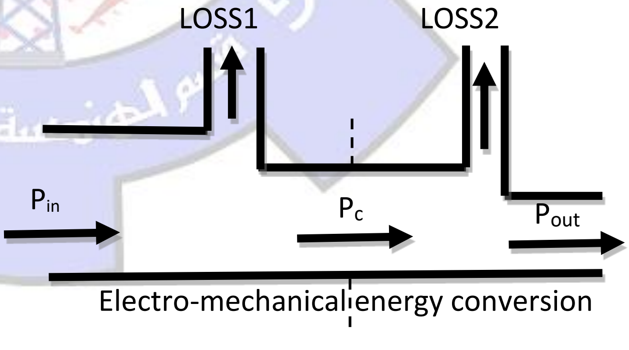

Fig. (7.2)

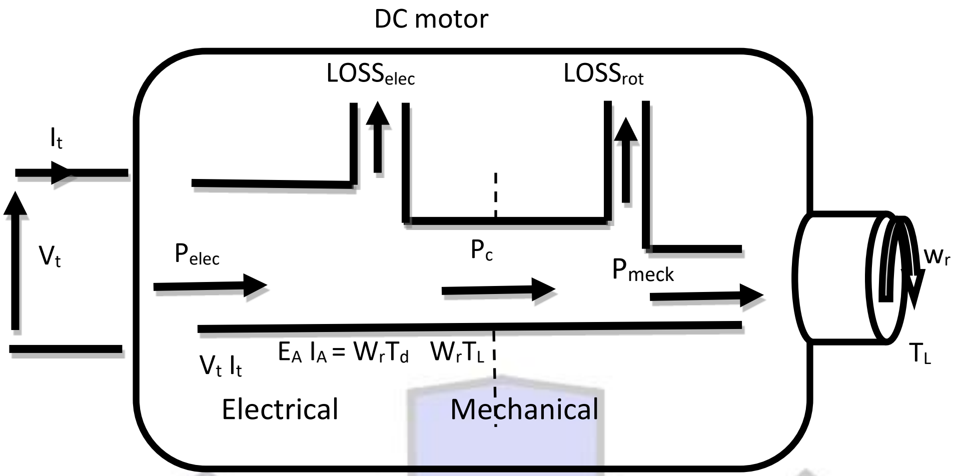

Fig. (7.3) Flow of power through dc motor

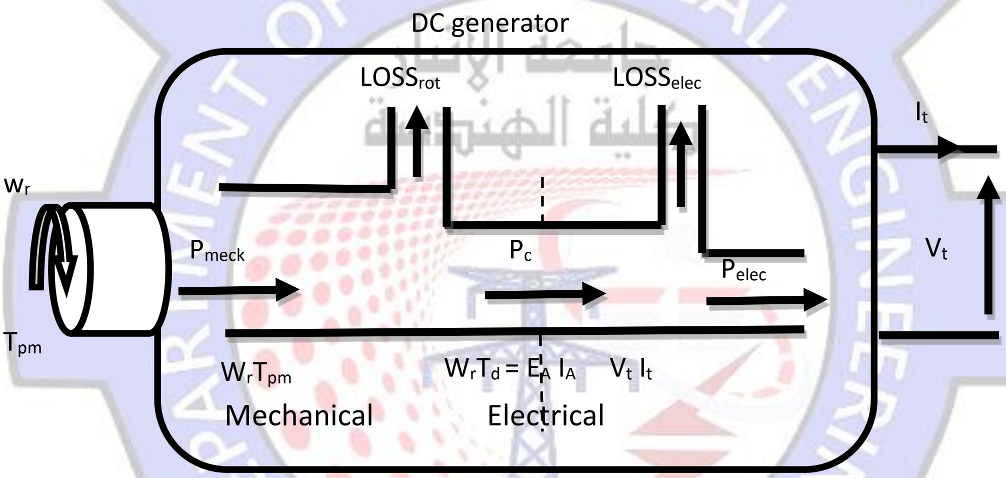

Fig. (7.4) Flow of power through dc generator

## 7.2 Motor Operation

The input power is electrical, and the output power is mechanical, fig. 7.3. Part of the input power is lost as electrical (copper)losses in the windings, and the remainder is available for electromechanical energy conversion; part of the converted power $P_c$ is lost in supplying the losses due to rotation, and the remainder is available as a mechanical output power to drive the load. Note that

$$P_{mech} < P_c \rightarrow \qquad \omega_r T_L < \omega_r T_d \qquad \rightarrow T_L < T_d \qquad (7.5)$$

That is, the Shaft torque available at the load, $T_L$, is lest than developed torque $T_d$; the difference is needed to overcome opposing torques within the motor (such as bearing friction).

