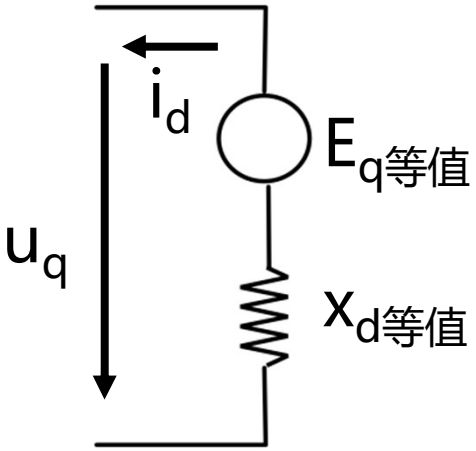
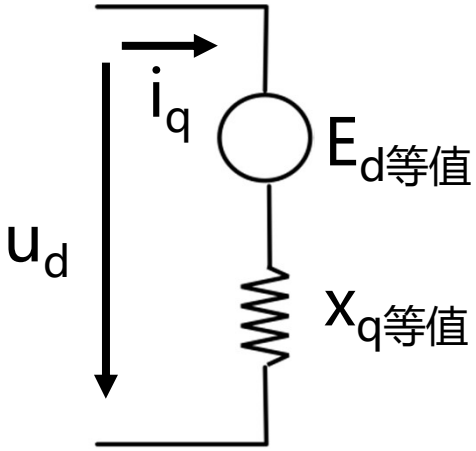
即将直播授课

- 下载腾讯课堂学生端APP：
  https://ke.qq.ocm/s
- 扫码进课
- 也可以看回放
- 进一次以后，下次再进课堂不需要再扫码：
  我的—最近看过—刘崇茹的课堂
- 请将昵称改为：学号姓名

派克变换的应用实例之三——发电机短路电流计算

- **发电机等值电路**





稳态

$$E_q = x_{ad} i_f \qquad E_d = 0$$

$$x_d = x_\sigma + x_{ad} \qquad X_q = X_\sigma + X_{aq}$$

$i_D=0$
$i_Q=0$
i_f=常数

暂态

$$E'_q = \frac{x_{ad}}{x_f}\psi_f \qquad E_d = 0$$

$$x'_d = x_\sigma + x_{ad} // x_{f\sigma} \qquad X_q = X_\sigma + X_{aq}$$

$i_D=0$
$i_Q=0$

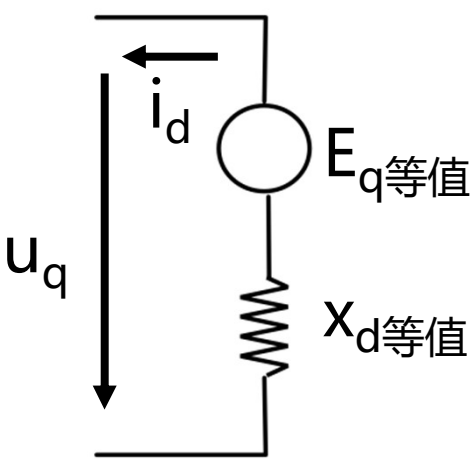
次暂态

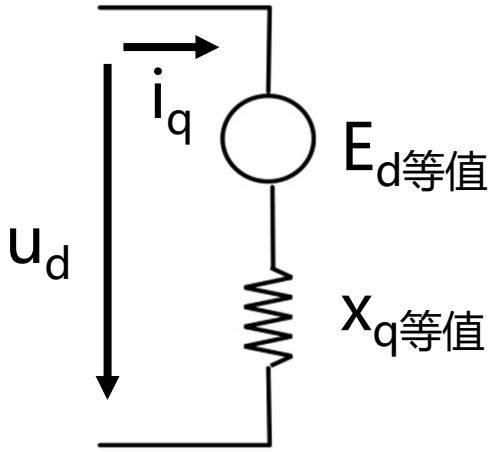
$$E''_q = \frac{x_{ad} // x_{D\sigma}}{x_{f\sigma} + x_{ad} // x_{D\sigma}}\psi_f + \frac{x_{ad} // x_{f\sigma}}{x_{D\sigma} + x_{ad} // x_{f\sigma}}\psi_D \qquad E''_d = \frac{x_{aq}}{x_Q}\psi_Q$$

$$x''_d = x_\sigma + x_{ad} // x_{f\sigma} // x_{D\sigma} \qquad x''_q = x_\sigma + x_{aq} // x_{Q\sigma}$$

派克变换的应用实例之三——发电机短路电流计算

- **发电机等值电路**





$$u_q = E_q^{eq} - i_d x_d^{eq}$$

$$u_d = E_d^{eq} + i_q x_q^{eq}$$

稳态

$$u_q = E_q - i_d x_d$$

$$u_d = E_d + i_q x_q = i_q x_q$$

暂态

$$u_q = E'_q - i_d x'_d$$

$$u_d = E_d + i_q x_q = i_q x_q$$

次暂态

$$u_q = E''_q - i_d x''_d$$

$$u_d = E''_d + i_q x''_q$$

派克变换的应用实例之三——发电机短路电流计算

- 空载情况下
  - d轴：$E_{q|0|}=E'_{q|0|}=E''_{q|0|}=u_{q|0|}$
  - q轴：$E_{d|0|}=E''_{d|0|}=u_{d|0|}=0$
- 空载短路电流初始值
  - 次暂态电流：D轴阻尼绕组电流没有衰减到零
    - 有效值：$I'' = I''_d = E''_{q|0|}/x''_d = E_{q|0|}/x''_d$
  - 暂态电流：励磁绕组的直流分量没有衰减结束
    - 有效值：$I' = I'_d = E'_{q|0|}/x'_d = E_{q|0|}/x'_d$
  - 稳态值：衰减过程结束后的稳态短路电流
    - 有效值：$I_\infty = I_{d\infty} = E_{q|0|}/x_d$

派克变换的应用实例之三——发电机短路电流计算

- **空载短路电流近似表达式**

衰减时间常数**T'd**

$$I'' = I''_{\mathrm{d}} = E_{\mathrm{q}|0|} \Big/ X''_{\mathrm{d}} \qquad I' = I'_{\mathrm{d}} = E_{\mathrm{q}|0|} \Big/ X'_{\mathrm{d}} \qquad I_{\infty} = I_{\mathrm{d}\infty} = E_{\mathrm{q}|0|} \Big/ X_{\mathrm{d}}$$

衰减时间常数**T"d**

$$I_m(t) = \left(\sqrt{2}I'' - \sqrt{2}I'\right)e^{-\frac{t}{T''_d}} + \left(\sqrt{2}I' - \sqrt{2}I_{\infty}\right)e^{-\frac{t}{T'_d}} + \sqrt{2}I_{\infty}$$

