Analysis of DC generator

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Abstract— **A DC generator is an electrical machine which converts mechanical energy into direct current electricity.**

Keywords— EMF, Characteristics, DC generator and alternator, shunting,

I. Construction and Working

a) Construction-

1. **Yoke**: The outer frame of a dc machine is called yoke. It is made of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes.

(i) they support field coils and
(ii) spread out the flux in air gap uniformly.

3. **Armature windings** are in a closed-circuit form and are connected in series to parallel to enhance the produced current sum.
4. **Commutator**- A commutator works like a rectifier that changes AC voltage to DC voltage within the armature winding. It is designed with a copper segment, and each copper segment is protected from the other with the help of mica sheets. It is located on the shaft of the machine.
5. **Brushes**- The electrical connections can be ensured between the commutator as well as the exterior load circuit with the help of brushes.

b) **Working principle-**

A DC generator operates on the principle of Faraday's laws of electromagnetic induction. According to Faraday's law, whenever a conductor is placed in a fluctuating magnetic field (or when a conductor is moved in a magnetic field) an EMF is induced in the conductor.

If the conductor is guided with a closed path, the current will get induced. The direction of the induced current (given by Fleming's right-hand rule) changes as the direction of movement of the conductor changes.

The induced current will flow along the closed path of the conductor when the situation is provided. The armature conductors are spun into the electromagnetic field created by the field coils in a DC generator. As a result, the conductors in the armature produce an electromagnetically induced emf.

II. Types of DC Generators

DC generators can be classified in two main categories, viz;

(i) Separately excited and (ii) Self-excited.

(i) **Separately excited:** In this type, field coils are energized from an independent external DC source.

(ii) **Self-excited:** In this type, field coils are energized from the current produced by the generator itself. Initial emf generation is due to residual magnetism in field poles. The generated emf causes a part of current to flow in the field coils, thus strengthening the field flux and thereby increasing emf generation. Self-excited dc generators can further be divided into three types -

(a) **Series wound** - field winding in series with armature winding

(b**) Shunt wound** - field winding in parallel with armature winding

(c) **Compound woun**d - combination of series and shunt winding

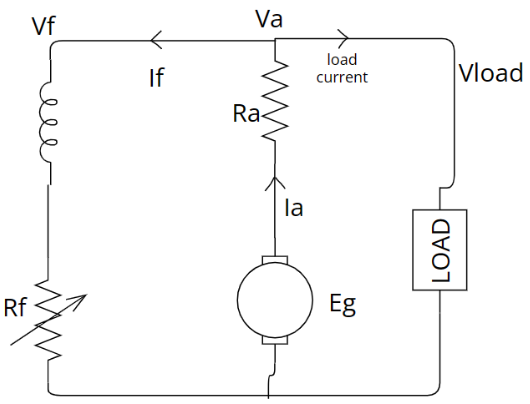
III. Analysis of various types

a. Shunt DC generator- The armature is parallel to the field windings' excitation. Here, the armature winding provides both the load & the field currents. For the excitation of a DC generator, it needs a DC field current. The DC field current may be excited separately through a DC source like a battery so that the DC generator also supplies the required energy for the field current.

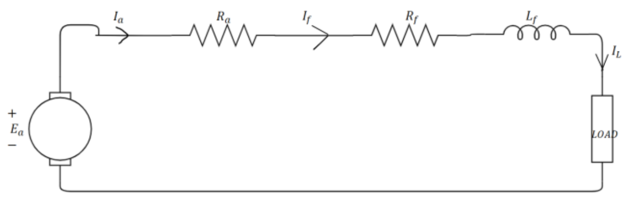
b. The DC shunt generator working principle is similar to a normal generator like electromagnetic induction. In this generator, the connection of field winding can be shunt toward the armature. Once input is provided through the prime mover, then the conductor can be turned within the permanent magnetic field. Because of this reason, the flow of current will be induced within the conductors which are arranged under the magnetic field influence.

c. The flow of current-induced throughout the armature winding is irregular. So the armature winding output is irregular frequently. Here AC is changed into the DC due to the commutator. In this way, a DC output can be attained within a DC shunt generator.

$$V_f = V_a = V_L$$
$$V_a = E_g - I_a R_a$$
$$I_a = I_f + I_L$$
$$V_f = Field\ voltage$$
$$V_a = Armature\ voltage$$
$$V_L = Load\ voltage$$
$$E_g = voltage\ of\ the\ generator$$
$$I_a = armature\ current$$
$$R_a = armature\ resistance$$



Series-



The field windings are connected in series with the armature. Thus, the current is same through all components of the circuit.

