Part 2 :DC Machines

2.1: What is Electrical Machine

- The machines is composed by Motors and Generators.(The word machine is commonly used for both generator and motor)
- The motors change Electrical power input $(v, i)$to Mechanical output(τ, ω).
- The generators change Mechanical power (τ, ω) to Electrical power output(v, i).
- The energy conservation can be written as : $vi = \tau\omega$
- The DC machine have several application :Washing machine, drill,automotive machines and medical surgery devices.

2.2: DC motors vs induction motors(AC)

- DC motors have more rated torque at low speed than AC motors.(High starting torque)
- Induction motors have much higher torque at high speed.
- DC motor advantages and disadvantages:
  - The Advantages:
    - High starting torque
    - Rapidly acceleration and deceleration
    - Speed can be easily controlled over a wide range.
    - Used in tough jobs.
    - Build in wide range of sizes
  - The disadvantages:
    - Need regular maintenance

  - Can not be employed in explosive (sparking) applications
  - High cost due to the complexity of armature construction

2.3: Principle of operation

2.3.1 Magnetic fields of current

- Use the right hand rules to get the direction of current caused by the magnetic fields and vice versa. (The direction and the strength of the magnetic field is a function of the current.)
- The Biot-Savart Law and the Ampere's Law can declare that function.
- Motor action
  - A conductor in a fixed magnetic field.
  - The conductor with current will produce another magnetic field(induced magnetic field).
  - The interaction between the two magnetic fields generate the force.
  - The left hand rules can get the direction of the force.(Field $\times$ current= Force)
  - Generated force: $F = Bil$
  - The same conductor with same current ,but the direction of the current are different at both sides.
  - The force exerted upon the each conductor:$F = B \times i \times l$
  - The torque is given:$\tau = F \times r = Bilr$
  - Torque of 1 turn(coil): $T = 2Bilr$
- Motor action: practical arrangement
  - For N series turns: $T = 2NBilr$
  - In a 2-pole machine, the flux per pole is $\phi = B \times \pi rl$

- The total torque for a 2 poles machine (N series turns) is: $T = 2NBilr$
- In a 2-pole machine, the flux per pole : $\phi = B \times \pi rl$
- The total torque for 2-pole machine as: $T = \dfrac{2N\phi i}{\pi}$
- We can rewrite as: $T = K_t\phi i_a$, K_t is the constant of the machine, i_a is the armature current.

- Generator action: operating principle
  - $e = 2Blv = 2Bl\omega r$
  - $T = 2Bilr$
  - $i = \dfrac{T}{2Blr}$
  - $ei = \dfrac{2Bl\omega rT}{2Blr} = \omega T$
  - i.e:power in= power out

2.3.2 Initial Points of DC machine

- Current through a conductor produce a magnetic field(circular).
- Current in a conductor will suffered a force (Ampere force) in a magnetic field.
- Mechanical output in form of controllable torque and speed.
- Torque is maximized by using multiple conductors and stronger flux(using core).

2.3.4 Continuous rotation

- How to archive a continuous rotation:
  - How to connect the DC supply to a rotation armature: The brushes (Carbon) are connected to the armatures.

- The opposite force applied on both sides cause the conductor to rotating.
- When it comes to the vertical position, the inertia will keep it moving to another horizontal position.

2.4 Machine Construction

- Basic parts of the DC machine:
  - The armature (rotating part)
    - The major power carrying element- situated on the armature.
    - Laminated core (reduce eddy current) and winding in slots, which given :
      - mechanical strength
      - shorter effective air-gap length
      - maximizing field flux
  - The commutators:
    - The set of coppers segments arranged as a cylinder
    - End of each coil attached to adjacent commutator segments.

    - The brushes:carbon
    - The field circuit
        - Wound fields and Permanent Magnet field circuits.
        - Wound type:
            - The magnetic filed is generated by electricity.
            - Field can be controlled(magnitude and direction)
            - More losses
        - Permanent Magnet:
            - Generated by magnetic materials.
            - Smaller and less losses.
            - Less controllability.