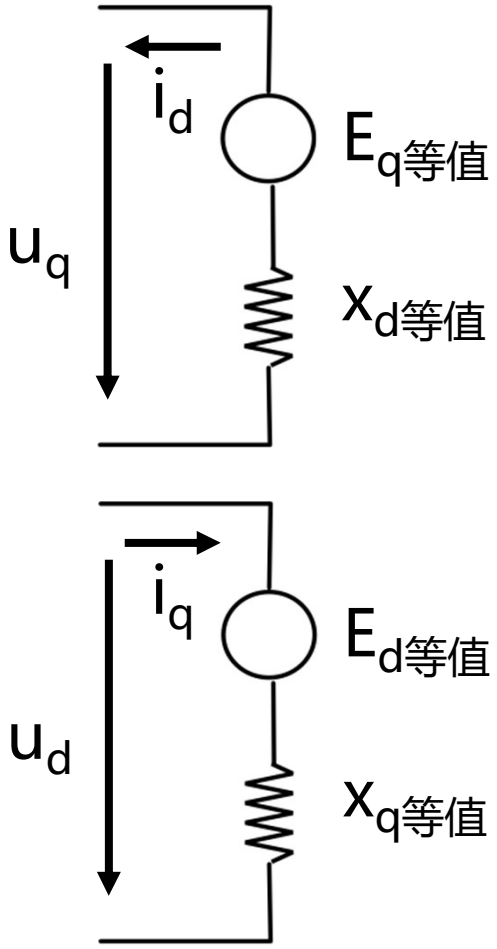
$$i_a = \sqrt{2}E_{q|0|}\left[\left(\frac{1}{x''_d} - \frac{1}{x'_d}\right)e^{-\frac{t}{T''_d}} + \left(\frac{1}{x'_d} - \frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \frac{1}{x_d}\right]\cos(\theta_0 + \omega_0 t) - \frac{\sqrt{2}E_{q|0|}}{x''_d}\cos\theta_0 e^{-\frac{t}{T_a}}$$

$$i_b = \sqrt{2}E_{q|0|}\left[\left(\frac{1}{x''_d} - \frac{1}{x'_d}\right)e^{-\frac{t}{T''_d}} + \left(\frac{1}{x'_d} - \frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \frac{1}{x_d}\right]\cos(\theta_0 + \omega_0 t - 120^\circ) - \frac{\sqrt{2}E_{q|0|}}{x''_d}\cos(\theta_0 - 120^\circ)e^{-\frac{t}{T_a}}$$

$$i_c = \sqrt{2}E_{q|0|}\left[\left(\frac{1}{x''_d} - \frac{1}{x'_d}\right)e^{-\frac{t}{T''_d}} + \left(\frac{1}{x'_d} - \frac{1}{x_d}\right)e^{-\frac{t}{T'_d}} + \frac{1}{x_d}\right]\cos(\theta_0 + \omega_0 t + 120^\circ) - \frac{\sqrt{2}E_{q|0|}}{x''_d}\cos(\theta_0 + 120^\circ)e^{-\frac{t}{T_a}}$$

派克变换的应用实例之三——发电机短路电流计算

- **负载情况下**



暂态电流初始值

$$\dot{I}'_d = \dot{E}'_{q|0|} / jx'_d$$

次暂态电流初始值

$$\dot{I}''_d = \dot{E}''_{q|0|} / jx''_d$$

$$\dot{I}''_q = \dot{E}''_{d|0|} / jx''_q$$

虚构次暂态电动势

$$\dot{E}''_{|0|} = \dot{U}_0 + j\dot{I}_0 x''_d$$

$$\dot{I}'' = \dot{E}''_{|0|} \Big/ jx''_d$$

(此定义与40页例1-3不一致)

空载

$$I' = E_{q|0|}/x'_d$$

$$I'' = E_{q|0|}/x''_d$$

负载

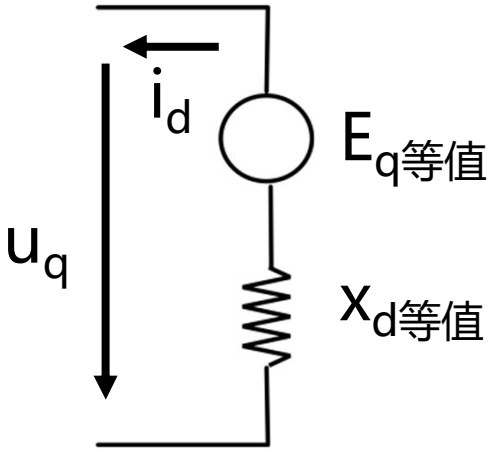
$$I' = E'_{q|0|}/x'_d$$

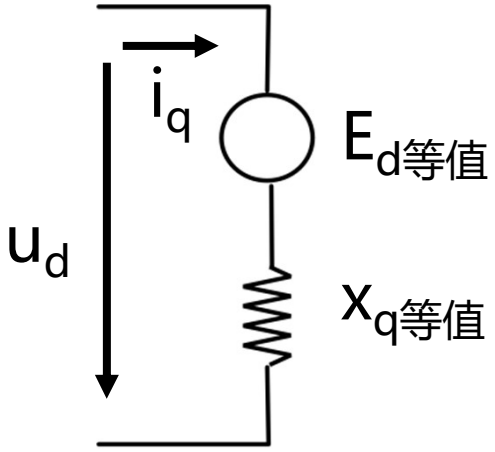
$$I'' = E''_{|0|}/x''_d$$

提问：负载短路电流和空载短路电流谁大?

派克变换的应用实例之三——发电机短路电流计算

- **负载情况下**





暂态电流初始值 $\dot{I}'_d = \dot{E}'_{q|0|} / jx'_d$

$$E'_{q0} = u_{q0} + i_{d0}x'_d$$

$$E_{q0} = u_{q0} + i_{d0}x_d$$

$$E'_{q0} = u_{q0} + i_{d0}x'_d = E_{q0} - i_{d0}x_d + i_{d0}x'_d \xrightarrow{x_d > x'_d} E'_{q0} \le E_{q0}$$