## 7.3 Generator Operation

The input power is mechanical, and the output power is electrical, fig. 7.4. Part of the input power is lost as rotational losses, and the remainder is available for electromechanical energy conversion; part of the converted power $P_c$ is lost as electrical (copper) losses in the windings, and the remainder is available as electrical output power to supply the load. Note that

$$P_{mech} \geq P_c \rightarrow \omega_r T_{pm} \geq \omega_r T_d \rightarrow T_{pm} \geq T_d \qquad (7.6)$$

That is, the shaft torque produced by the prime mover, $T_{pm}$, is greater than the developed torque $T_d$; the difference is the torque needed to overcome friction and other opposing torques (other than $T_d$).

**Remark**

It is good practice to keep power balance always in mind :every power we define must come from somewhere and, conversely, every bit of it must go somewhere. This is true net only in dc machines, but in all physical systems; it often helps us in understanding the processes we study.

## 7.4 Losses

The losses of a dc machine are of various types and occur in different parts of the machine. Although different losses are produced differently, they all appear as heat, i.e. they represent conversion to useless thermal energy. The heat generated by the losses has two major effects:

(i)Losses raise the temperature inside the machine, and thus affect the performance and life of the materials of the machine, particularly insulation. Therefore, losses determine the upper limits on machine rating.

(ii)Losses are a waste of energy, and energy costs money; therefore, losses result in a waste of money (in the operating cost of the machine).

Losses cannot be eliminated, but they can be reduced by proper design; the design must also provide for ventilation to disperse the heat generated. Thus, losses have a significant effect on the initial cost of the machine.

The cost of wasted energy in item (ii)above is important with industrial motors where the powers involved are quite high; it is not important with small control motors where the powers involved are very small. However, the temperature rise in item (i)is important for all motors.

### 7.4.1 Electrical Losses

Electrical losses are also called copper losses, winding losses, $I^2R$ losses, and ohmic losses. Copper losses occur in all windings (see fig. 6.11) due to the flow of current through them; they are:

$LOSS_{arm} = I_A^2 R_A$ =armature circuit copper loss (7.7a)

$LOSS_{ser} = I_s^2 R_s$ =series field copper loss (7.7b)

$LOSS_{sh} = I_f^2 R_f$= shunt field copper loss (7.7c)

In computing $LOSS_{arm}$, $R_A$ includes the resistances of commutating and compensating windings (if present). The series field current $I_s$ may or may not be equal to the armature current $I_A$, see fig. 4.3.

The copper loss in a given wdg is proportional to the square of the current in that wdg; if the current is doubled, the copper loss increases four times. $LOSS_{arm}$ and $LOSS_{ser}$ depend on armature current, and hence they depend on the load on the machine ($I_A$ increases with load) LOSSsh depends on the terminal voltage, and varies with its square.

The above expressions can be used to calculate copper losses using measured values of winding resistances. The wdg resistance must be at the correct wdg temperature; if the temperature at which the less is required is not known, it is assumed to be 75 $^oC$. If the wdg resistance is known (say by measurement) at a temperature $T_1$, it can be found at a different temperature $T_2$ from

$$\frac{R_2}{R_1} = \frac{T_2 + 234.5}{T_1 + 234.5} \qquad (7.8)$$

The brush contact loss is also an electrical loss. Since the brush contact drop $V_b$ is approximately constant over a wide range of armature currents, the loss is proportional to the armature current itself (and not it's square as in wdg losses):

$$LOSS_{contact} = I_A V_b \qquad (7.9)$$

## 7.4.2 Magnetic Losses

Magnetic losses are also called iron loses or core losses. They result from hysteresis and eddy currents in cores subjected to varying magnetization, i.e. mainly in the armature teeth and core, but also in the pole shoes (due to armature slotting -see fig. 4.2b).