Using KVL across the loop,

$$V_f = E_a - I_a(R_a + R_f)$$
$$I_a = I_f = I_L$$

Characteristics-

a. **Winding characteristics:**
Since the current in the circuit is high, the MMF required to create flux will require a smaller number of turns. If the resistance is very high the drop across I_a would be high and the generator regulation would be very poor. Thus, the resistance should be low for the field winding.

Since $R = \frac{\rho l}{A}$, the area of cross-section should be more. Thus, the winding characteristics imply that few turns and thicker winding with low resistance are the favourable conditions.

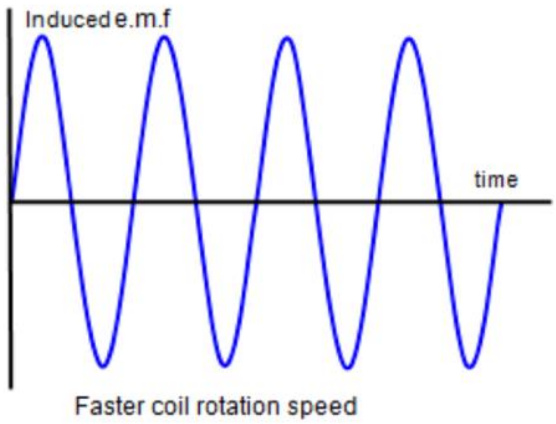
IV. General Rise/Fall

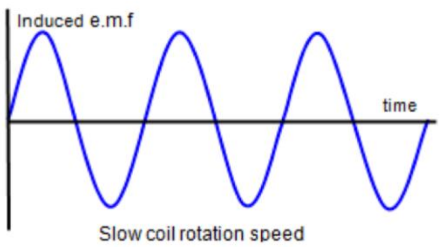
Using the Faraday's Law-

$$\varepsilon = -N\frac{\Delta \emptyset}{\Delta t}$$

- We see that when the coil is rotated fast, the angular frequency (ω) increases and it passes through a greater number of magnetic field lines. It thus increases the flux generated which gives high EMF or rise in the amplitude of the output voltage in less time (the period of one revolution becomes shorter).

T=1/f



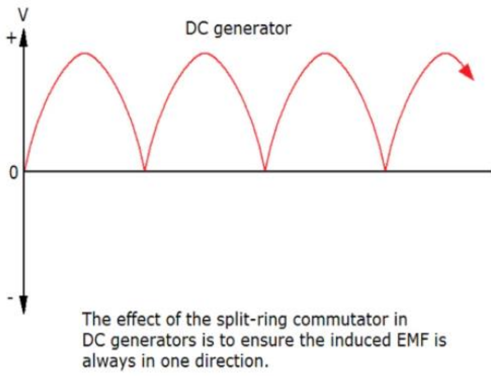


V. Effect of Frequency

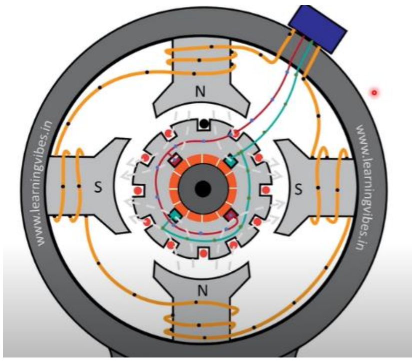
A DC generator produces direct current, which has no 'frequency'. The voltage it produces, all else being equal, is proportional to the rotational speed of the machine. However, most DC generators have some ripple. The frequency and severity of the ripple depends on the number of armatures and the speed at which the generator is turning.

But as discussed above, we see the effect on angular frequency on changing the rotational velocity f the armature.

Moreover, DC generators produce unidirectional current so their emf are all positive. The DC generator graph is the absolute value of the AC generator graph. This makes sense as all we are doing with the split ring is reversing the direction (i.e., reflecting every negative portion about the x-axis).