空载 $I'_d = \dfrac{E_{q0}}{x'_d}$　　**负载** $I'_d = \dfrac{E'_{q0}}{x'_d}$

空载短路电流大于负载短路电流

派克变换的应用实例之三——发电机短路电流计算

- **不计阻尼绕组负载短路情况下，不计自由分量的衰减**

$$\psi_d = u_q$$

$$\psi_q = -u_d$$

$$\psi_{abc} = P^{-1}\psi_{dq0}$$

$$P^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos(\theta-120^\circ) & -\sin(\theta-120^\circ) & 1 \\ \cos(\theta+120^\circ) & -\sin(\theta+120^\circ) & 1 \end{bmatrix}$$

$$\psi_a = \psi_d\cos\theta - \psi_q\sin\theta = u_q\cos\theta + u_d\sin\theta$$

$$u_q = E'_q - i_d x'_d$$

$$u_d = E_d + i_q x_q = i_q x_q$$

$$\psi_a = \left(E'_{q|0|} - i_d x'_d\right)\cos\theta + i_q x_q \sin\theta$$

假设各绕组磁链不衰减

$$\psi_a = \psi_{a|0|} = u_{q|0|}\cos\theta_0 + u_{d|0|}\sin\theta_0 = \left(E'_{q|0|} - i_d x'_d\right)\cos\theta + i_q x_q \sin\theta$$

$$\psi_b = \psi_{b|0|} = u_{q|0|}\cos(\theta_0 - 120^\circ) + u_{d|0|}\sin(\theta_0 - 120^\circ)$$

$$= \left(E'_{q|0|} - i_d x'_d\right)\cos(\theta - 120^\circ) + i_q x_q \sin(\theta - 120^\circ)$$

派克变换的应用实例之三——发电机短路电流计算

- 不计阻尼绕组负载短路情况下，不计自由分量的衰减

$$i_d = \frac{E'_{q|0|}}{x'_d} - \left(\frac{u_{q|0|}}{x'_d}\cos\omega t - \frac{u_{d|0|}}{x'_d}\sin\omega t \right)$$

$$i_q = \frac{u_{q|0|}}{x_q}\sin\omega t + \frac{u_{d|0|}}{x_q}\cos\omega t$$

$$i_d = \frac{E'_{q|0|}}{x'_d} - \left(\frac{u_{|0|}}{x'_d}\cos\delta_0\cos\omega t - \frac{u_{|0|}}{x'_d}\sin\delta_0\sin\omega t \right)$$

$$i_q = \frac{u_{|0|}}{x_q}\cos\delta_0\sin\omega t + \frac{u_{|0|}}{x_q}\sin\delta_0\cos\omega t$$

$$i_d = \frac{E'_{q|0|}}{x'_d} - \frac{u_{|0|}}{x'_d}\cos(\omega t + \delta_0)$$

$$i_q = \frac{u_{|0|}}{x_q}\sin(\omega t + \delta_0)$$

派克变换的应用实例之三——发电机短路电流计算

- 不计阻尼绕组负载短路情况下，不计自由分量的衰减

$$i_d = \frac{E'_{q|0|}}{x'_d} - \frac{u_{|0|}}{x'_d}\cos\left(\omega t + \delta_0\right)$$

$$i_q = \frac{u_{|0|}}{x_q}\sin\left(\omega t + \delta_0\right)$$

$$P = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - 120^\circ\right) & \cos\left(\theta + 120^\circ\right) \\ -\sin\theta & -\sin\left(\theta - 120^\circ\right) & -\sin\left(\theta + 120^\circ\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

$$i_a = \frac{E'_{q|0|}}{x'_d}\cos\left(\omega t + \theta_0\right) - \frac{u_{|0|}}{2}\left(\frac{1}{x'_d} + \frac{1}{x_q}\right)\cos\left(\delta_0 - \theta_0\right) - \frac{u_{|0|}}{2}\left(\frac{1}{x'_d} - \frac{1}{x_q}\right)\cos\left(2\omega t + \delta_0 + \theta_0\right)$$

同步交流周期分量　　直流分量　　两倍频周期分量

派克变换的应用实例之三——发电机短路电流计算

- **不计阻尼绕组负载短路情况下，不计自由分量的衰减**

$$i_d = \frac{E'_{q|0|}}{x'_d} - \left(\frac{u_{q|0|}}{x'_d}\cos\omega t - \frac{u_{d|0|}}{x'_d}\sin\omega t \right) \qquad i_{d|0|} = \frac{E'_{q|0|} - u_{q|0|}}{x'_d}$$

$$\Rightarrow \quad \Delta i_d = \frac{u_{q|0|}}{x'_d} - \left(\frac{u_{q|0|}}{x'_d}\cos\omega t - \frac{u_{d|0|}}{x'_d}\sin\omega t \right)$$

磁链守恒 $x_{ad}\Delta i_d = x_f \Delta i_f$

$$\Rightarrow \quad \Delta i_f = \frac{x_{ad}}{x_f}\left(\frac{u_{q|0|}}{x'_d} - \frac{u_{q|0|}}{x'_d}\cos\omega t + \frac{u_{d|0|}}{x'_d}\sin\omega t \right)$$

$$i_f = i_{f|0|} + \frac{x_{ad}}{x_f}\left(\frac{u_{q|0|}}{x'_d} - \frac{u_{q|0|}}{x'_d}\cos\omega t + \frac{u_{d|0|}}{x'_d}\sin\omega t \right) = \frac{E_{q|0|}}{x_{ad}} + \frac{x_{ad}}{x_f}\frac{u_{q|0|}}{x'_d} - \frac{x_{ad}}{x_f}\frac{u_{|0|}}{x'_d}\cos\left(\omega t + \delta_0\right)$$

直流分量　　同步交流周期分量

$$\frac{x_{ad}}{x_f} = \frac{x_d - x'_d}{x_{ad}}$$

（P40式（1-68）有误）

派克变换的应用实例之三——发电机短路电流计算

衰减时间常数T'd

$$I'_d = \frac{E'_{q|0|}}{x'_d} \qquad I_{d\infty} = I_\infty = \frac{E_{q|0|}}{x_d}$$

- **计及自由分量的衰减**

$$i_d = \frac{E_{q|0|}}{x_d} + \left(\frac{E'_{q|0|}}{x'_d} - \frac{E_{q|0|}}{x_d}\right) e^{-\frac{t}{T'_d}} - \frac{u_{|0|}}{x'_d}\cos(\omega t + \delta_0) e^{-\frac{t}{T_a}}$$

$$i_q = \frac{u_{|0|}}{x_q}\sin(\omega t + \delta_0) e^{-\frac{t}{T_a}}$$

$$i_d = \frac{E_{q|0|}}{x_d} + u_{|0|}\left(\frac{1}{x'_d} - \frac{1}{x_d}\right)\cos\delta_0 e^{-\frac{t}{T'_d}} - \frac{u_{|0|}}{x'_d}\cos(\omega t + \delta_0) e^{-\frac{t}{T_a}}$$

$$i_q = \frac{u_{|0|}}{x_q}\sin(\omega t + \delta_0) e^{-\frac{t}{T_a}}$$

$$i_d = \frac{E'_{q|0|}}{x'_d} - \frac{u_{|0|}}{x'_d}\cos(\omega t + \delta_0)$$

$$i_q = \frac{u_{|0|}}{x_q}\sin(\omega t + \delta_0)$$

$$i_{d|0|} = \frac{E'_{q|0|} - u_{q|0|}}{x'_d}$$

$$i_{d|0|} = \frac{E_{q|0|} - u_{q|0|}}{x_d}$$

(P45公式有误)

