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Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Theory of Electric Machines 2

KEV/TS2

Karel Hruška / r20201122

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- They are “Direct Current” by the name only – in all cases they are work with alternating current :-)
- The commonly used amount of phases may be arbitrary, the most common are two or three phase versions

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  - 3 phases: - star (less used)
    - delta (advantageous; the current flows through all phases in any moment)

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- The rotor position is detected by Hall sensor (sensors)

  => it is not possible to use “higher” physical principles (reluctance torque etc.)

  => almost in all cases they feature surface mounted permanent magnets

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- Direct switching of winding phases to the DC power source generated significant torque pulsations

  => it is not possible for driving loads with low moment of inertia and torque-pulsation sensitive loads

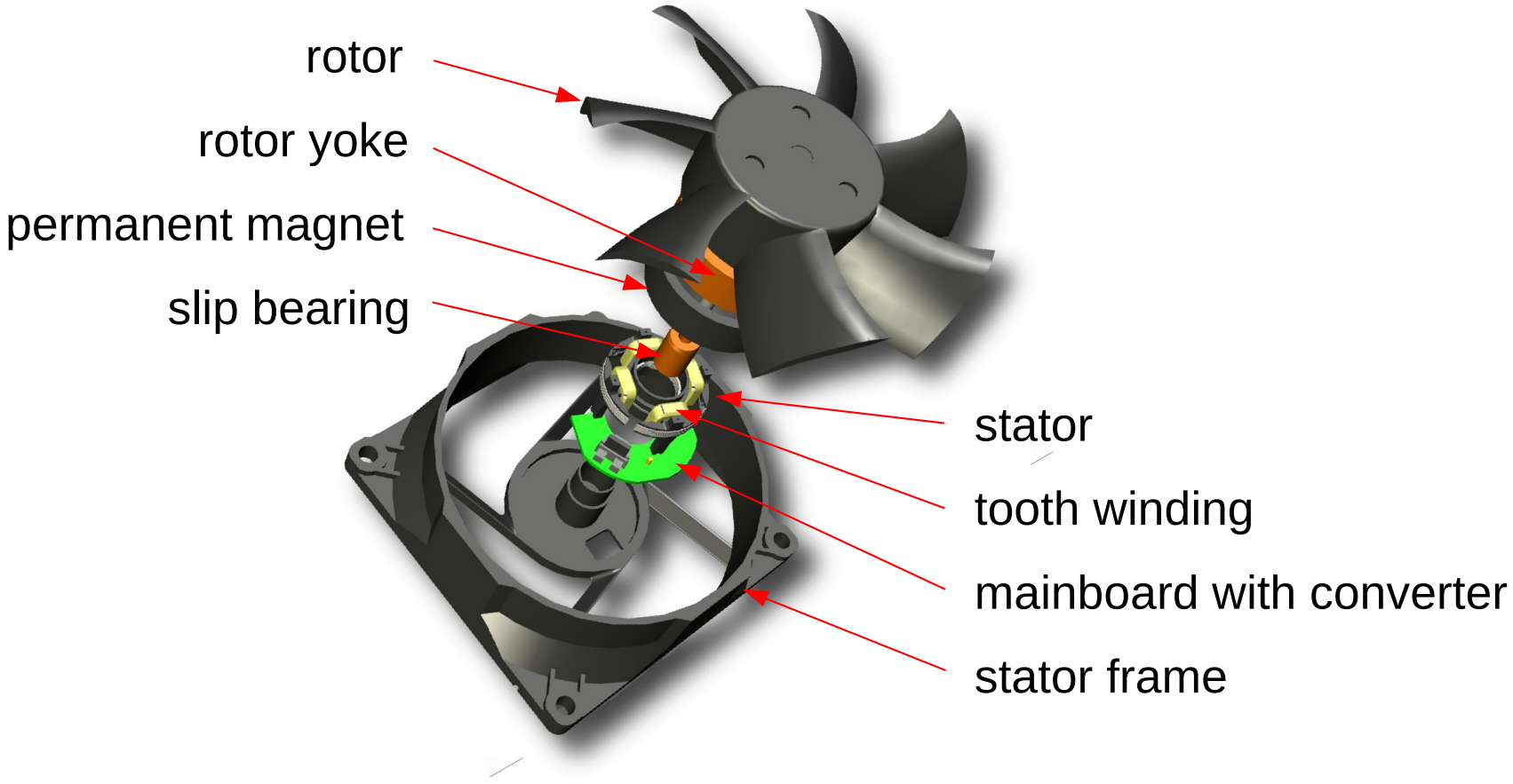
Brushless Direct Current Machines

- Direct switching of winding phases to the DC power source generated significant torque pulsations
  => it is not possible for driving loads with low moment of inertia and torque-pulsation sensitive loads
- The frequency and the magnitude of torque pulsations are proportional to the pole pitch of the machine
  => effort to make possibly highest amount of poles
  => leads to usage of almost exclusive usage of tooth windings

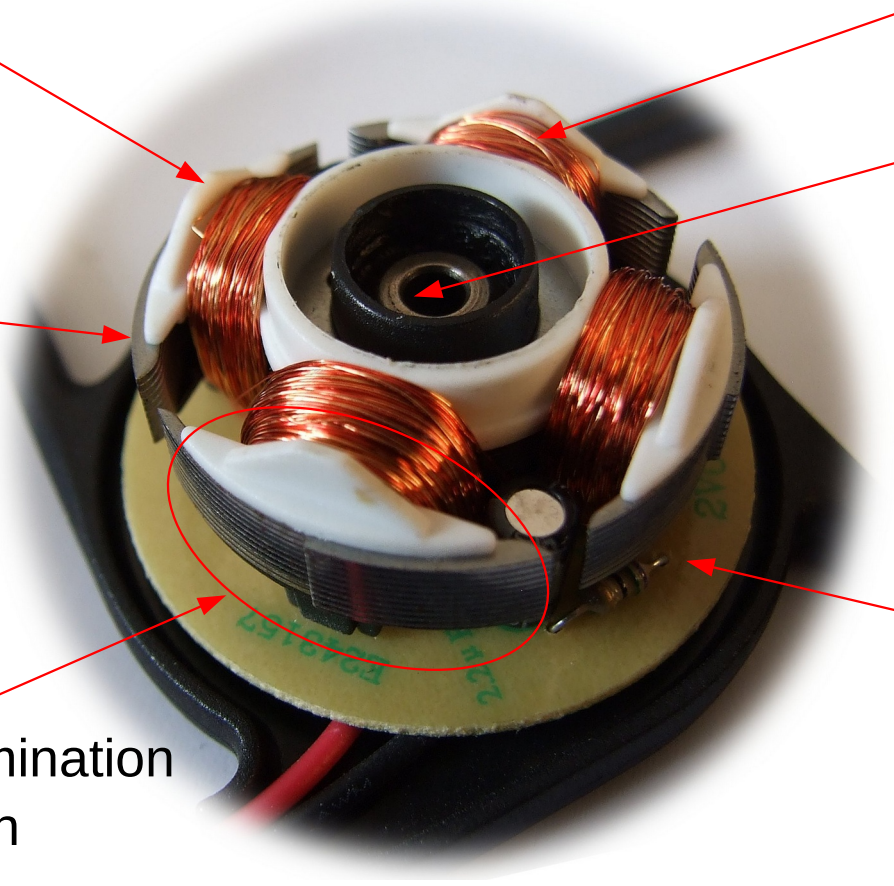
Brushless Direct Current Machines

- Fields of usage:
  - Fans (PC fas, electric paragliding)
  - PC drives motor (ODD, HDD)
  - Pumps, washing machines (LG), models of vehicles, etc...