2.5 Machine Configuration (types)

- Separately excited:
    - The armature and fields windings are electrically separate.
    - The field winding is supplied by a separate DC source whose voltage is variable.
    - Good Speed control.
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        -
    -
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- Self-excited:
    - shunt:
        - Armature and field windings connected in parallel across the same DC supply.
        - Constant speed characteristic.
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            -
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            -
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            -
    - Series:
        - Specially constructed motor wit field winding in series with armature.
        - Field winding only as a few turns as it take the full load current.
        - High starting torque.

- Compound
- Permanent Magnet:
  - Advantage:
    - Low cost
    - Simple operation
    - No copper losses
  - Disadvantage:
    - Less controllability
    - Strong potential source of electromagnetic interference.

2.6 The equivalent circuit of DC machine

2.6.1 Separately excited DC motor

- The armature voltage is given by: $v_a = L_a \frac{di_a}{dt} + i_a R_a + e_b$.
- The field voltage is given by: $v_f = L_f \frac{di_f}{dt} + i_f R_f$
- The steady-state armature voltage is given by: $V_a = I_a R_a + E_b$.
- The steady-state filed voltage is given by: $V_f = I_f R_f$.

- The developed torque is given by $T_d = K_t \phi I_a = B\omega + T_L$, (B is friction coefficient)
- The developed power is : $P_d = T_d \omega$.

2.6.2 DC Machine Model

$\leftarrow V_a, I_a \rightarrow K_t, \phi, E_b \leftarrow T_d, \omega \rightarrow$

2.7 Open circuit of DC machines

- Equivalent circuit:the field circuit:
  - When the magnetic filed is supplied by magnets the flux will be fixed.
  - When the field is provided by a coil(wound machine), the field flux varies withe current: $I_f \propto \phi$.
  - Consequently, we can write: $T_d = K_t I_f I_a, E_b = K_t I_f \omega$
- Equivalent circuit: open circuit test
  - Run the machine on no load.
  - Measure the armature voltage variation with field current.
  - $V_a \approx K_t \phi \omega (I_f \propto \phi, I_a R_a = 0)$.
  - $E_b = V_a$

2.8 Motor vs. generator

- Generator action: operating principle
  - $e = 2Blv = 2Bl\omega r$
  - $T = 2Bilr$
  - $i = \frac{T}{2Blr}$
  - $ei = \frac{2Bl\omega rT}{2Blr} = \omega T$
- Motoring and generating

2.9 Speed control of a DC motor

2.9.1 Speed control

- As for Separately excited dc motor.
- $V_a = I_a R_a + K_t \phi \omega$, $E_b = K_t \phi \omega$
- Three parameters control the speed: V_a, R_a, ϕ

2.9.2 Armature voltage control

- $\omega = \dfrac{V_a}{K_t \phi} - \dfrac{R_a}{(K_t \phi)^2} T_d$

2.9.2 Armature resistance control

- $\omega = \dfrac{V_a}{K_t \phi} - \dfrac{R_a}{(K_t \phi)^2} T_d$

2.9.3 Field control

2.9.4 Field weakening

- Base speed ω_{base}= speed at rate V_a, I_f, I_a.
- $\omega = 0 to \omega_{base} \rightarrow$ speed control by V_a.
- $\omega > \omega_{base} \rightarrow$ speed control by field weakening.

2.10 Losses & power flow in DC machine

2.10.1 Losses

- Electrical loss

- Brush loss
- Core loss
- Mechanical loss
- Stray loss

2.10.2 Power flow (shunt motor)

2.10.3 Power flow (shunt generator)

2.10.4 Efficiency of DC motor

- $\eta = \dfrac{P_{out}}{P_{in}}$
- $\eta = \dfrac{P_{in} - P_{loss}}{P_{in}}$
- $\eta = 1 - \dfrac{\Sigma I^2 R - Rotational \quad losses}{V_T I_T}$
- $\eta = \dfrac{E_b I_a - Rotational \quad Losses}{V_T I_T}$