派克变换的应用实例之三——发电机短路电流计算

- **计及自由分量的衰减**

$$i_d = \frac{E_{q|0|}}{x_d} + u_{|0|}\left(\frac{1}{x'_d} - \frac{1}{x_d}\right)\cos\delta_0 e^{-\frac{t}{T'_d}} - \frac{u_{|0|}}{x'_d}\cos\left(\omega t + \delta_0\right)e^{-\frac{t}{T_a}}$$

$$i_q = \frac{u_{|0|}}{x_q}\sin\left(\omega t + \delta_0\right)e^{-\frac{t}{T_a}}$$

- **a相电流表达式**

$$i_a = \left(\frac{E_{q|0|}}{x_d} + u_{|0|}\left(\frac{1}{x'_d} - \frac{1}{x_d}\right)\cos\delta_0 e^{-\frac{t}{T'_d}}\right)\cos\left(\omega t + \theta_0\right)$$

$$-\frac{u_{|0|}}{2}\left(\frac{1}{x'_d} + \frac{1}{x_q}\right)\cos\left(\delta_0 - \theta_0\right)e^{-\frac{t}{T_a}} - \frac{u_{|0|}}{2}\left(\frac{1}{x'_d} - \frac{1}{x_q}\right)\cos\left(2\omega t + \delta_0 + \theta_0\right)e^{-\frac{t}{T_a}}$$

（P43式（1-70）有误）

派克变换的应用实例之三——发电机短路电流计算

- **计及阻尼绕组负载短路情况下，不计自由分量的衰减**

$$\psi_d = u_q \qquad \psi_q = -u_d$$

$$\psi_{abc} = P^{-1}\psi_{dq0}$$

$$\psi_a = \psi_d\cos\theta - \psi_q\sin\theta = u_q\cos\theta + u_d\sin\theta$$

$$u_q = E''_q - i_d x''_d \qquad u_d = E''_d + i_q x''_q$$

$$\psi_a = \left(E''_{q|0|} - i_d x''_d\right)\cos\theta + \left(E''_{d|0|} + i_q x''_q\right)\sin\theta$$

假设各绕组磁链不衰减

$$\psi_a = \psi_{a|0|} = u_{q|0|}\cos\theta_0 + u_{d|0|}\sin\theta_0 = \left(E''_{q|0|} - i_d x''_d\right)\cos\theta + \left(E''_{d|0|} + i_q x''_q\right)\sin\theta$$

$$\psi_b = \psi_{b|0|} = u_{q|0|}\cos\left(\theta_0 - 120^o\right) + u_{d|0|}\sin\left(\theta_0 - 120^o\right)$$

$$= \left(E''_{q|0|} - i_d x''_d\right)\cos\left(\theta - 120^o\right) + \left(E''_{d|0|} + i_q x''_q\right)\sin\left(\theta - 120^o\right)$$

派克变换的应用实例之三——发电机短路电流计算

- 计及阻尼绕组负载短路情况下，不计自由分量的衰减

$$i_d = \frac{E''_{q|0|}}{x''_d} - \left(\frac{u_{q|0|}}{x''_d}\cos\omega t - \frac{u_{d|0|}}{x''_d}\sin\omega t \right)$$

$$i_q = -\frac{E''_{d|0|}}{x''_q} + \frac{u_{q|0|}}{x''_q}\sin\omega t + \frac{u_{d|0|}}{x''_q}\cos\omega t$$

$$i_d = \frac{E''_{q|0|}}{x''_d} - \left(\frac{u_{|0|}}{x''_d}\cos\delta_0\cos\omega t - \frac{u_{|0|}}{x''_d}\sin\delta_0\sin\omega t \right)$$

$$i_q = -\frac{E''_{d|0|}}{x''_q} + \frac{u_{|0|}}{x''_q}\cos\delta_0\sin\omega t + \frac{u_{|0|}}{x''_q}\sin\delta_0\cos\omega t$$

$$i_d = \frac{E''_{q|0|}}{x''_d} - \frac{u_{|0|}}{x''_d}\cos\left(\omega t + \delta_0\right)$$

$$i_q = -\frac{E''_{d|0|}}{x''_q} + \frac{u_{|0|}}{x''_q}\sin\left(\omega t + \delta_0\right)$$

（P44式（1-72）有误）

派克变换的应用实例之三——发电机短路电流计算

- **计及阻尼绕组负载短路情况下，不计自由分量的衰减**

$$i_d = \frac{E''_{q|0|}}{x''_d} - \frac{u_{|0|}}{x''_d}\cos(\omega t + \delta_0)$$

$$i_q = -\frac{E''_{d|0|}}{x''_q} + \frac{u_{|0|}}{x''_q}\sin(\omega t + \delta_0)$$

$$i_a = \frac{E''_{q|0|}}{x''_d}\cos(\omega t + \theta_0) - \frac{E''_{d|0|}}{x''_q}\sin(\omega t + \theta_0)$$ 同步交流周期分量

$$-\frac{u_{|0|}}{2}\left(\frac{1}{x''_d} + \frac{1}{x''_q}\right)\cos(\delta_0 - \theta_0) - \frac{u_{|0|}}{2}\left(\frac{1}{x''_d} - \frac{1}{x''_q}\right)\cos(2\omega t + \delta_0 + \theta_0)$$

直流分量　　两倍频周期分量

派克变换的应用实例之三——发电机短路电流计算

$$I''_d = \frac{E''_{q|0|}}{x''_d} \qquad I'_d = \frac{E'_{q|0|}}{x'_d} \qquad I_{d\infty} = I_\infty = \frac{E_{q|0|}}{x_d}$$

衰减时间常数T'd

衰减时间常数T''d

$$I''_q = -\frac{E''_{d|0|}}{x''_q} \qquad I_q = -\frac{E_{d|0|}}{x_q} = 0$$

衰减时间常数T''q

- **等效定子电流的完整表达式**

$$i_d = \frac{E_{q|0|}}{X_d} + u_{|0|}\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\cos\delta_0 e^{-t/T''_d} + u_{|0|}\left(\frac{1}{X'_d} - \frac{1}{X_d}\right)\cos\delta_0 e^{-t/T'_d} - \frac{u_{|0|}}{X''_d}\cos(\omega t + \delta_0)e^{-t/T_a}$$

$$i_q = -u_{|0|}\left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\sin\delta_0 e^{-t/T''_q} + \frac{u_{|0|}}{X''_q}\sin(\omega t + \delta_0)e^{-t/T_a}$$