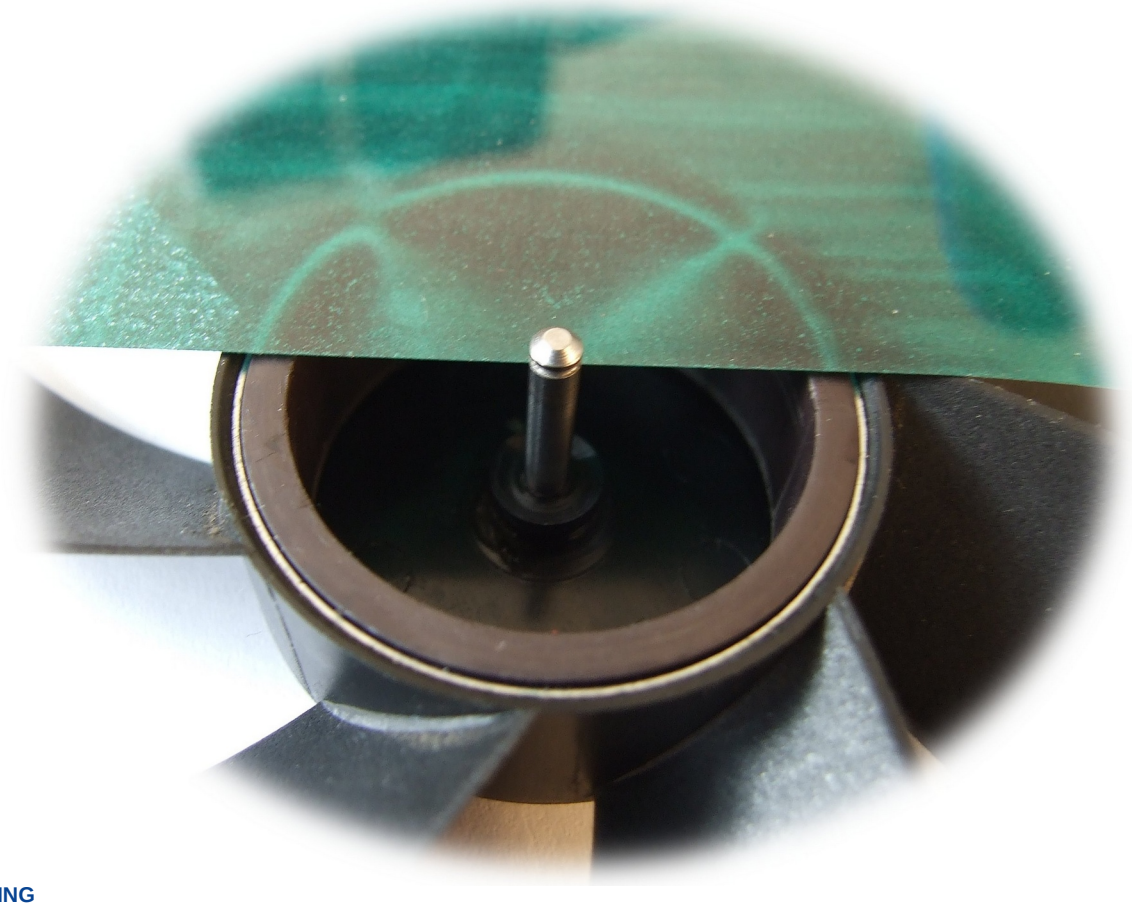
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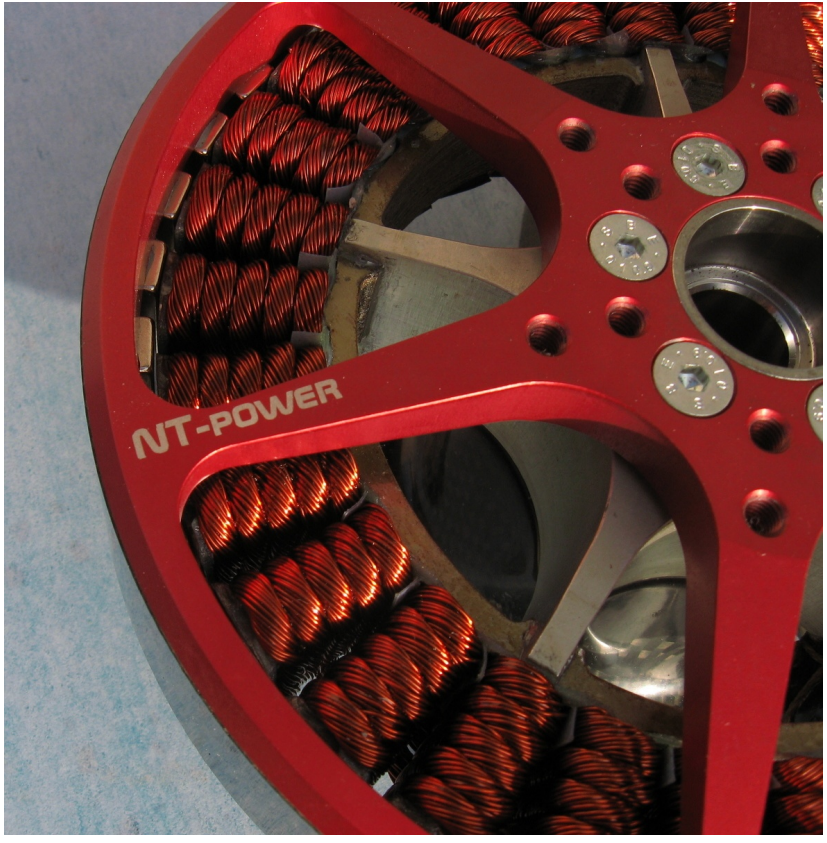
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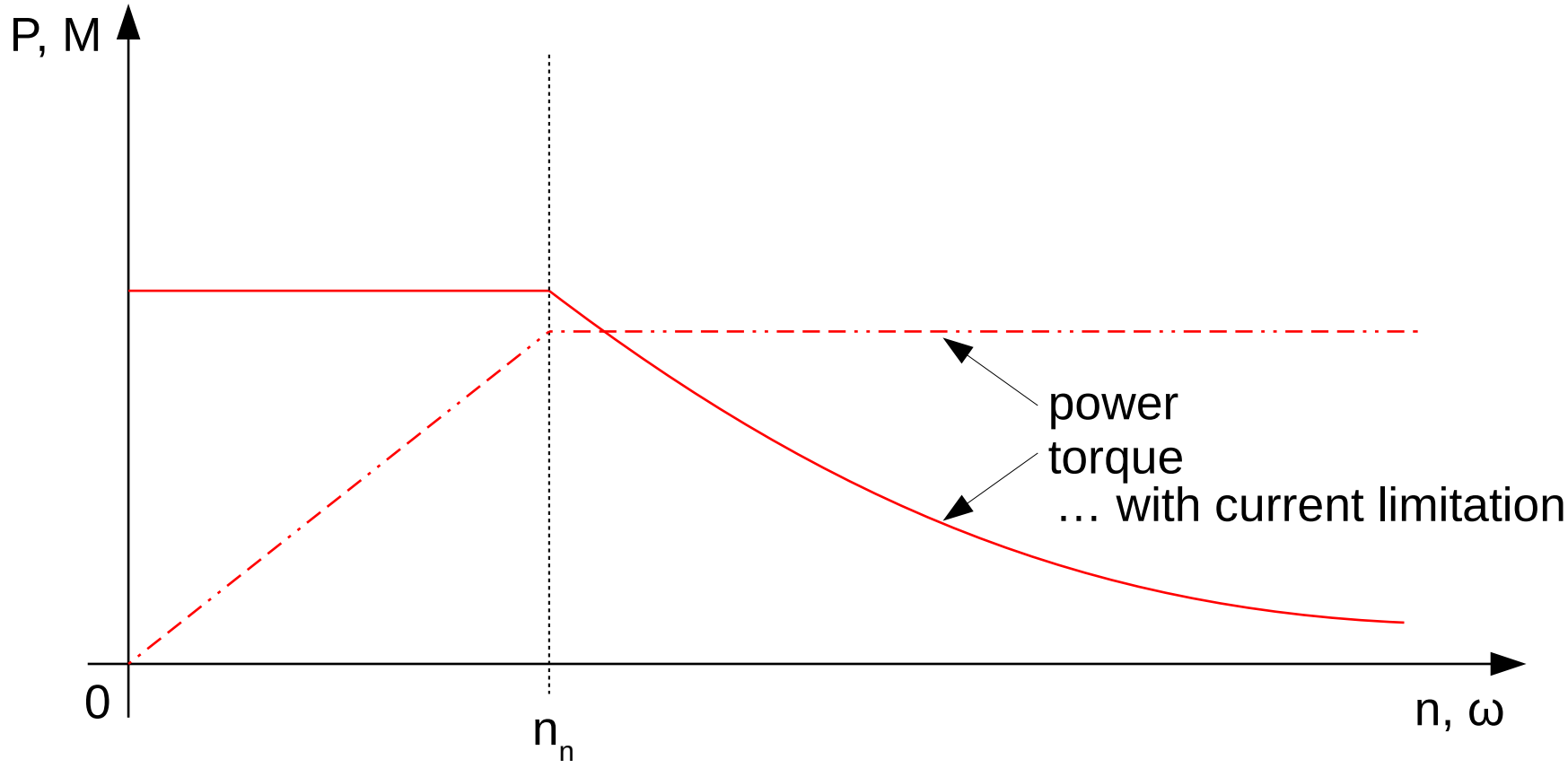
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  - A real flux-weakening would require advanced control algorithms with possibility of shifting of the switching angle

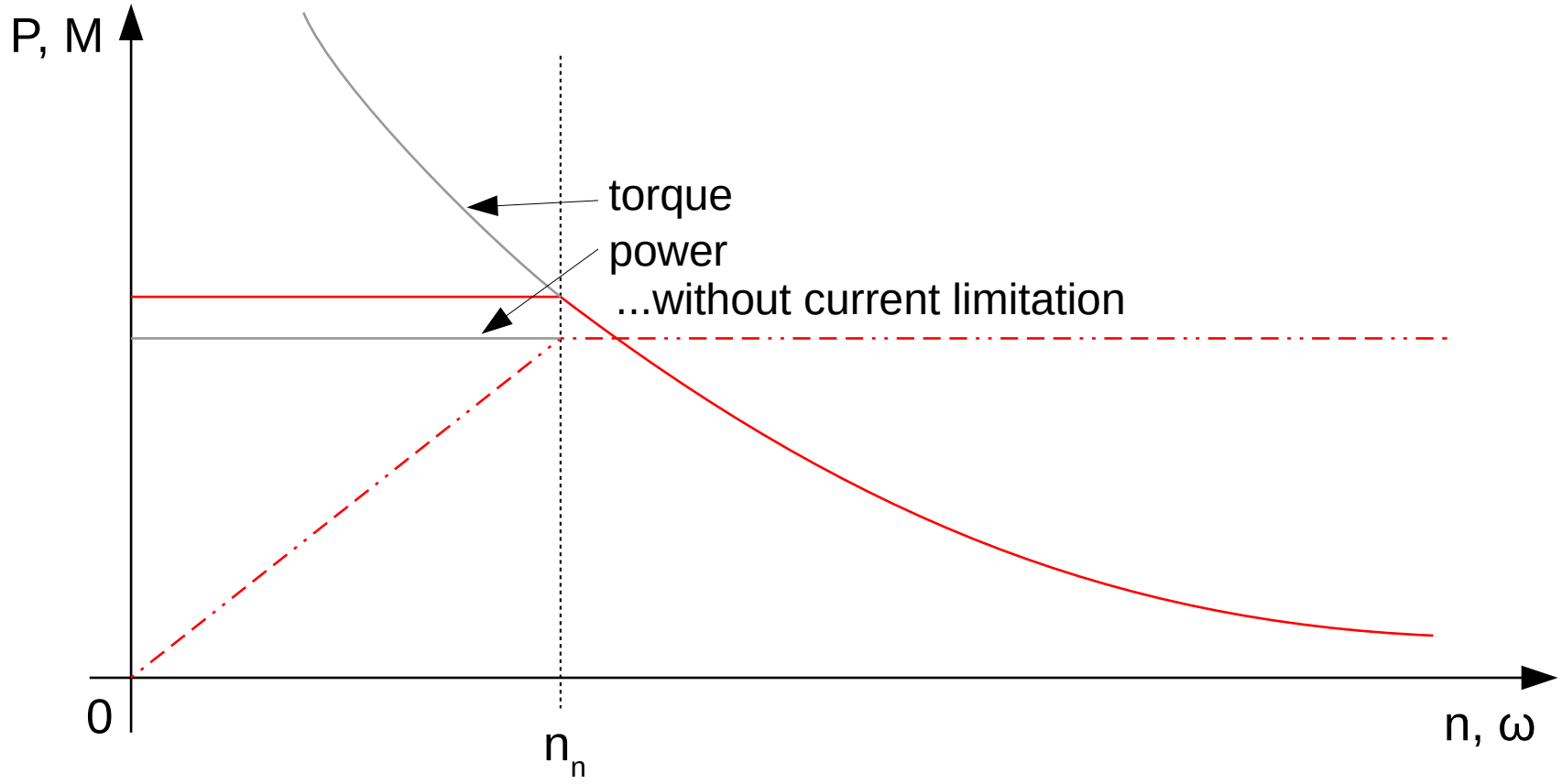
Properties and Characteristics of Brushless Direct Current Machines

- In case of simplest control they act similarly to traditional direct current machines with permanent magnet excitation:
  - In lo-load state they rotate at no-load speed
  - With increasing load they slow down
  - The rated point is given by balance between induced voltage (~speed) and torque of the machine (~current)

Properties and Characteristics of Brushless Direct Current Machines



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  - DC machines:
    - Average values of variables are considered
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    - No phases, currents and voltages have constant values
  - AC machines:
    - RMS values of electrical values are considered
    - Presumed harmonic time-dependencies
    - Equivalent circuit is solved using symbolic complex method
    - Both resistances and inductances are considered

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    => it is not possible to use similar design approach as in case of DC machines

    => it is necessary to analyse the work of CLDC machine and modify the design approach for AC machine

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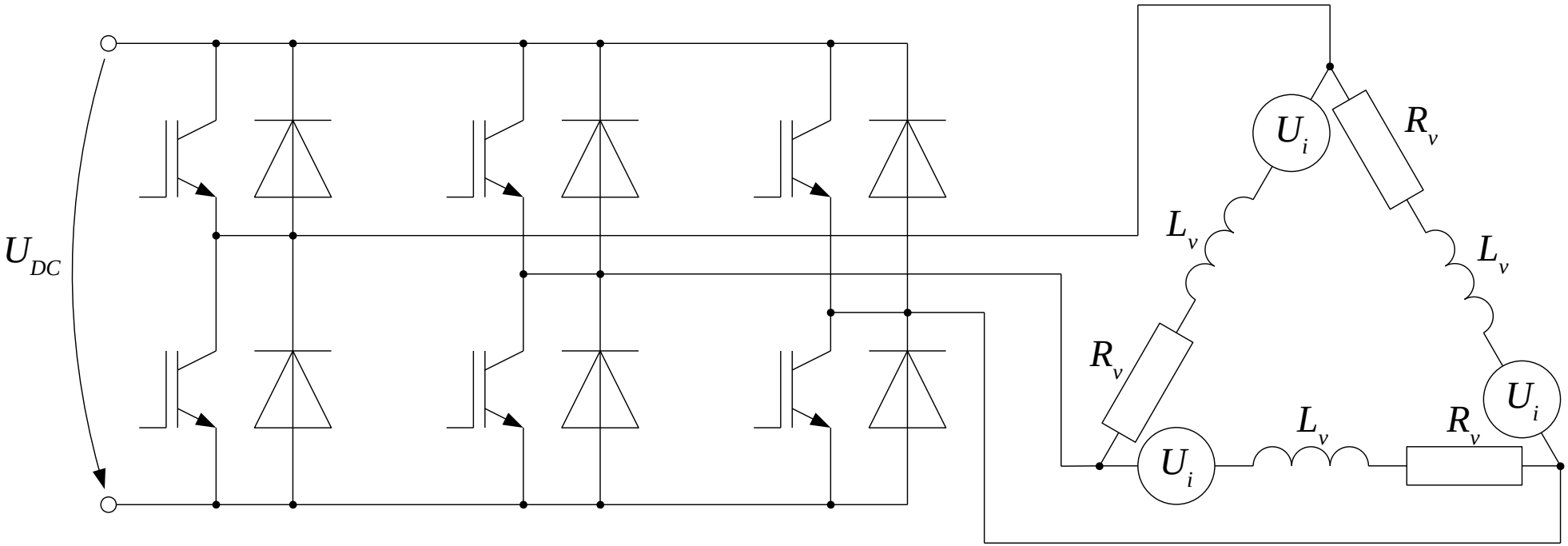
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- For further progress let us presume:
  - Simple control switching each winding phase in identical moment
  - Usage of all harmonic components for generation of the torque
- And let us neglect:
  - Phase shift of the induced voltag of the machine
  - Winding inductance
  - Switching components voltage drop and deadtimes