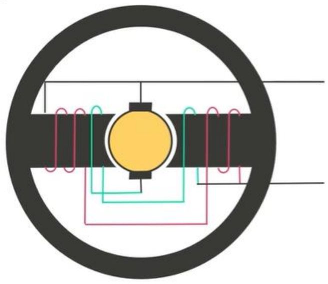
VI. Equations of The Induced EMF of the DC Generator

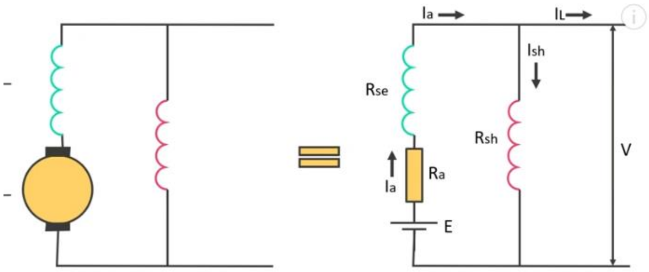


E=change in flux/change in time
P=Number of poles (here 4)
Φ=The Flux per pole
Z=Number of armature conductors
N=Speed of the armature
A=Number of paths in armature

From here we get the expression we need.
The net change in flux is given by PΦ
Now we determine the time taken for one revolution
Speed of the armature is N rpm
Hence N revolutions in 60 seconds -> 1 Revolution in 60/N seconds.
Hence the time taken is 60/N
Plugging the given results in the given expression we get
E=NPΦ/60
However we can go even further with this expression
If there are A parallel paths inside the conductor, the number of armature conductors will be
A-the original number of armature conductors
A-Z

Hence the number of conductors in series are Z/A
Hence the induced EMF is given by PΦNZ/60A

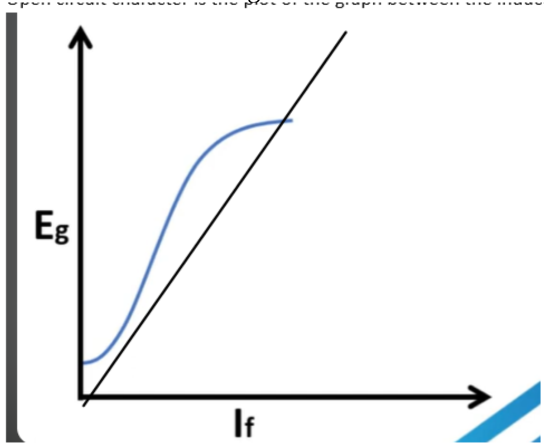




Here from the analysis of the circuit we have the following relations
Ish=V/Rsh
Also applying KCL towards the top middle node we get
Ia = Il +Ish
V=E- IaRa – Ia Rse

VII. Open circuit characteristics of the DC generator

Open circuit character is the plot of the graph between the induced voltage and the field current.



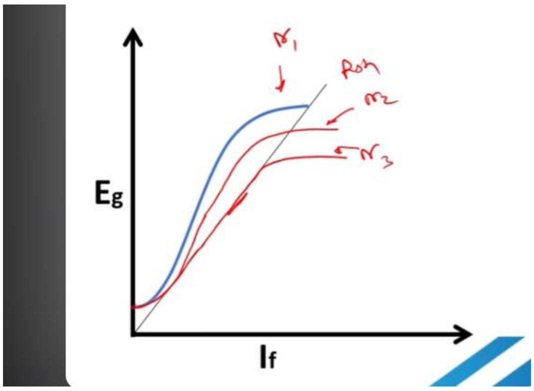
This graph is also defined as the magnetising curve of the circuit or the magnetising characteristics of the dc generator
We have derived the expression
E= PΦNZ/60A
If PZ/60A is assumed to be constant,
then E=kΦN

Hence the induced emf is directly proportional to the flux and the induced current is directly proportional to the flux

Here we make an assumption before drawing this graph that the velocity of the plot for a specific graph remains constant so that it could be represented as a constant too.