派克变换的应用实例之三——发电机短路电流计算

- **等效定子电流的完整表达式**

$$i_{\mathrm{d}}=\frac{E_{\mathrm{q}|0|}}{X_{\mathrm{d}}}+u_{|0|}\left(\frac{1}{X_{\mathrm{d}}''}-\frac{1}{X_{\mathrm{d}}'}\right)\cos\delta_0\mathrm{e}^{-t/T_{\mathrm{d}}''}+u_{|0|}\left(\frac{1}{X_{\mathrm{d}}'}-\frac{1}{X_{\mathrm{d}}}\right)\cos\delta_0\mathrm{e}^{-t/T_{\mathrm{d}}'}-\frac{u_{|0|}}{X_{\mathrm{d}}''}\cos\left(\omega t+\delta_0\right)\mathrm{e}^{-t/T_{\mathrm{a}}}$$

$$i_{\mathrm{q}}=-u_{|0|}\left(\frac{1}{X_{\mathrm{q}}''}-\frac{1}{X_{\mathrm{q}}}\right)\sin\delta_0\mathrm{e}^{-t/T_{\mathrm{q}}''}+\frac{u_{|0|}}{X_{\mathrm{q}}''}\sin\left(\omega t+\delta_0\right)\mathrm{e}^{-t/T_{\mathrm{a}}}$$

- **派克反变换** 机端负载时，对应的a相短路全电流表达式

$$i_a=\left(u_{|0|}\left(\frac{1}{x_d''}-\frac{1}{x_d'}\right)\cos\delta_0 e^{-\frac{t}{T_d''}}+u_{|0|}\left(\frac{1}{x_d'}-\frac{1}{x_d}\right)\cos\delta_0 e^{-\frac{t}{T_d'}}+\frac{E_{q|0|}}{x_d}\right)\cos\left(\omega t+\theta_0\right)$$

$$+u_{|0|}\left(\frac{1}{x_q''}-\frac{1}{x_q}\right)\sin\delta_0 e^{-\frac{t}{T_q''}}\sin\left(\omega t+\theta_0\right)$$

$$-\frac{u_{|0|}}{2}\left(\frac{1}{x_d''}+\frac{1}{x_q''}\right)\cos\left(\delta_0-\theta_0\right)e^{-\frac{t}{T_a}}-\frac{u_{|0|}}{2}\left(\frac{1}{x_d''}-\frac{1}{x_q''}\right)\cos\left(2\omega t+\delta_0+\theta_0\right)e^{-\frac{t}{T_a}}$$

第三次作业（短路电流）

- P64
  - 1-1，1-2，1-3

派克变换的应用实例之四

——发电机各电抗、电动势大小的比较

派克变换的应用实例之四——电抗、电势大小关系

电压方程

$$u_d = -r_a i_d + \dot{\psi}_d - \omega\psi_q$$

$$u_q = -r_a i_q + \dot{\psi}_q + \omega\psi_d$$

假设：

1、电磁暂态过程中，转速维持同步速；

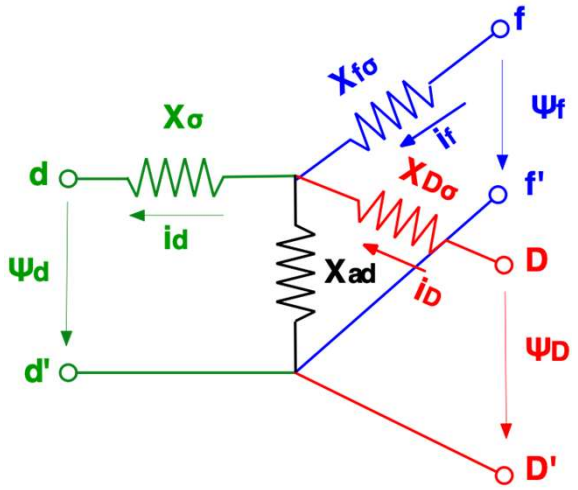
2、忽略定子回路的电磁暂态过程；

3、忽略定子电阻。

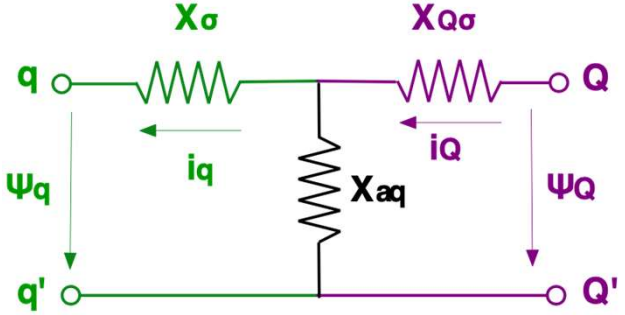
$$u_d = -\psi_q \qquad u_q = \psi_d$$

将磁链和电流的关系带入电压与磁链的关系即可得到发电机在稳态、暂态和次暂态情况下的戴维南等值电路及其参数。

d轴磁链和电流的关系

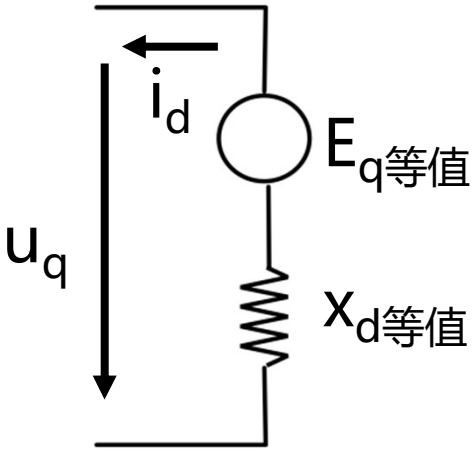


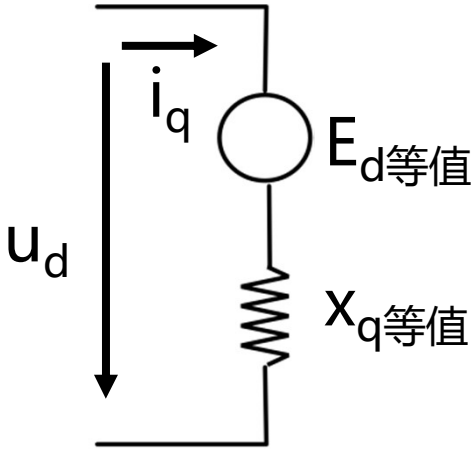
q轴磁链和电流的关系



派克变换的应用实例之四——电抗、电势大小关系

- **发电机等值电路**





稳态

$$E_q = x_{ad} i_f \qquad E_d = 0$$

$$x_d = x_\sigma + x_{ad} \qquad X_q = X_\sigma + X_{aq}$$

暂态

$$E'_q = \frac{x_{ad}}{x_f}\psi_f \qquad E_d = 0$$

$$x'_d = x_\sigma + x_{ad} // x_{f\sigma} \qquad X_q = X_\sigma + X_{aq}$$

X'ad

次暂态

$$E''_q = \frac{x_{ad} // x_{D\sigma}}{x_{f\sigma} + x_{ad} // x_{D\sigma}}\psi_f + \frac{x_{ad} // x_{f\sigma}}{x_{D\sigma} + x_{ad} // x_{f\sigma}}\psi_D \qquad E''_d = \frac{x_{aq}}{x_Q}\psi_Q$$