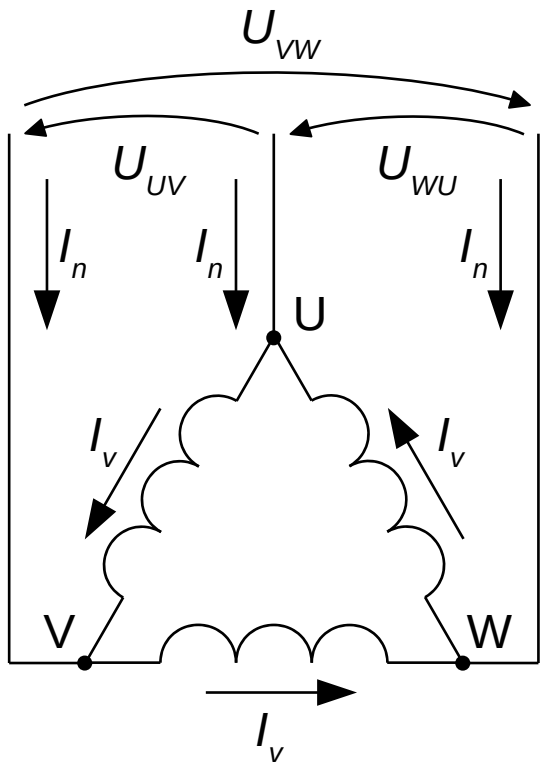
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- Each phase is connected to U_{DC} directly
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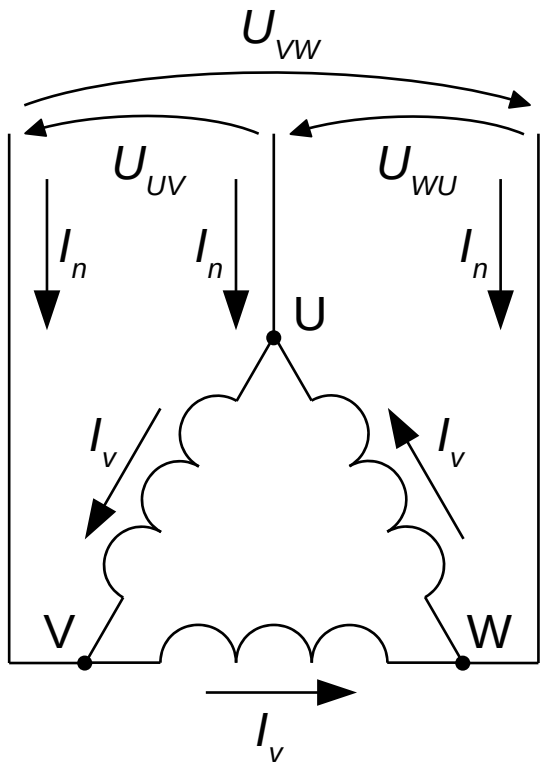


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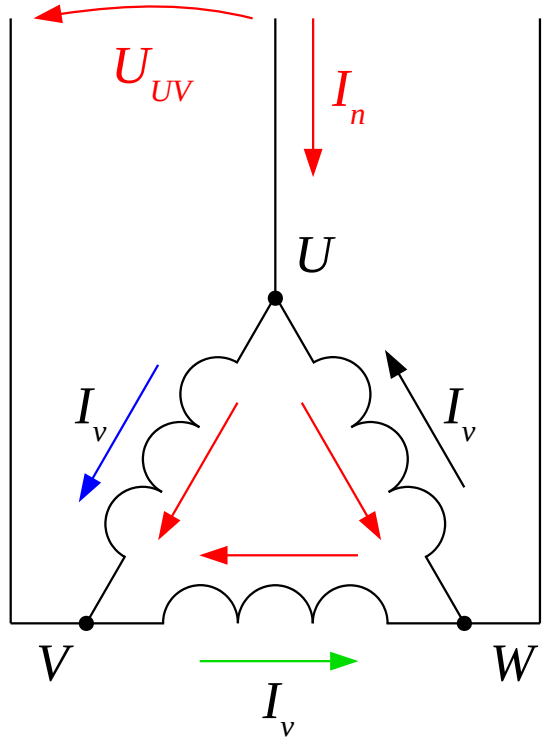
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- For the purpose of machine design it is necessary to analyse:
    1) Current curve and its RMS value
    2) Voltage curve and its RMS value



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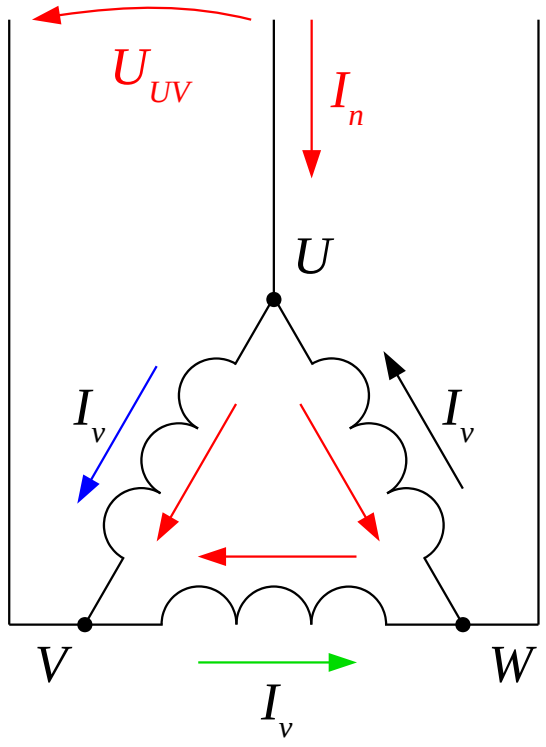
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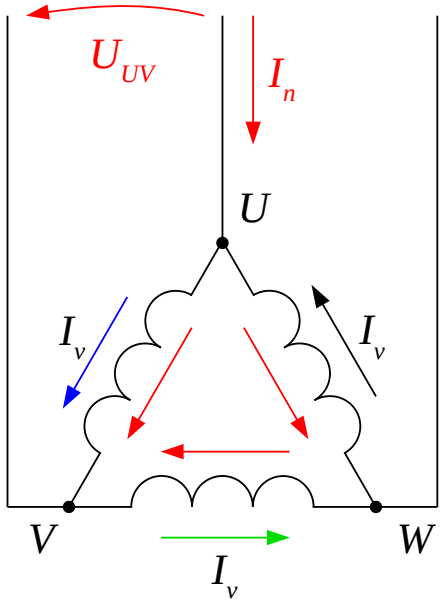
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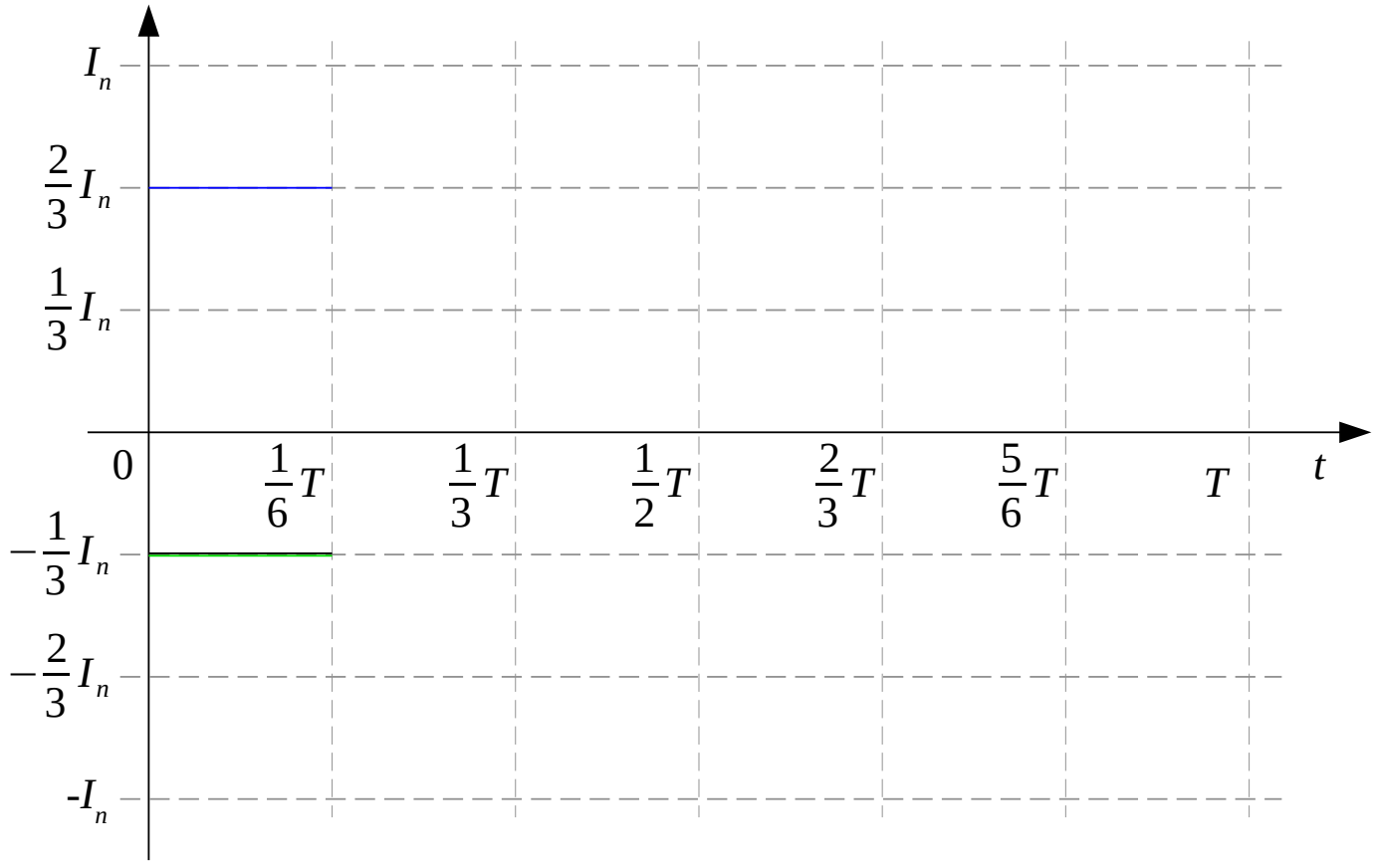
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    => The current I_n divides into 2/3 of I_n going
    through winding UV and a 1/3 of I_n going
    through phases VW a WU (in negative direction)