Iron losses are distributed in the cores in complicated patterns, so that there are no simple formulae that give their values accurately. It is known, however, that iron losses depend on the magnetization level (flux density) in the cores, and on the frequency with which it alternates, f =np. For the hysteresis loss, we have:

$$LOSS_{hyst} \alpha\ f\ B^x_{MAX} \qquad (7.10)$$

Where the constant of proportionality is determined by the volume of the core and its magnetic characteristics (hysteresis loop). The Steinmetz exponent x depends on the type of iron used, and ranges from 1.5 to 2.5 (usually around 2); it is an empirical constant (obtained from experience and testing, not from electromagnetic theory). For the eddy current loss, we have:

$$LOSS_{eddy} \alpha\ f^2\ B^2_{MAX}\ (\text{lamination thickness})^2 \qquad (7.11)$$

Where the constant of proportionality is determined by the volume of the core and its electrical characteristics (resistivity). Clearly, thin laminations reduce eddy current losses. The armature is always laminated, and the pole shoes are usually laminated. If a motor is to be driven from a modern solid-state controlled rectifier, all cores are laminated (including poles and yoke).

## 7.4.3 Mechanical Losses

Mechanical losses arise from friction and windage (friction with air) during rotation. They depend on the speed of rotation, each type mechanical loss being proportional to some power of n. Bearing friction loss depends on the type of bearing used and on the viscosity of the lubricant; improper lubrication (too little or too much) increases the loss. Brush friction loss is proportional to the area of contact and to the brush pressure; it also depends on the brush and commutator materials, their slate of polisn, and the temperature at the contact surface; it is often the largest friction loss. Windage losses arise from moving the air around the armature (air friction); they depend on the shape of the rotating surface (smooth or rough).

Ventilation loss is an additional windage loss duo to fans and vent ducts used to cool the machine.

### 7.4.4 Stray Load Loss

Stray load losses are additional losses that occur in the machine when loaded, and cannot be included with the conventional losses listed above. They include:

-Additional core loss resulting from armature reaction distortion;

-Copper loss due to short circuit current during commutation (in commutating coils, commutator segments, and brushes);

-Non uniform current distribution in large armature conductors.

Stray load losses are small and difficult to calculate. They may be neglected for small machines, and are usually assumed 1 %of output for large machines.

## 7.5 Classification of Losses

Table 7.1 is a brief summary of the losses described in section 7.2; it gives their types (electrical, magnetic, or mechanics) and the main factors they depend on. The table also classifies the losses according to whether or not they are 'rotational' losses, and according to whether they are constant or vary with load. We now explain these two classifications.

### 7.5.1 Rotational losses

Rotational losses are the losses arising from the rotation of the armature. They include friction and windage losses, as well as core losses (in dc machines, the power lost in the core is not supplied by the source of the field, but by the torque that rotates the armature-see figures 7.3 and 7.4)

$$LOSS_{rot} = LOSS_{core} + LOSS_{mech} \quad (7.12)$$

Rotational losses increase with speed; the various component losses are functions of different powers of speed. Rotational losses exist even when the machine is running at no load because they do not depend on the armature current; therefore, they are sometimes called 'no load losses'.

Rotational losses are supplied by the difference between the external and developed torques:

Motor (fig. 7.3) : $LOSS_{rot}=P_c-P_{mech}=\omega_r(T_d-T_L)$ (7.13)

Generator (fig. 7.4) : $LOSS_{rot}=P_{mech}-P_c=\omega_r(T_{pm}-T_d)$ (7.14)

Table 7.1 classification of losses in dc machines.

| | loss | type | Rotational | With load | dependence |
|---|---|---|---|---|---|
| 1 | Armature circuit copper loss | Elec. | x | variable | α I2A |
| 2 | Series field copper loss | Elec. | x | variable | α I2A |
| 3 | Shunt field copper loss | Elec. | x | constant | α Vt2 |
| 4 | Brush contact loss | Elec. | x | variable | α Ia |
| 5 | Hysteresis loss | Mag. | √ | constant | α fBmaxx |
| 6 | Eddy current loss | Mag. | √ | constant | α f2 Bmax2 |
| 7 | Friction loss | Mech. | √ | constant | α powers of n |
| 8 | Windage loss | Mech. | √ | constant | α powers of n |
| 9 | Stray load loss | | √ | variable | indeterminate |

Table 7.2typical values of dc machine losses for industrial meters in the range 1-100 KW. Lower percentage losses are for the higher rated motors.