X''ad

$$x''_d = x_\sigma + x_{ad} // x_{f\sigma} // x_{D\sigma} \qquad x''_q = x_\sigma + x_{aq} // x_{Q\sigma}$$

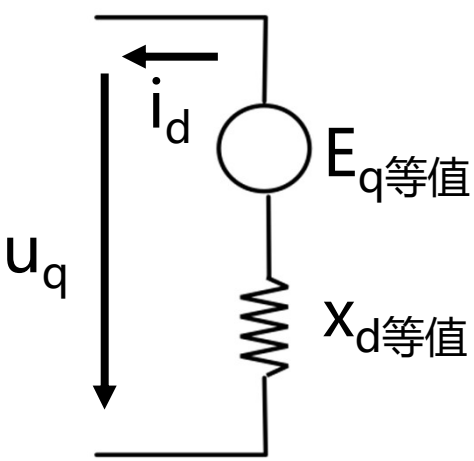
派克变换的应用实例之四——电抗、电势大小关系

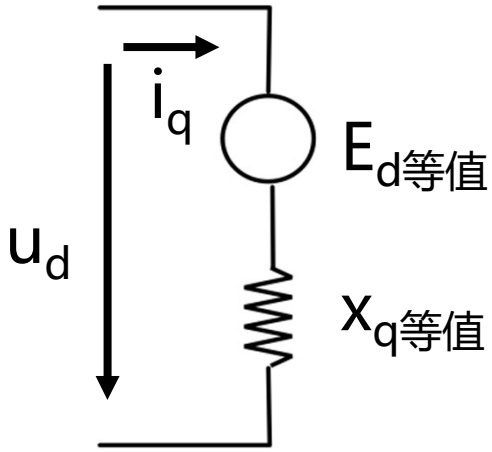
- 同步电抗、暂态电抗、次暂态电抗 $x_d'' < x_d' < x_d$
- 电枢反应电抗 $x_{ad}'' < x_{ad}' < x_{ad}$

电抗类型	水轮发电机	汽轮发电机
X_d	0.7-1.4	1.2-2.2
X_d'	0.2-0.35	0.15-0.24
X_d''	0.14-0.26	0.1-0.15
X_q	0.45-0.7	1.2-2.2
X_q''	0.15-0.35	0.1-0.15

派克变换的应用实例之四——电抗、电势大小关系

- **发电机等值电路**





$$u_q = E_q^{eq} - i_d x_d^{eq}$$

$$u_d = E_d^{eq} + i_q x_q^{eq}$$

稳态	暂态	次暂态
$u_q = E_q - i_d x_d$	$u_q = E'_q - i_d x'_d$	$u_q = E''_q - i_d x''_d$
$u_d = E_d + i_q x_q = i_q x_q$	$u_d = E_d + i_q x_q = i_q x_q$	$u_d = E''_d + i_q x''_q$

空载情况下：各等值电势有什么关系？

发电机空载情况下，空载电动势、暂态电动势、次暂态电动势的关系：

A 空载电动势最大

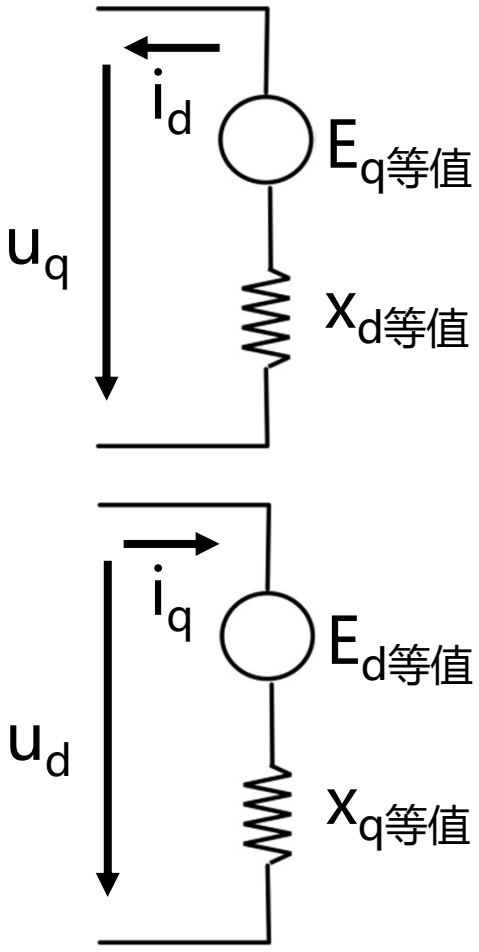
B 暂态电动势最大

C 次暂态电动势最大

D 一样大

E 不确定

派克变换的应用实例之四——电抗、电势大小关系



稳态

$$u_q = E_q - i_d x_d \qquad u_d = E_d + i_q x_q = i_q x_q$$

$$\Rightarrow \quad E_q = u_q + i_d x_d \qquad E_d = 0$$

暂态

$$u_q = E'_q - i_d x'_d \qquad u_d = E_d + i_q x_q = i_q x_q$$

$$\Rightarrow \quad E'_q = u_q + i_d x'_d \qquad E_d = 0$$

次暂态

$$u_q = E''_q - i_d x''_d \qquad u_d = E''_d + i_q x''_q$$

$$\Rightarrow \quad E''_q = u_q + i_d x''_d \qquad E''_d = u_d - i_q x''_q$$

$$E_q \geq E'_q \geq E''_q$$

$$E''_d = i_q \left(x_q - x''_q \right)$$

派克变换的应用实例之四——电抗、电势大小关系

- **相量图**

$$\dot{U}_d = u_d \qquad \dot{I}_d = i_d \qquad \dot{E}_q = jE_q$$

$$\dot{U}_q = ju_q \qquad \dot{I}_q = ji_q \qquad \dot{E}'_q = jE'_q$$

$$\dot{E}''_q = jE''_q \qquad \dot{E}''_d = E''_d$$

$$\begin{aligned} E_q &= u_q + i_d x_d \\ 0 &= u_d - i_q x_q \end{aligned} \Rightarrow \begin{aligned} \dot{E}_q &= \dot{U}_q + j\dot{I}_d x_d \\ \dot{E}_q &= \dot{U} + j\dot{I}x_q + j\dot{I}_d\left(x_d - x_q\right) \end{aligned}$$

$$\begin{aligned} E'_q &= u_q + i_d x'_d \\ 0 &= u_d - i_q x_q \end{aligned} \Rightarrow \begin{aligned} \dot{E}'_q &= \dot{U}_q + j\dot{I}_d x'_d \\ \dot{E}'_q &= \dot{U} + j\dot{I}x_q - j\dot{I}_d\left(x_q - x'_d\right) \end{aligned}$$