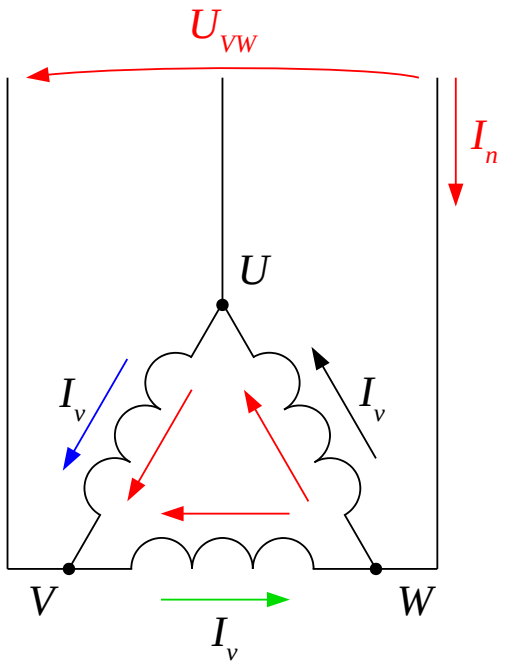


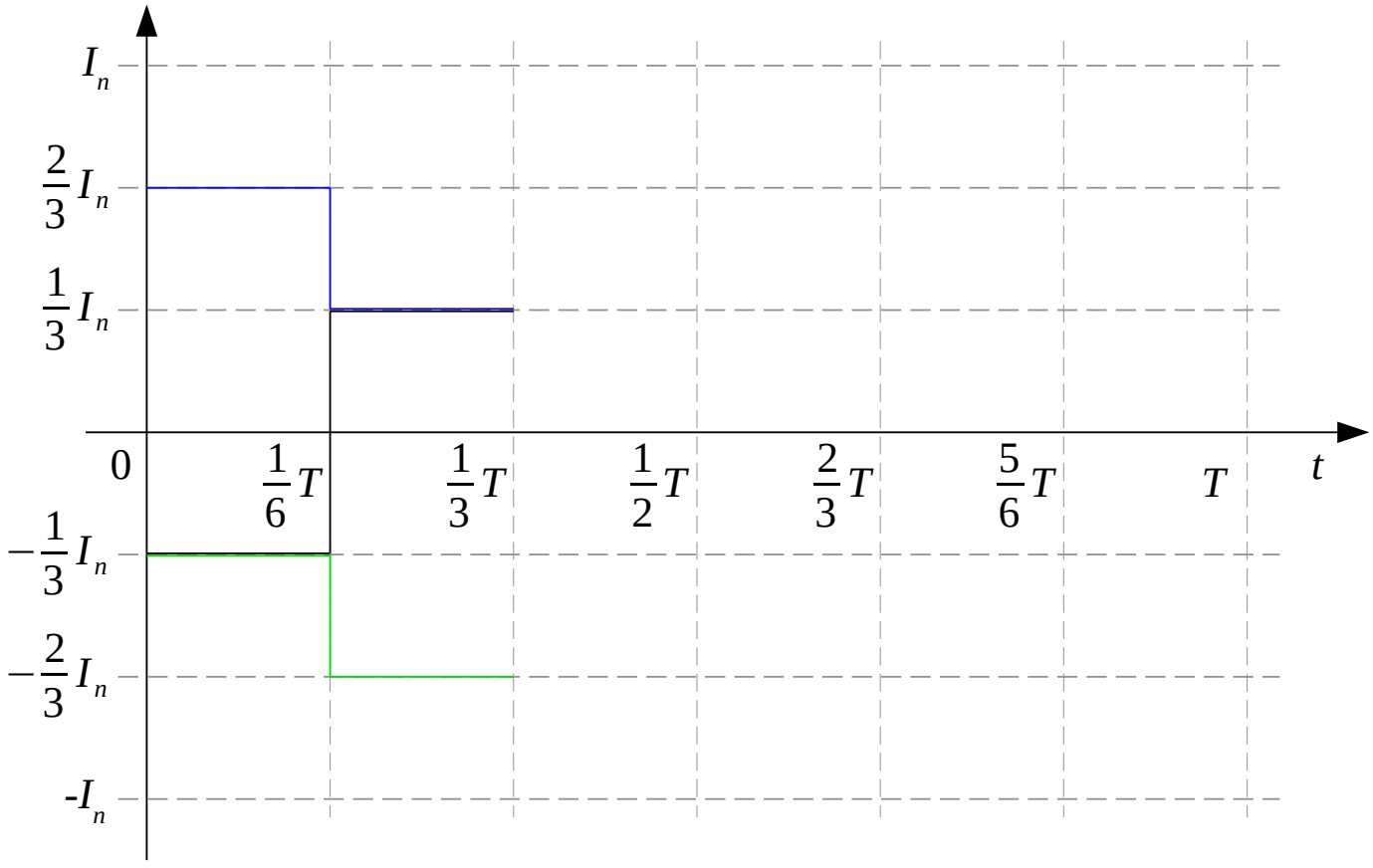
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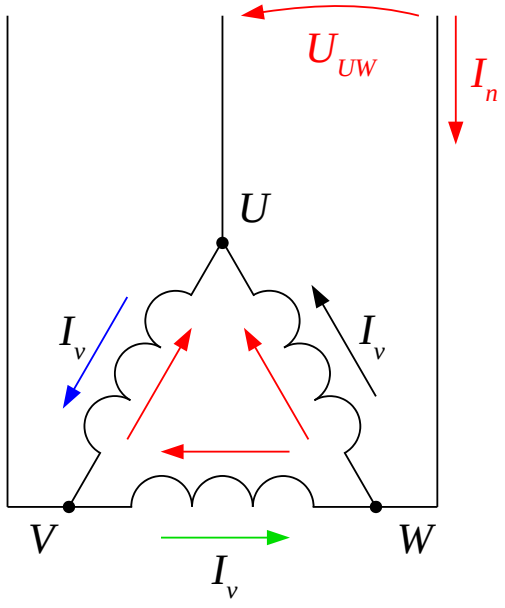


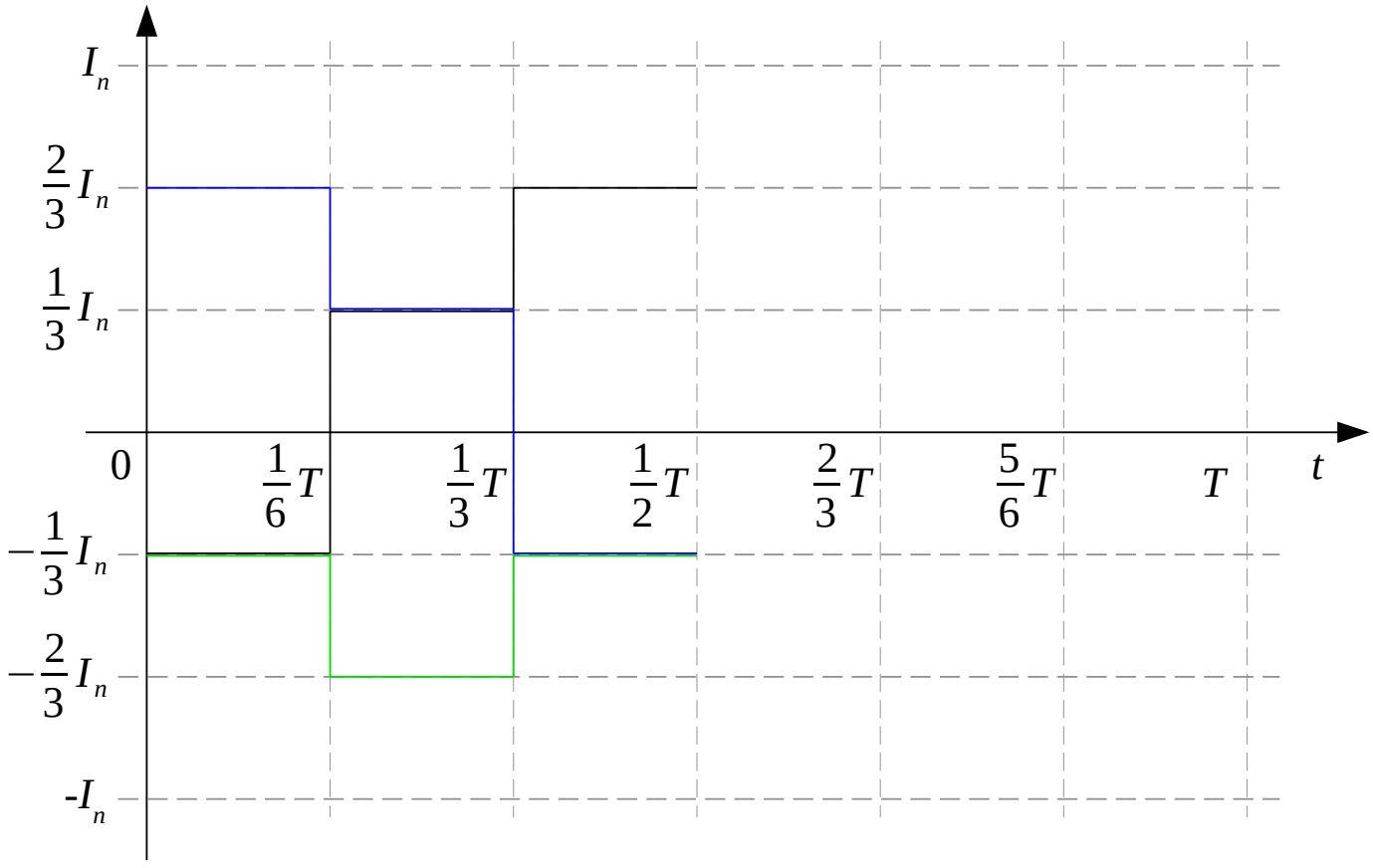
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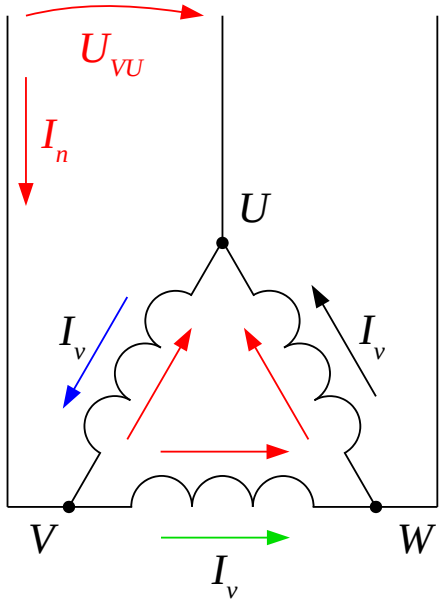


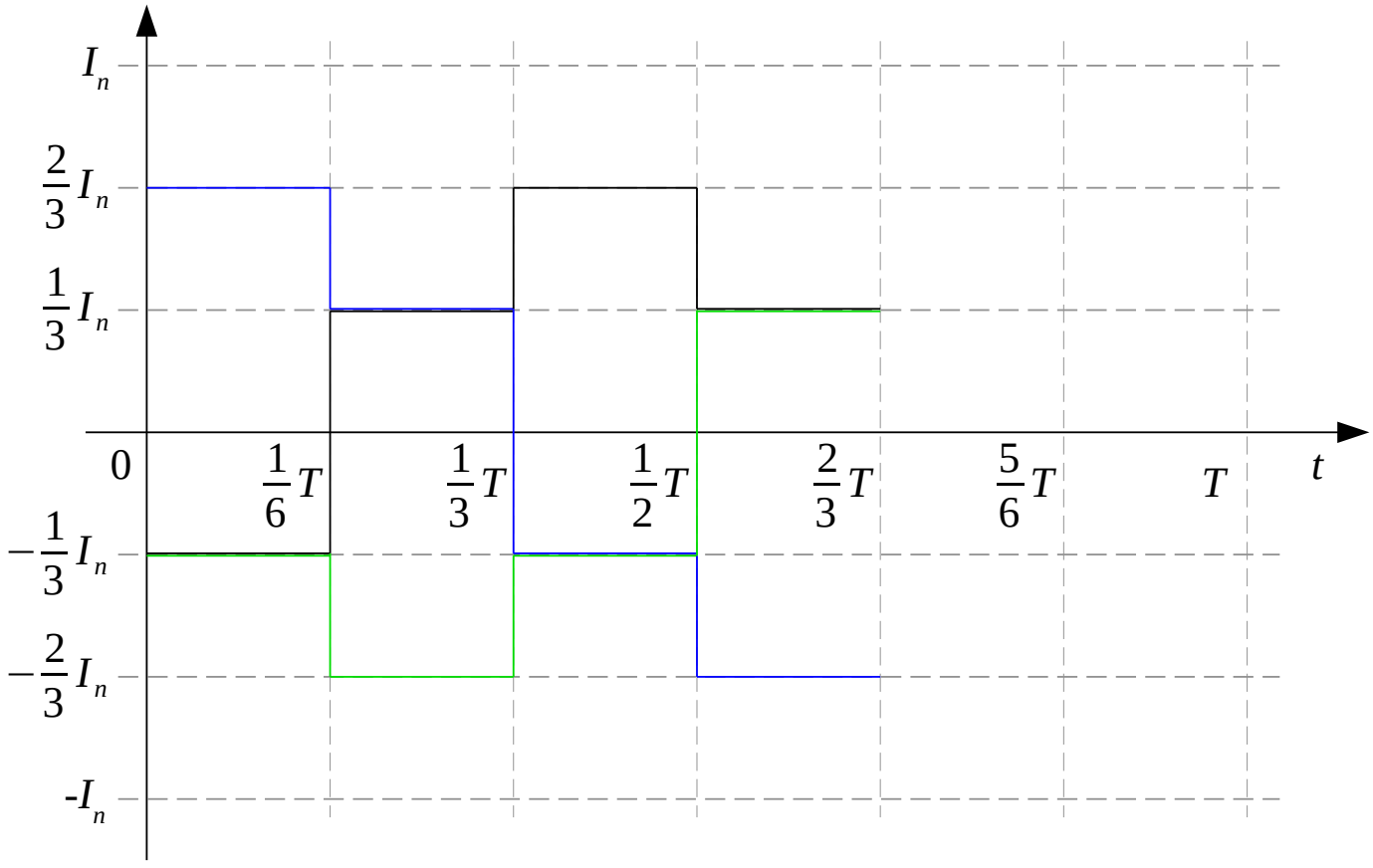
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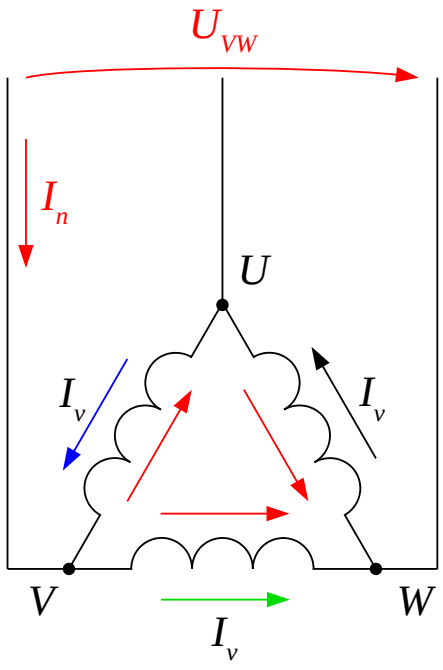