This can be verified by changing the field current and changing the flux.
If the ratio of the emf and the current is taken, then the result comes out to be constant and is called as R_{sh} or is also referred to as shunt filled winding resistance.
The point where the graph meets with the Rsh is referred to as a stable point.
Here we could have three different cases for resistance R sh (In the figure it's a straight line)
When the line is a secant to the given curve then the condition is said to be a stable condition hence we get a proper amount of induced emf
whereas whenever the line becomes a tangential condition then the resistance is referred to as critical resistance and that is a critical condition, and we get at a stage where it is referred to as an unstable point of reference.
But if the line does not intersect the graph then in this case we get a very low voltage at the terminal.
Note that in all these cases the speed is assumed to be constant then the curve shifts downward or upward depending on whether the speed is increasing or decreasing.

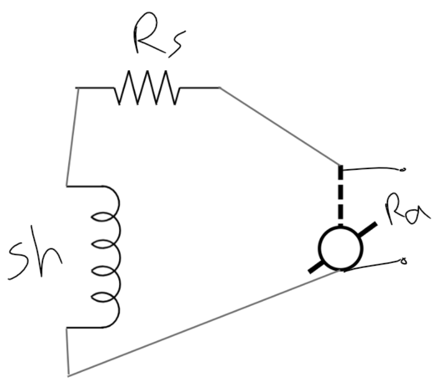
i.e. if the speed is increasing then the graph shifts upwards and if the speed is decreasing then the graph shifts downwards



This can be verified by $E=kN_1\Phi$
Hence this can be written in some other form
E1/N1=E2/N2

This can be applied in many different ways:

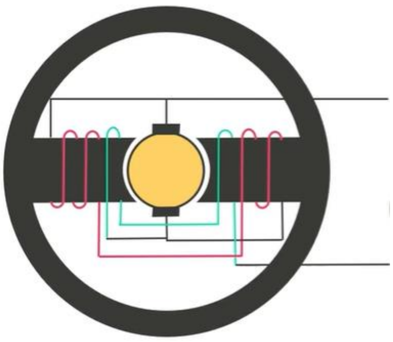
1. Calculation of the critical resistance
2. Calculation of the critical speed
3. Equation verification
4. Characteristic verification after rewinding

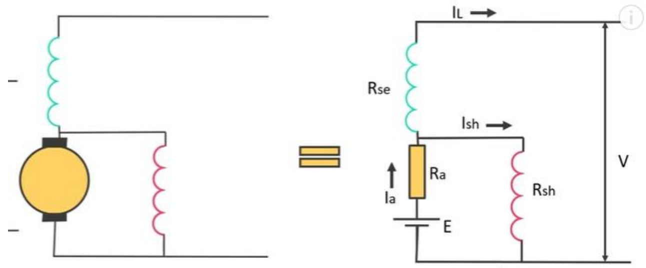


5.

VIII. Shunting of a Generator

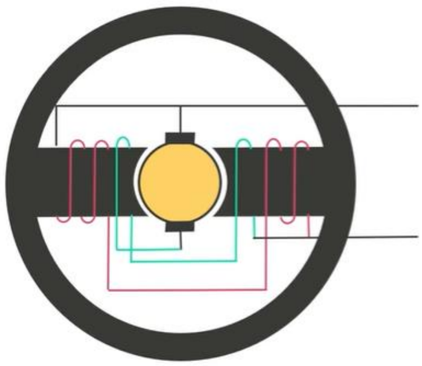
a. Short Shunting

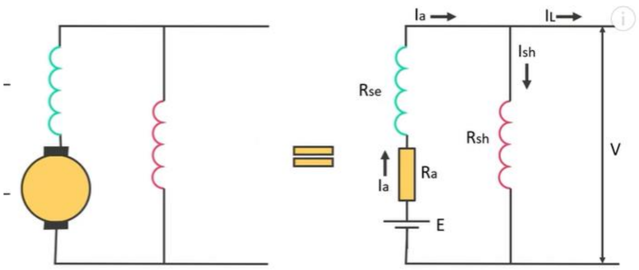




The short shunting involves the shunting across the terminals of the armature rather than the actual shorting of the entire system. We will discuss the necessity of each of the individual type of shunting in the aforementioned pages below.
Here applying KCL in the node just above Ra we get the following equation
Ia=Ish+Il
Now applying kvl in the bigger loop we get the following
V=E-IaRa-IlRse
Now this is also possible:
Vsh=V-IlRse
And Ish=Vsh/Rsh
Now finally E=V+IaRa+IlRse
Analysing this equation gives a certain conclusion that E>V.

b. Long Shunting





On contrast to the short shunting, long shunting shunts the entire section including the Rse resistor.