| Losses | % of rated power |
|---|---|
| Armature circuit electrical loss | 3-6% |
| Shunt field electrical loss | 1-3% |
| Rotational losses | 3-13% |

Table 7.3 typical efficiencies of industrial motors.

| Rated power, KW | Efficiency |
|---|---|
| 1 | 75% |
| 50 | 90% |
| 500 | 94% |
| 5000 | 97% |

### 7.5.2 Constant and Variable Losses

Constant losses are losses that do not change as the load on the machine changes; they are independent of armature current, and Include -mechanical losses, core losses, and shunt field loss. Variable losses are losses that increase as the load on the machine increases; they are electrical losses including armature circuit copper loss, series field loss, and brush contact loss. Copper losses increase with $I_A^2$, while brush contact loss increases with $1_A$ itself. We may therefore write:

$$LOSSES_{total} = K_0+K_1I_A+K_2I_A^2 \qquad (7.15)$$

The first term on the RHS represents constant losses, while the second and third terms represent variable losses. At full load, constant losses are 4-20 %and variable losses are 3-6%; see table 7.2.

**Remark**

Stray load losses are indeterminate functions of armature current and speed. They complicate classification, but are small enough to be neglected in most cases.

## 7.6 Measurement of Losses

There are a number of practical tests to measure the various machine losses. In most cases, a given test yields the sum of two or more losses together; sometimes the component losses can be separated by further testing.

In testing, it is quite easy to measure electrical Quantities (resistance, voltage, and current) and speed, somewhat difficult to measure torque, and quite difficult to measure magnetic quantities (flux and flux density). Powers are determined, on the electrical side by the product of voltage and current, and on the mechanical side by the product of torque and angular speed.

In a load test, the machine is loaded at a given speed and field excitation (i.e. field current); the input and output powers are measured. The total loss at that speed, excitation, and load is obtained from eqn. 7.1:

$$LOSSES_{total}=P_{in}-P_{out} \qquad (7.16)$$

The total loss can be separated into electrical and rotational losses by calculating $I^2R$ products in the various windings using wdg currents measured during the load test and (hot) wdg resistances measured previously. With the electrical losses thus calculated, the rotational losses are obtained from

$$LOSS_{rot} = LOSSES_{total} - LOSS_{elec} \qquad (7.17)$$

Load tests for large machines are impractical in test labs: they require very large loads, and waste large amounts of energy. There are other tests that yield the losses individually.

In a no-load test, the machine is driven by a suitable prime mover (possibly another machine-see fig. 7.6) with Its terminals open circuited (i.e. it operates as an unloaded generator). The input power to the test machine is measured mechanically (torque and speed), or electrically by measuring the input power to the drive motor and subtracting its losses (which must therefore be known). If the test machine is unexcited then $p_{in} = LOSS_{mech}$. If the test machine is then excited but left unloaded we get $P_{in} = LOSS_{rot}$; the core loss is obtained from $LOSS_{core} = LOSS_{rot} - LOSS_{mech}$. (Exercise :suggest a test for separating the brush friction loss).

If no suitable drive (prime mover) is available, rotational losses may be obtained by running the machine as a motor with no external load; this is the running light test, or Swinburne test. The input power will mainly go to rotational losses, but there will also be a little copper loss (why?) The copper loss may be computed and subtracted from the input power to yield rotational losses. In the running light test, rotational losses cannot be separated into mechanical and core losses (why?).

As seen from the above tests, it is always possible to determine copper losses from the measured values of wag currents during the tests, and previously measured wdg resistances. Winding resistances are measured by standard methods (voltmeter-ammeter, wheatstone bridge, etc.); the wdg temperatures must be monitored at the time of resistance measurement (why?), or the measurement is made with the machine hot (for example directly after a load test).

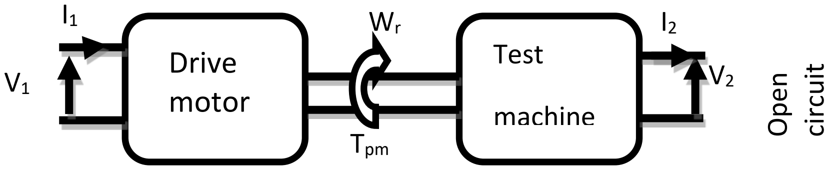

Fig. (7.5) no load test of dc machine