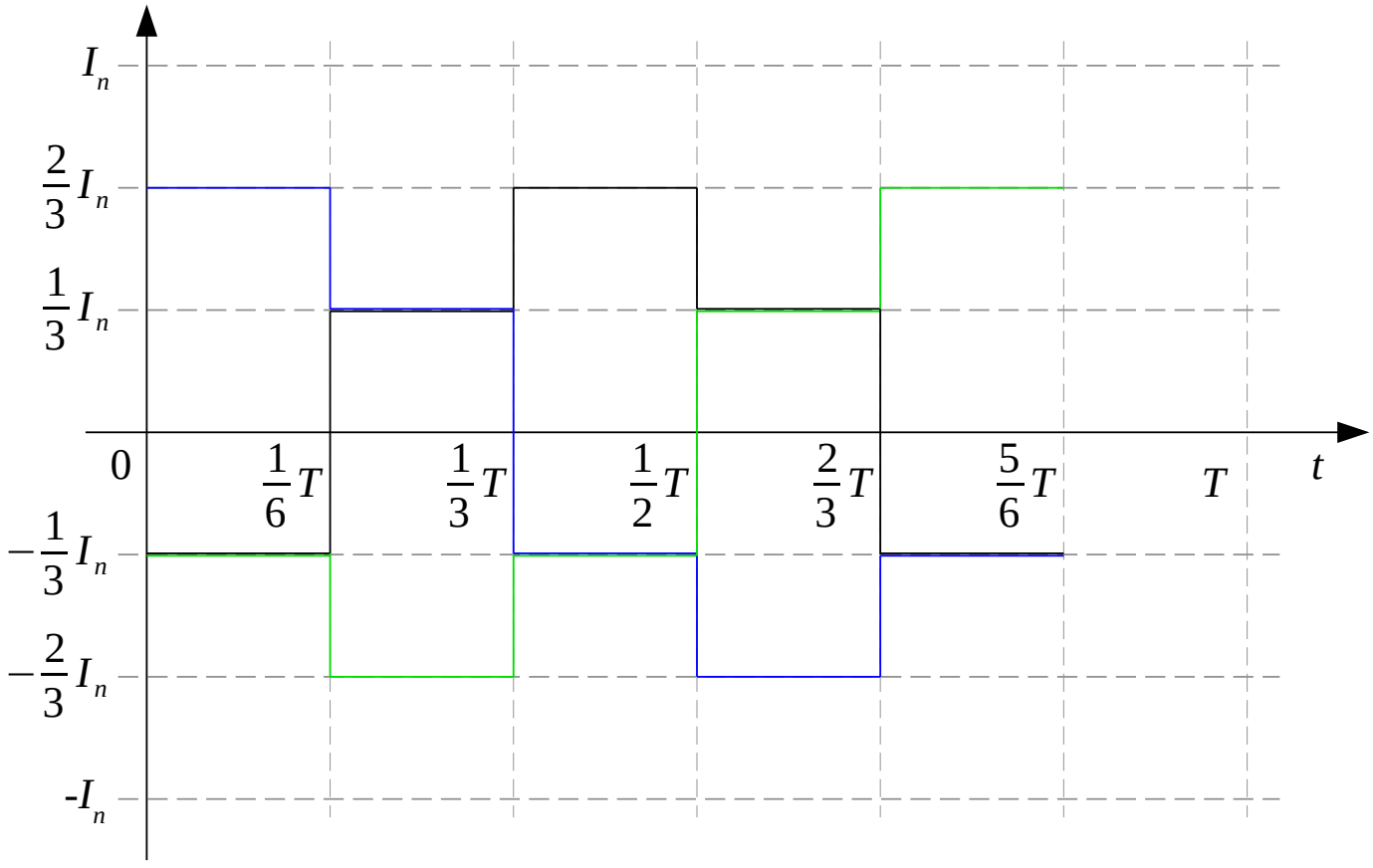
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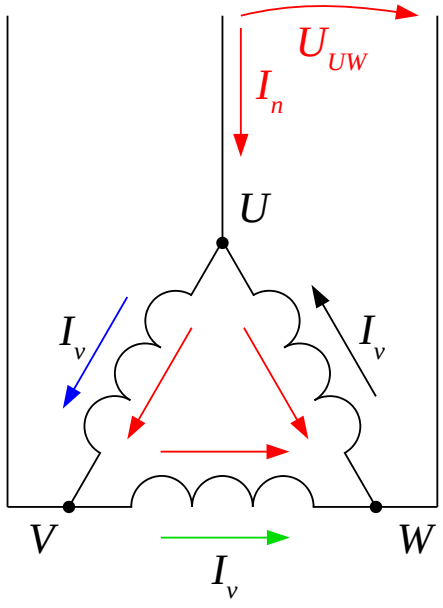


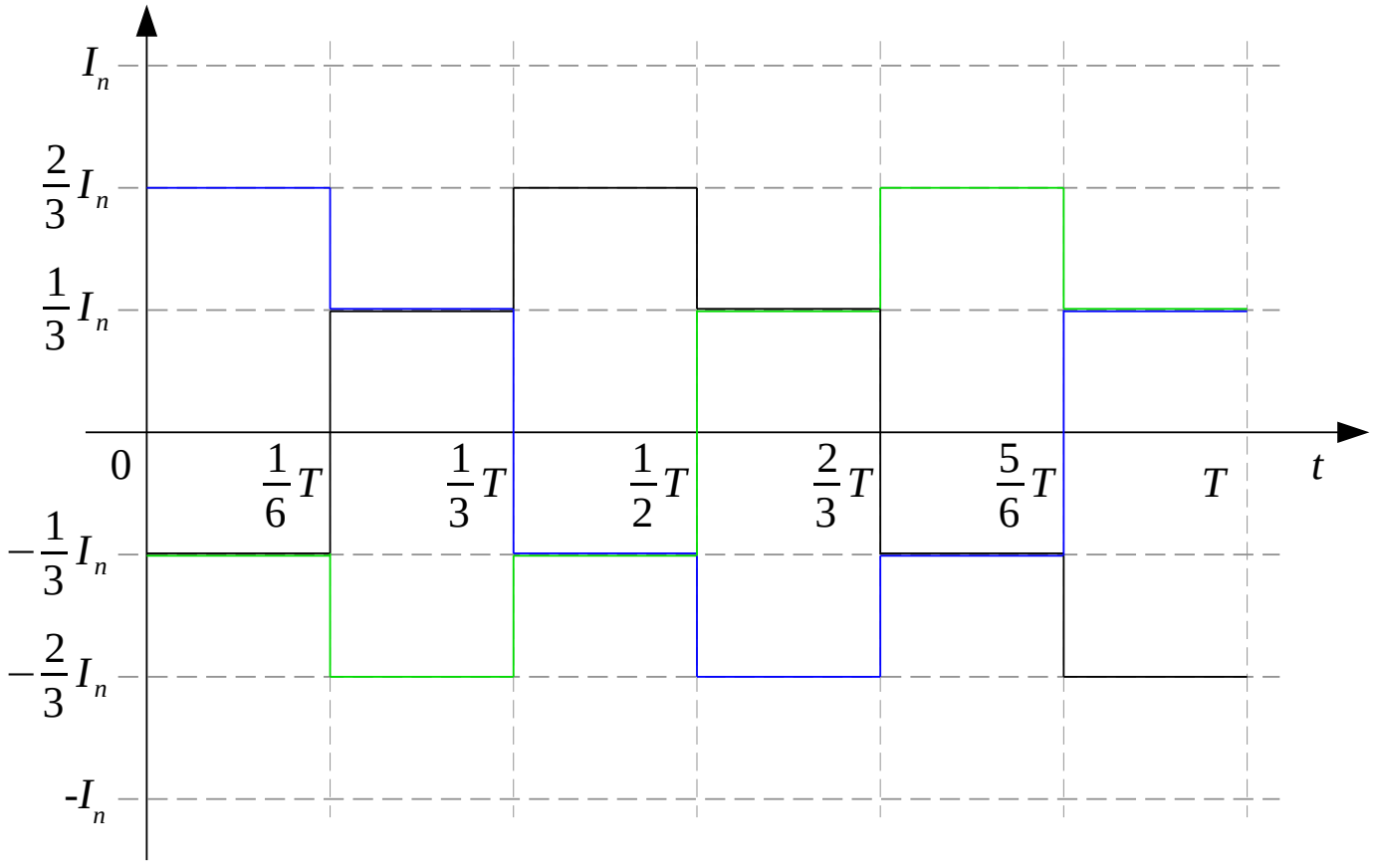
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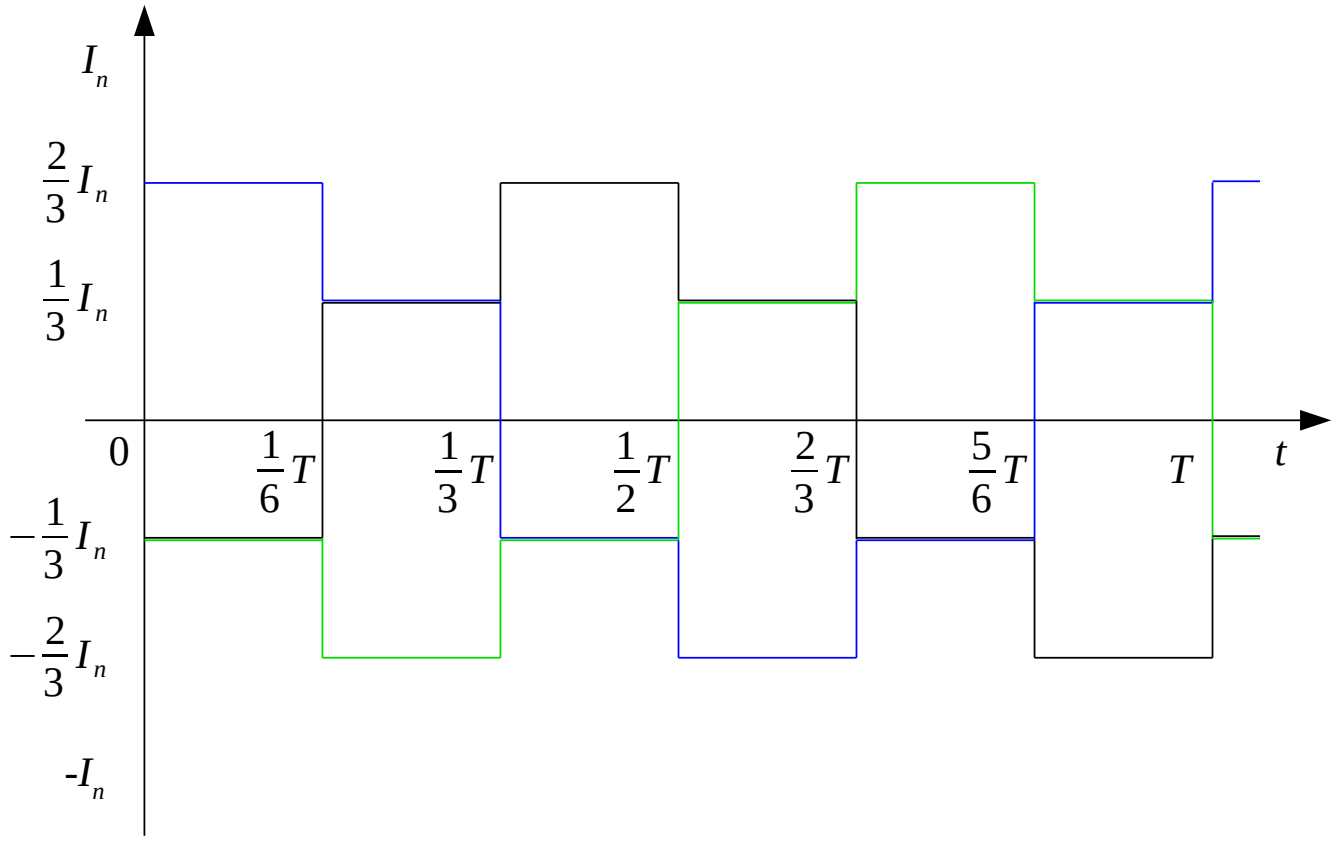