Here applying KCL in the bottom left node we get the following equation

$$I_{sh}=V_{sh}/R_{sh}$$

Now applying kvl in the bigger loop we get the following

$$I_a=I_{sh}+I_l$$

$$V=E-I_aR_a-I_aR_{se}$$

So the final expression becomes $V=E-I_a(R_a+R_{se})$

$$E=V+I_a(R_a+R_{se})$$

From this equation we can also come to the conclusion that $E>V$

Hence for any case if the generator is shunted $E>V$

Where the machine has a series compounding winding, the field may be connected at the armature side (short shunt) or load side (long shunt). The different connections give different voltage regulation characteristics on load. So as it is connected in shunt it has constant characteristics.

Since the DC shunt generator provides a relatively constant output voltage, they are used to recharge batteries and also used as an excitation source for large alternators.

IX. AC/DC RESPONSE OF A GENERATOR

An AC generator is called an alternator.

Both initially produce AC voltage.

In an alternator, the current reverses it's direction periodically due to which AC current is produced. But we have unidirectional current in DC generator.

In an alternator, the poles are rotating but the armature is constant.

But in DC generator the poles are stationary.

The output in AC generator varies both in amplitude and time, but in case of DC , we obtain a steady output with zero frequency.

Because of such constraints of a DC generator, the range of output power is very less compared to alternator.

We can obtain a DC generator by-

1. An AC generator equipped with a device called a "commutator" can produce direct current
2. Use of a device called a "rectifier" that converts AC to DC

X. STEADY STATE ANALYSIS

Steady-state analysis of a DC generator involves examining the generator's behavior when it has reached a stable operating condition, where the system variables no longer change with time. This analysis is crucial for understanding the generator's performance under constant conditions.

Some of the key aspects of the steady-state analysis for a DC generator:

Voltage Buildup:

In steady state, the generator voltage has reached its final, stable value. This voltage is often referred to as the generated voltage also referred to as Eg.

The generated voltage is influenced by factors such as magnetic field strength (field current), speed of rotation, and the number of turns in the armature coil.

Terminal Voltage:

The terminal voltage V of a DC generator is the voltage available at its output terminals. It is equal to the generated voltage minus the voltage drop due to armature resistance ($I_a \cdot R_a$).

$V=E_g-I_a \cdot R_a$, where Ia is the armature current and Ra is the armature resistance.

Load Characteristics:

The steady-state analysis involves studying the generator's response to different loads.

The load characteristics graphically represent the relationship between terminal voltage and load current at a constant speed and field current.

A typical DC generator has a drooping characteristic, meaning that as the load current increases, the terminal voltage decreases slightly.

Field Excitation Control:

The field current determines the strength of the magnetic field, affecting the generated voltage. Steady-state analysis considers the impact of field current variations on the generator's performance.

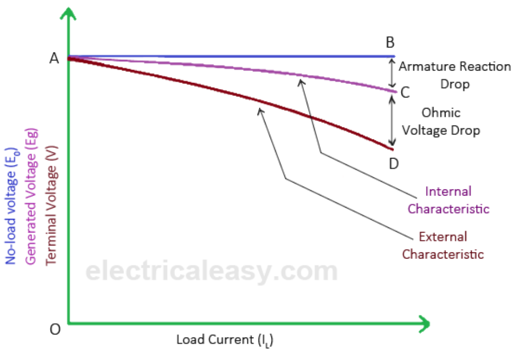
Efficiency:

Steady-state analysis also involves evaluating the efficiency of the generator, which is the ratio of electrical power output to mechanical power input.

The steady state external performance characteristic of a dc generator has the relationship between terminal voltage and load current at constant speed.

External Characteristic (V/IL)

An external characteristic curve shows the relation between terminal voltage (V) and the load current (IL). Terminal voltage V is less than the generated emf Eg due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as **performance characteristic** or **load characteristic**. Characteristics Of Separately Excited DC Generator



Characteristics of separately excited DC generator

If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs. load current IL. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current IL i.e. internal characteristic (as Ia = IL for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Acknowledgment

We thank the professors and the TAs for the consistent help provided all along. We also appreciate the suggestions from many resources online.

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