简化 $\dot{E}' = \dot{U} + j\dot{I}x'_d$

$$\begin{aligned} E''_q &= u_q + i_d x''_d \\ E''_d &= u_d - i_q x''_q \end{aligned} \Rightarrow \begin{aligned} \dot{E}''_q &= \dot{U}_q + j\dot{I}_d x''_d \\ \dot{E}''_d &= \dot{U}_d + j\dot{I}_q x''_q \end{aligned}$$

简化 $\dot{E}'' = \dot{U} + j\dot{I}x''_d$

派克变换的应用实例之四——电抗、电势大小关系

- **相量图**

$$\dot{E}_q = \dot{U}_q + j\dot{I}_d x_d$$
$$\dot{E}_q = \dot{U} + j\dot{I}x_q + j\dot{I}_d\left(x_d - x_q\right)$$

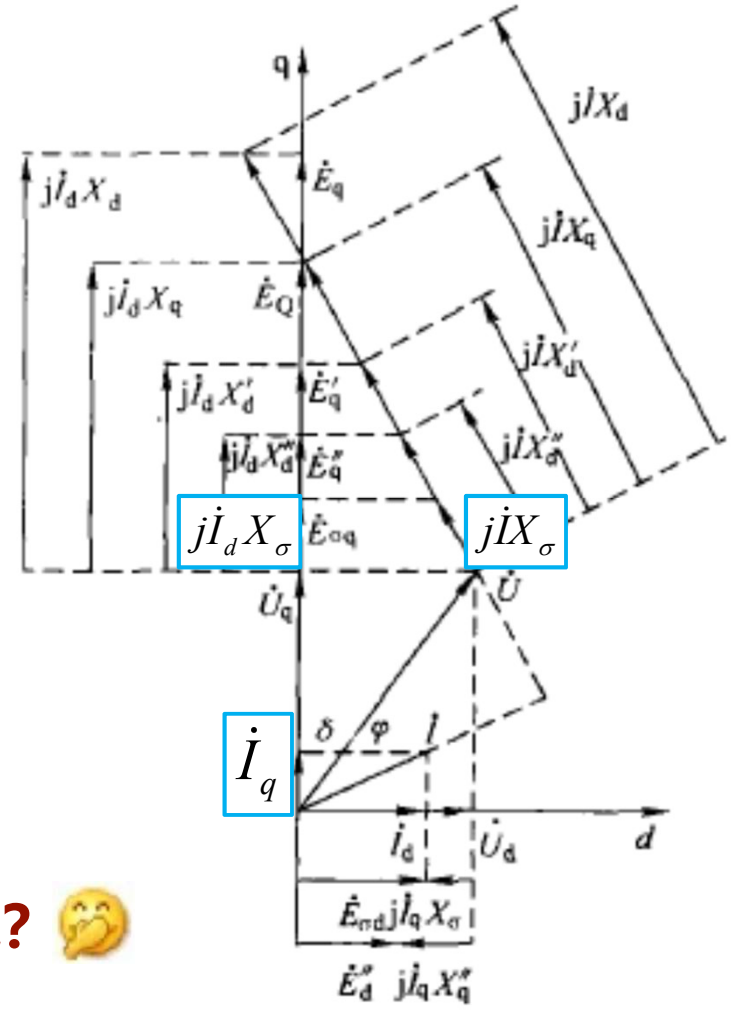
$$\dot{E}'_q = \dot{U}_q + j\dot{I}_d x'_d$$
$$\dot{E}'_q = \dot{U} + j\dot{I}x_q - j\dot{I}_d\left(x_q - x'_d\right)$$

$$\dot{E}''_q = \dot{U}_q + j\dot{I}_d x''_d$$
$$\dot{E}''_d = \dot{U}_d + j\dot{I}_q x''_q$$

简化

$$\dot{E}' = \dot{U} + j\dot{I}x'_d$$
$$\dot{E}'' = \dot{U} + j\dot{I}x''_d$$

电流的关系呢? 🤔



(P39 图1-30有一些笔误的小错误)