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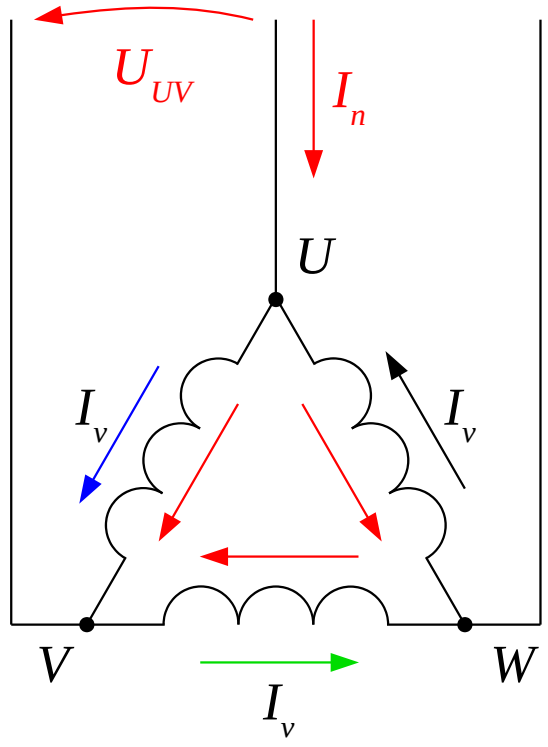


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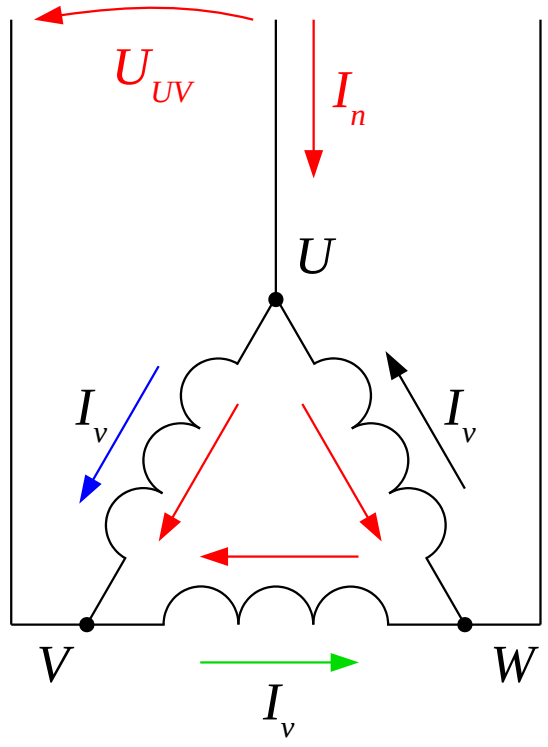
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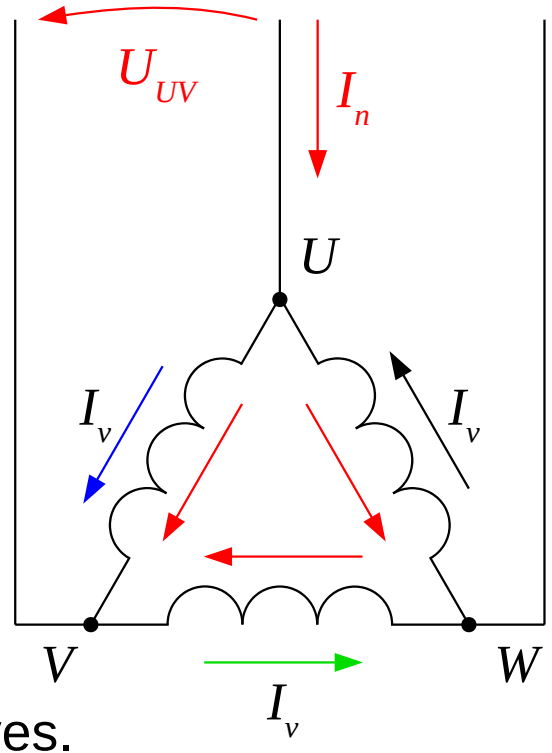


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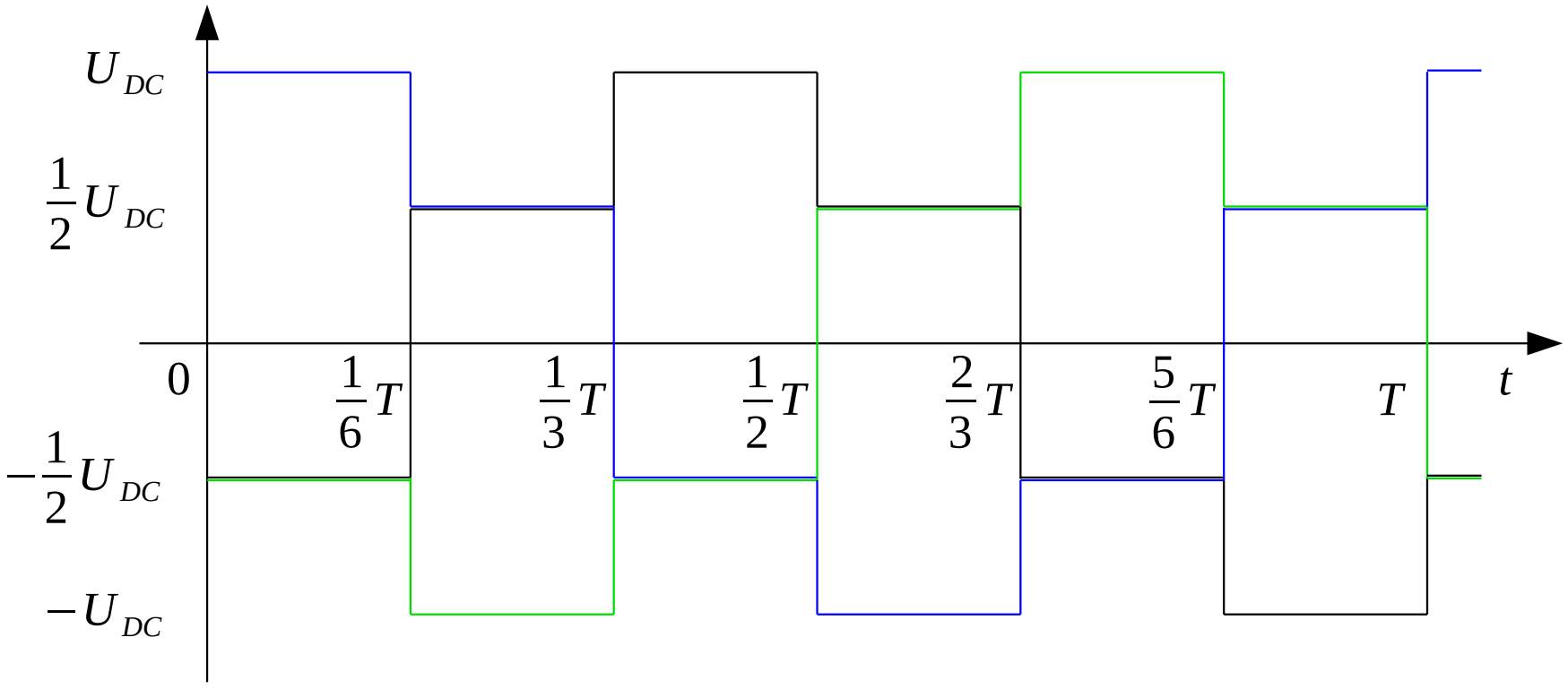
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    => The winding UV will have a full U_{DC} voltage, while on phases VW and WU it will divide to halves.



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- The RMS value is from definition:

$$I_v = \sqrt{\frac{1}{T}\int_0^T i(t)\,dt}$$

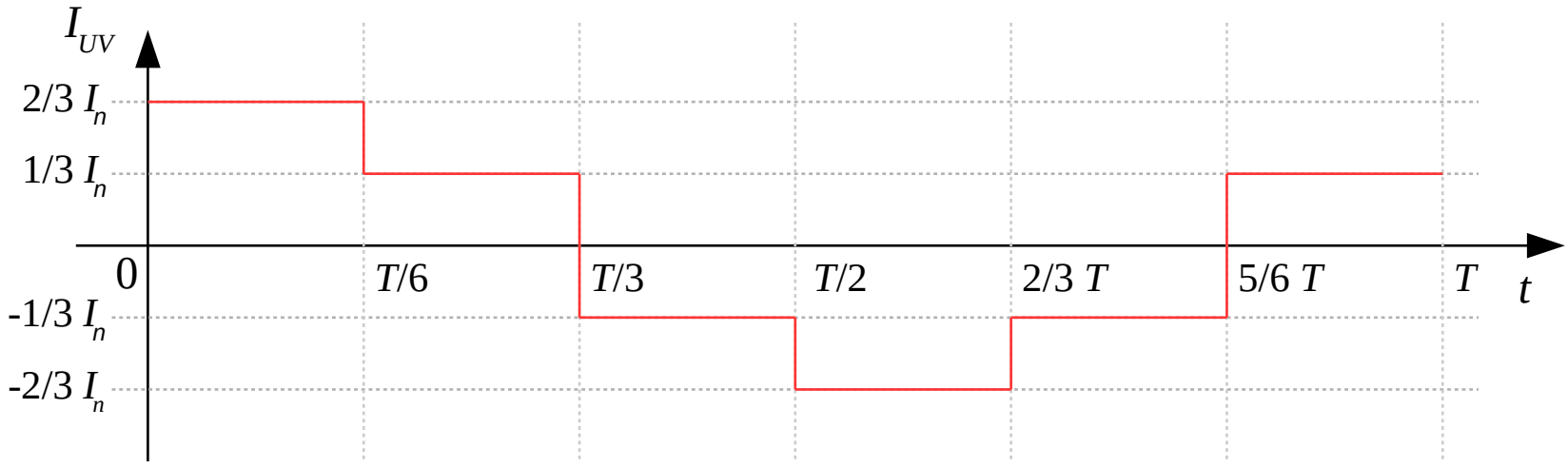
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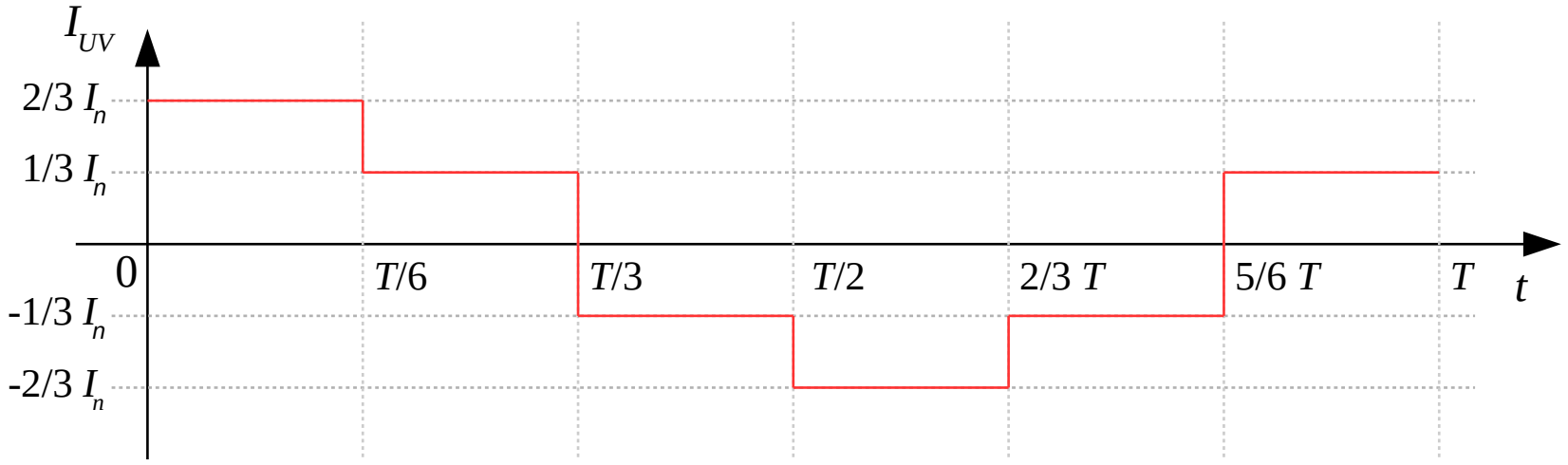
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- In this case it is necessary to divide the integral to six separate intervals for each value of the current
- Each interval will have different integration limits

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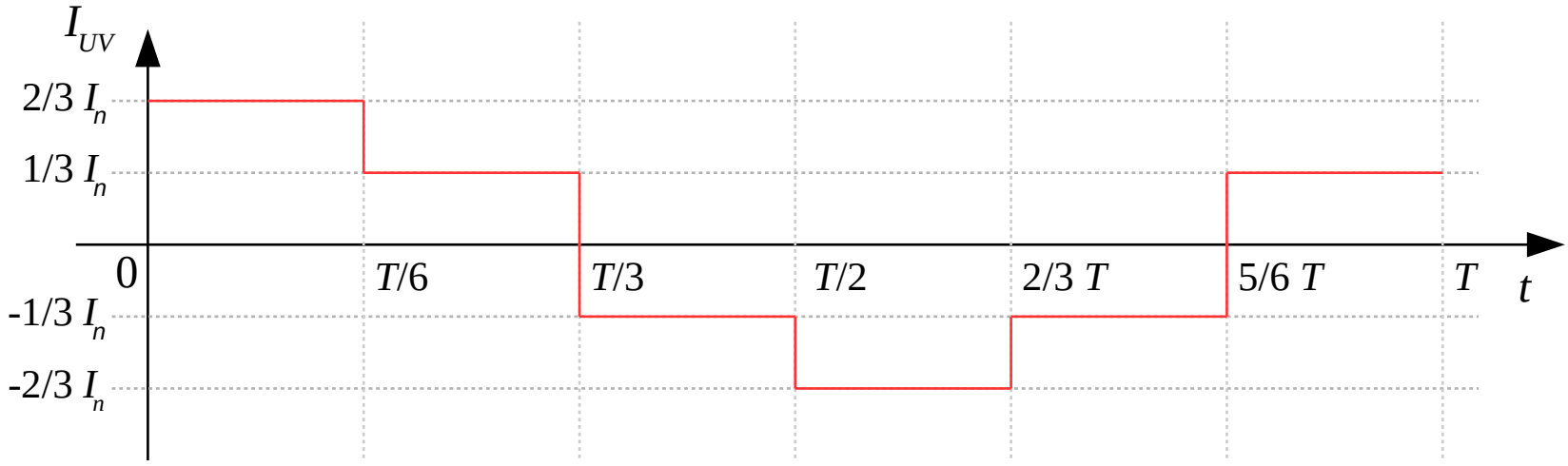


Analysis of the Work of Brushless Direct Current Machines



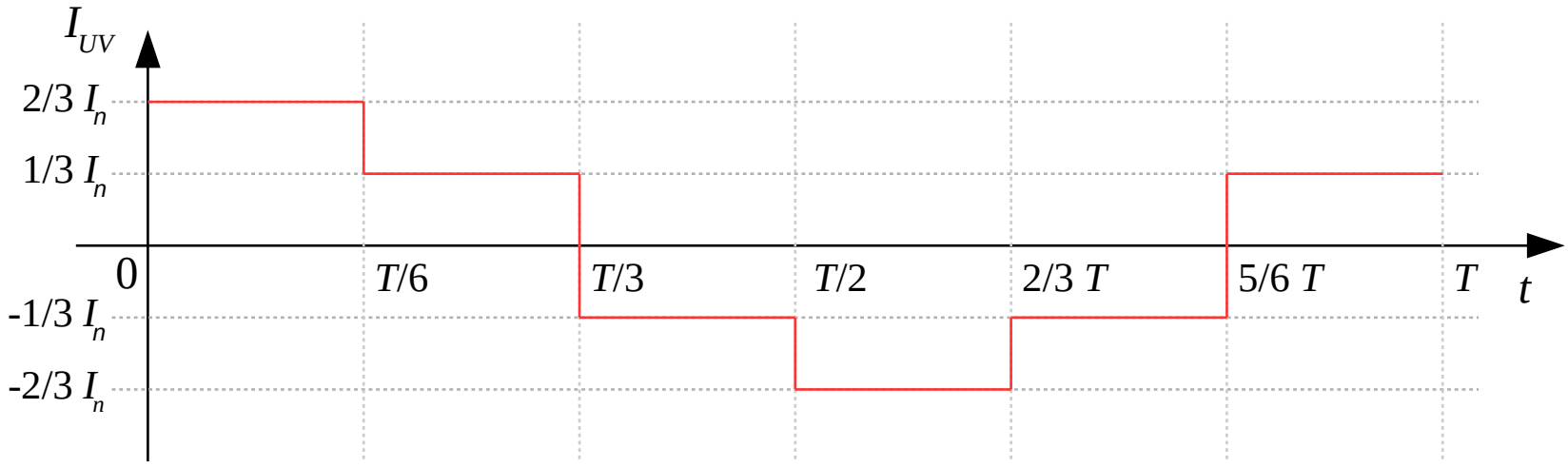
$$I_v = \sqrt{\frac{1}{T}\left[\int_0^{\frac{T}{6}}\left(\frac{2}{3}I_n\right)^2 dt + \int_{\frac{T}{6}}^{\frac{T}{3}}\left(\frac{1}{3}I_n\right)^2 dt + \int_{\frac{T}{3}}^{\frac{T}{2}}\left(-\frac{1}{3}I_n\right)^2 dt + \int_{\frac{T}{2}}^{\frac{2}{3}T}\left(-\frac{2}{3}I_n\right)^2 dt + \int_{\frac{2}{3}T}^{\frac{5}{6}T}\left(-\frac{1}{3}I_n\right)^2 dt + \int_{\frac{5}{6}T}^{T}\left(\frac{1}{3}I_n\right)^2 dt\right]}$$

Analysis of the Work of Brushless Direct Current Machines



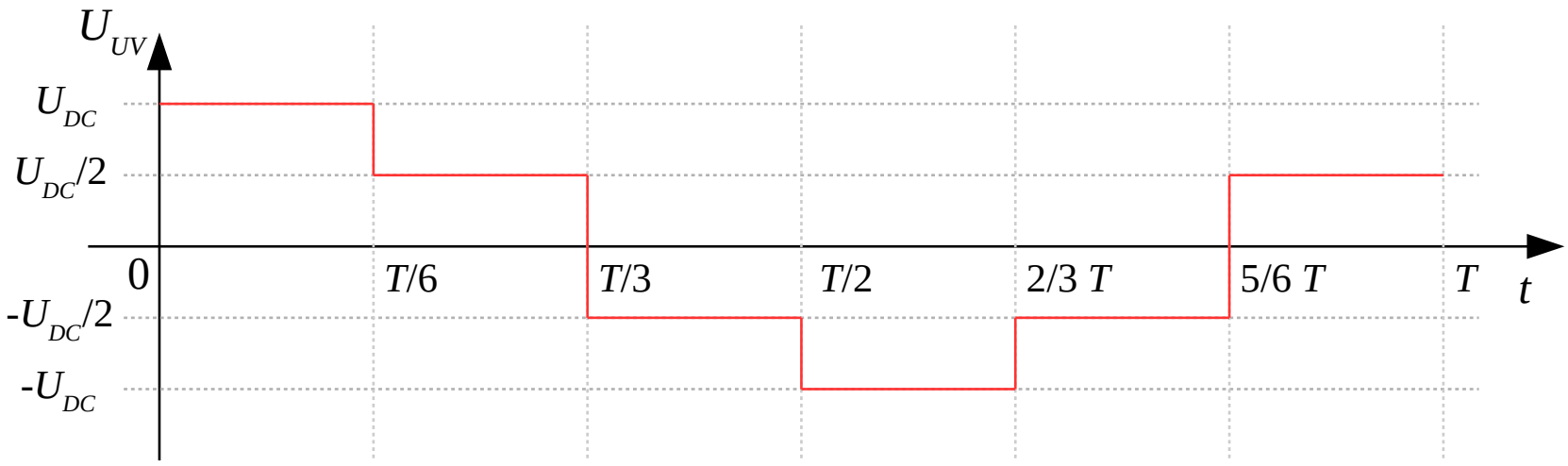
$$I_v = \sqrt{\frac{1}{T}\left(\frac{4}{9}I_n^2 \cdot \frac{T}{6} + \frac{1}{9}I_n^2 \cdot \frac{T}{6} + \frac{1}{9}I_n^2 \cdot \frac{T}{6} + \frac{4}{9}I_n^2 \cdot \frac{T}{6} + \frac{1}{9}I_n^2 \cdot \frac{T}{6} + \frac{1}{9}I_n^2 \cdot \frac{T}{6}\right)}$$

Analysis of the Work of Brushless Direct Current Machines

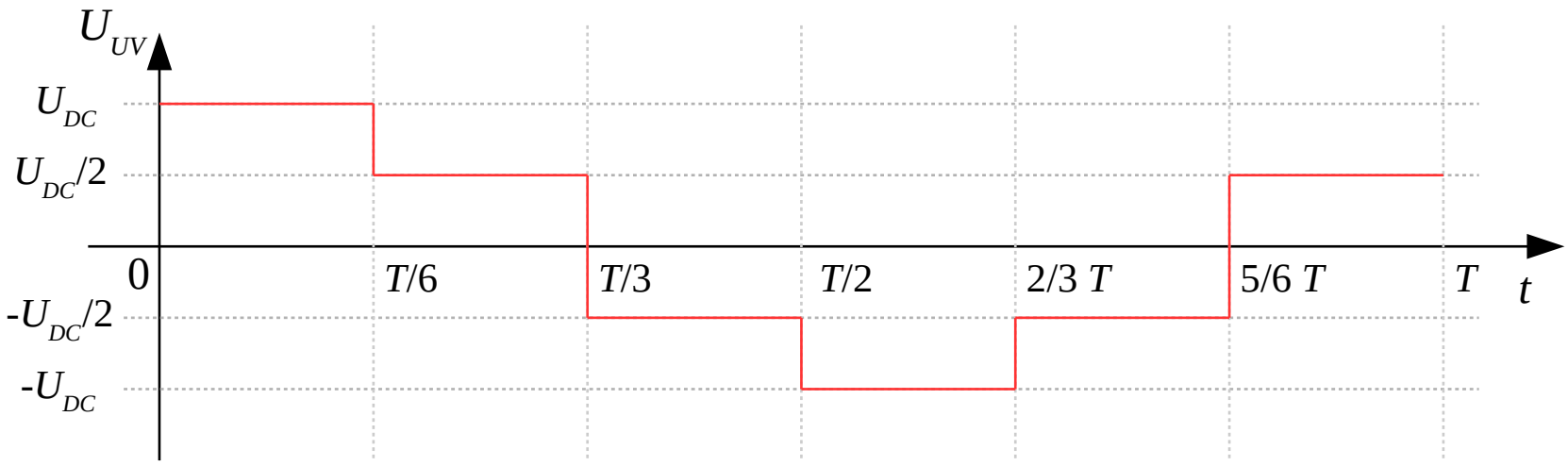


$$I_v = \sqrt{\frac{2}{9} I_n^2} = \frac{\sqrt{2}}{3} I_n$$

Analysis of the Work of Brushless Direct Current Machines

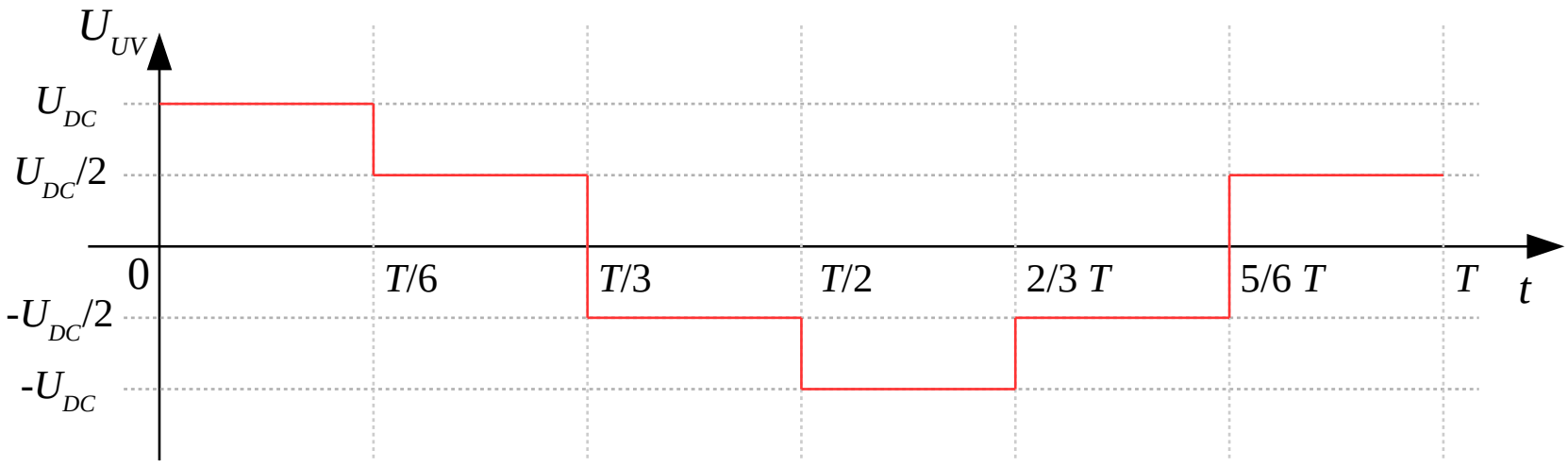


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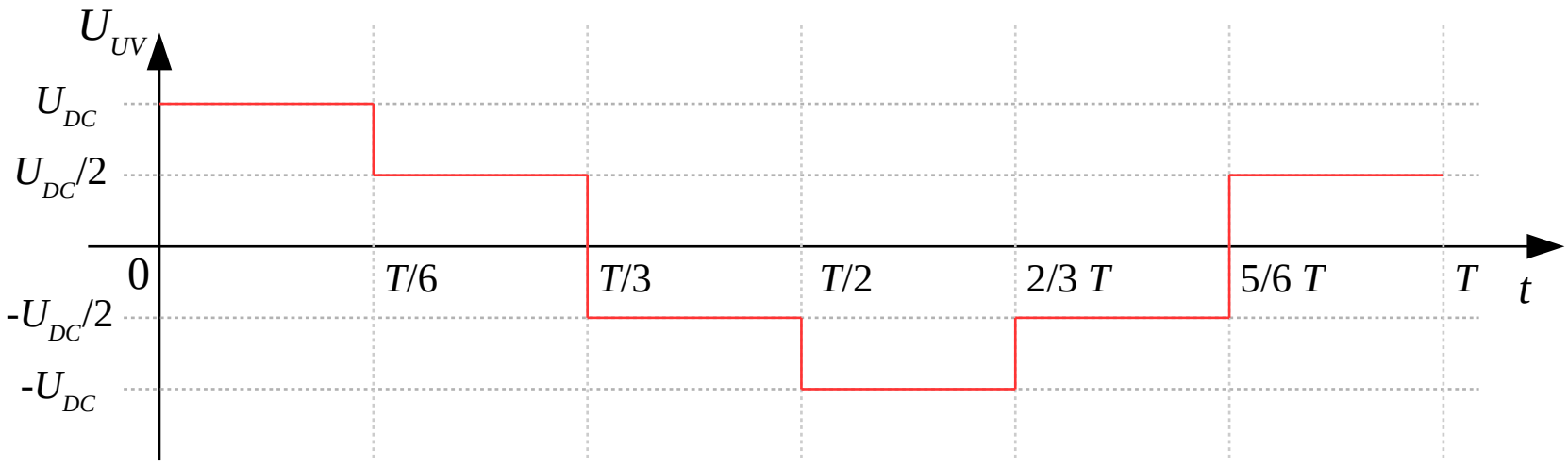
$$U_v = \sqrt{\frac{1}{T}\left[\int_0^{\frac{T}{6}} U_{DC}^2\,dt + \int_{\frac{T}{6}}^{\frac{T}{3}} \left(\frac{1}{2}U_{DC}\right)^2 dt + \int_{\frac{T}{3}}^{\frac{T}{2}} \left(-\frac{1}{2}U_{DC}\right)^2 dt + \int_{\frac{T}{2}}^{\frac{2}{3}T} \left(-U_{DC}\right)^2 dt + \int_{\frac{2}{3}T}^{\frac{5}{6}T} \left(-\frac{1}{2}U_{DC}\right)^2 dt + \int_{\frac{5}{6}T}^{T} \left(\frac{1}{2}U_{DC}\right)^2 dt\right]}$$

Analysis of the Work of Brushless Direct Current Machines



$$U_v = \sqrt{\frac{1}{T}\left(U_{DC}^2 \cdot \frac{T}{6} + \frac{1}{4}U_{DC}^2 \cdot \frac{T}{6} + \frac{1}{4}U_{DC}^2 \cdot \frac{T}{6} + U_{DC}^2 \cdot \frac{T}{6} + \frac{1}{4}U_{DC}^2 \cdot \frac{T}{6} + \frac{1}{4}U_{DC}^2 \cdot \frac{T}{6}\right)}$$

Analysis of the Work of Brushless Direct Current Machines



$$U_v = \sqrt{\frac{12}{24} U_{DC}^2} = \frac{1}{\sqrt{2}} U_{DC}$$

Analysis of the Work of Brushless Direct Current Machines

- The check of validity of obtained results may be based on calculation of power of a three phase motor:

$$P_{AC} = 3 U_v I_v$$

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Analysis of the Work of Brushless Direct Current Machines

- The design of a BLDC machine may be performed as a design of equivalent PMSM with delta winding connection, whereas:
  - RMS valu of the winding voltages is:

$$U_n = \frac{1}{\sqrt{2}} U_{DC}$$

and the RMS value of winding current will be:

$$I_v = \frac{\sqrt{2}}{3} I_n$$

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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

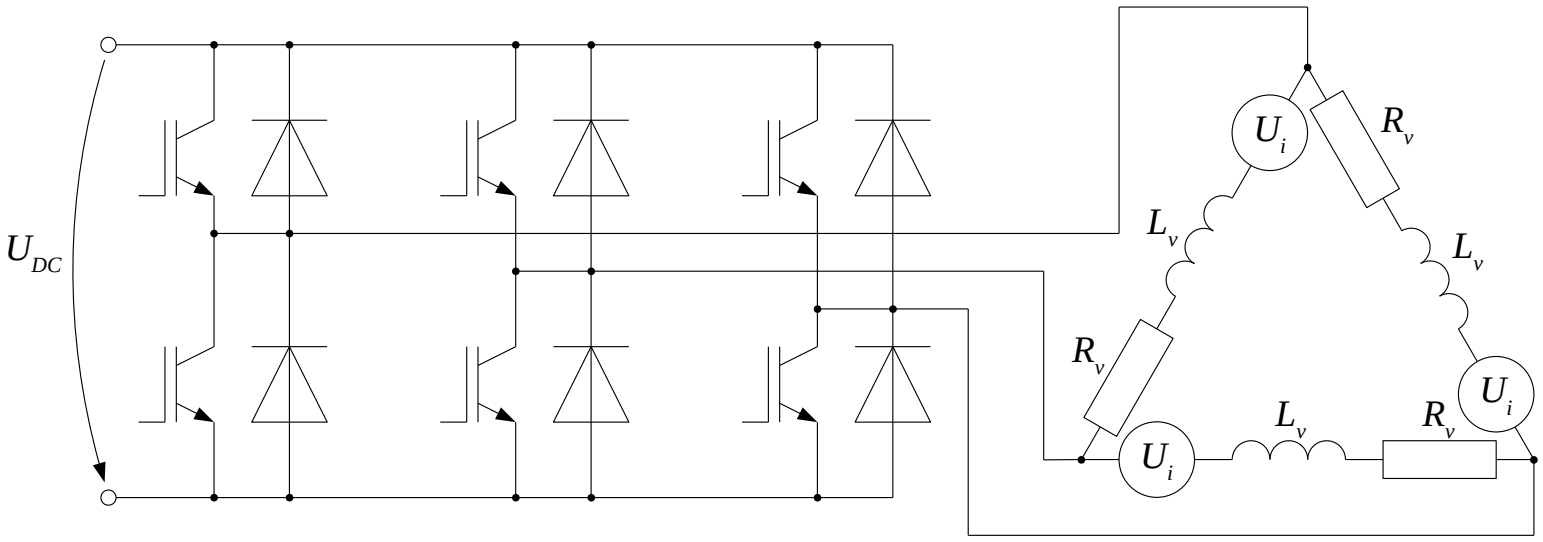
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Mathematical Description of Brushless Direct Current Machines

Mathematical Description of Brushless Direct Current Machines

- To achieve a full scale model of the BLDC machine, it is necessary to consider time-variable parameters

  => a modelling may be based on differential equations only



Mathematical Description of Brushless Direct Current Machines

- For each phase we can write

$$U_{DC} = R_v i_v(t) + L_v \frac{di_v(t)}{dt} + u_{iv}(t)$$

Mathematical Description of Brushless Direct Current Machines

- For each phase we can write

$$U_{DC} = R_v i_v(t) + L_v \frac{di_v(t)}{dt} + u_{iv}(t)$$

- In any time moment only one line-to-line voltage is active
- The remaining phases form a parallel connection

Mathematical Description of Brushless Direct Current Machines

- Presuming connection of winding UV to the DC circuit:
  - For phase UV we have

$$U_{DC} = R_v i_{uv} + L_v \frac{di_{uv}}{dt} + u_{iuv}$$

Mathematical Description of Brushless Direct Current Machines

- Presuming connection of winding UV to the DC circuit:
  - For phase UV we have

$$U_{DC} = R_v i_{uv} + L_v \frac{di_{uv}}{dt} + u_{iuv}$$

  - For remaining two then

$$U_{DC} = R_v i_{vw} + L_v \frac{di_{vw}}{dt} - u_{ivw} + R_v i_{wu} + L_v \frac{di_{wu}}{dt} - u_{iwu}$$

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$$U_{DC} = R_v i_{vw} + L_v \frac{di_{vw}}{dt} - u_{ivw} + R_v i_{wu} + L_v \frac{di_{wu}}{dt} - u_{iwu}$$

    whereas

$$i_{vw} = i_{wu}$$

Mathematical Description of Brushless Direct Current Machines

- Presuming harmonic and symmetric shape of the induced voltage for all phases, we can write

$$u_{uv} + u_{vw} + u_{wu} = 0$$

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Mathematical Description of Brushless Direct Current Machines

- Presuming harmonic and symmetric shape of the induced voltage for all phases, we can write

$$u_{uv} + u_{vw} + u_{wu} = 0$$

- After switching to the next phase all equations change in similar way
- If a perfectly symmetrical machine is presumed, it is possible to use a simplified approach in d-q coordinate system

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Thank You for Your Attention!

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