发电机发生机端三相短路时：

A 空载短路电流大

B 负载短路电流大

C 一样大

D 不确定

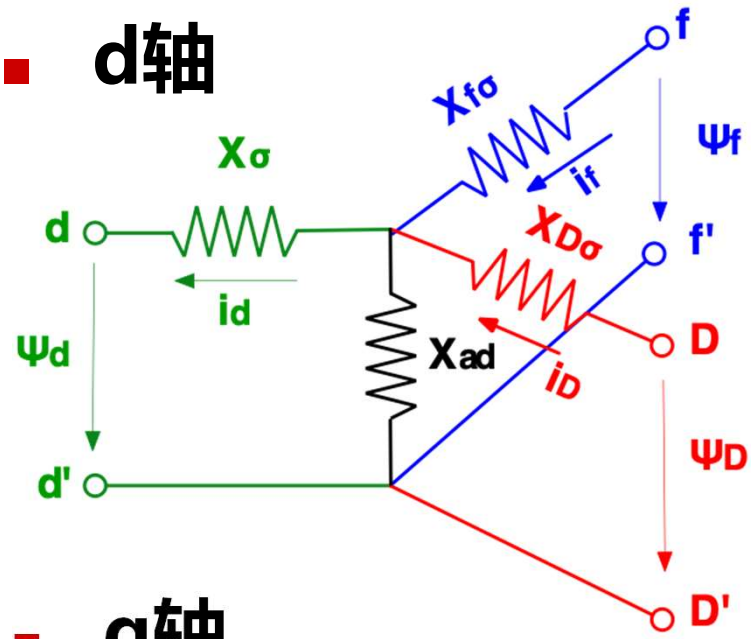
E 不知道

派克变换的应用实例之五

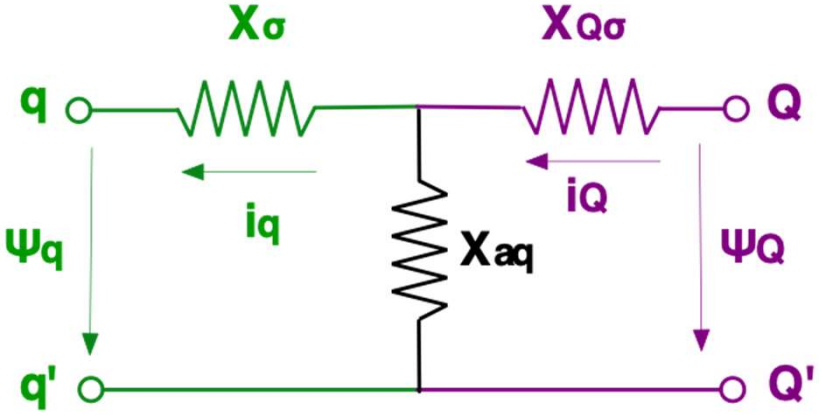
——有关的时间常数计算

派克变换的应用实例之五——有关的时间常数计算

- d轴



- q轴



- 定子绕组开路，各时间常数
  - 阻尼绕组开路时，励磁绕组本身的时间常数

$$T_f = \frac{x_f}{R_f}$$

  - 励磁绕组开路时，D阻尼绕组本身的时间常数

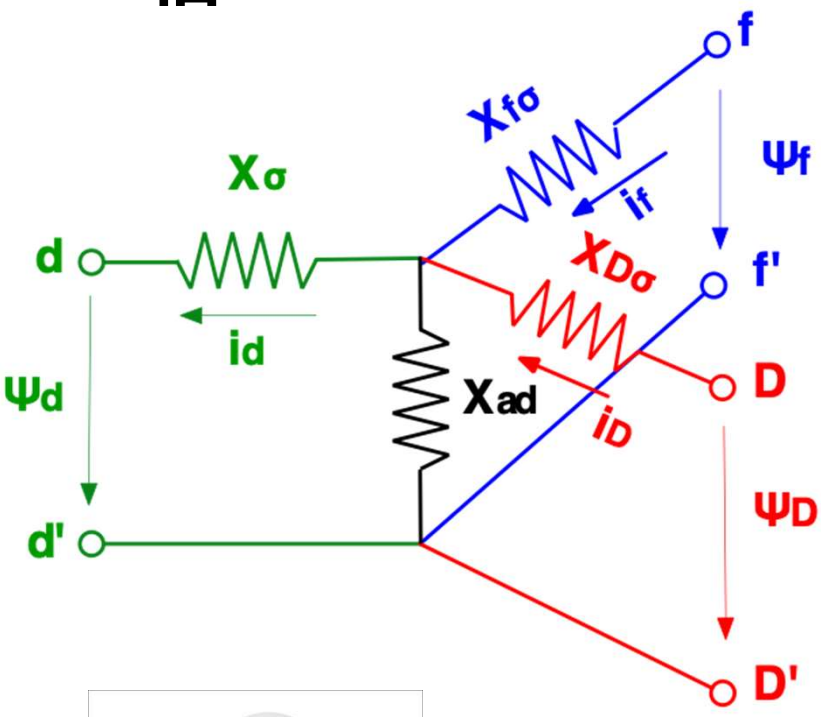
$$T_D = \frac{x_D}{R_D}$$

  - 励磁绕组开路时，Q阻尼绕组本身的时间常数

$$T_Q = \frac{x_Q}{R_Q}$$

派克变换的应用实例之五——有关的时间常数计算

- d轴



- 定子绕组短路、阻尼绕组开路时，励磁绕组的时间常数

$$T_d' = \left(x_{f\sigma} + \frac{x_{ad} x_\sigma}{x_{ad} + x_\sigma} \right) \Big/ R_f$$

- 定子绕组短路、励磁绕组短路（$R_f=0$）时，D阻尼绕组的时间常数

$$T_d'' = \left(x_{D\sigma} + \frac{x_{ad} x_\sigma x_{f\sigma}}{x_{ad} x_\sigma + x_{ad} x_{f\sigma} + x_\sigma x_{f\sigma}} \right) \Big/ R_D$$

派克变换的应用实例之五——有关的时间常数计算

- 定子绕组短路、阻尼绕组开路时，励磁绕组的时间常数

$$T_d' \approx T_f \frac{x_d'}{x_d}$$

$$T_d' = \left(x_{f\sigma} + \frac{x_{ad} x_\sigma}{x_{ad} + x_\sigma} \right) \Big/ R_f$$

- 定子绕组开路、励磁绕组短路 （R_f=0） 时， D阻尼绕组的时间常数

$$T_d'' \approx T_{d|0|}'' \frac{x_d''}{x_d'}$$

$$T_{d0}'' = \frac{1}{R_D}(x_D - \frac{x_{ad}^2}{x_f})$$

$$T_d'' = \left(x_{D\sigma} + \frac{x_{ad} x_\sigma x_{f\sigma}}{x_{ad} x_\sigma + x_{ad} x_{f\sigma} + x_\sigma x_{f\sigma}} \right) \Big/ R_D$$

派克变换的应用实例之五——有关的时间常数计算

$$T_d' \approx T_f \frac{x_d'}{x_d}$$

$$T_d' = \left(x_{f\sigma} + \frac{x_{ad} x_\sigma}{x_{ad} + x_\sigma} \right) \Big/ R_f$$

$$T_d' = T_f \frac{x_d'}{x_d} = \frac{x_f}{R_f} \frac{x_d'}{x_d} = \frac{(x_{f\sigma} + x_{ad})}{R_f} \frac{\left(x_\sigma + \frac{x_{ad} x_{f\sigma}}{x_{f\sigma} + x_{ad}} \right)}{x_d} = \frac{1}{R_f} \frac{(x_{f\sigma} + x_{ad}) x_\sigma + x_{ad} x_{f\sigma}}{x_d}$$

$$= \frac{1}{R_f} \frac{x_{f\sigma} x_\sigma + x_{ad} x_\sigma + x_{ad} x_{f\sigma}}{x_d} = \frac{1}{R_f} \frac{x_{f\sigma}(x_\sigma + x_{ad}) + x_{ad} x_\sigma}{x_d} = \frac{1}{R_f} \left(x_{f\sigma} + \frac{x_{ad} x_\sigma}{x_d} \right)$$

派克变换的应用实例之五——有关的时间常数计算

$$T_d'' \approx T_{d|0|}'' \frac{x_d''}{x_d'}$$

$$T_d'' = \left(x_{D\sigma} + \frac{x_{ad} x_\sigma x_{f\sigma}}{x_{ad} x_\sigma + x_{ad} x_{f\sigma} + x_\sigma x_{f\sigma}} \right) \Big/ R_D$$

$$T_d'' = T_{d|0|}'' \frac{x_d''}{x_d'} = \frac{1}{R_D}\left(x_D - \frac{x_{ad}^2}{x_f}\right)\frac{x_d''}{x_d'}$$

$$= \frac{1}{R_D}\left(x_{D\sigma} + x_{ad} - \frac{x_{ad}^2}{x_f}\right)\frac{\left(x_\sigma + \dfrac{x_{ad}x_{f\sigma}x_{D\sigma}}{x_{ad}x_{f\sigma} + x_{ad}x_{D\sigma} + x_{f\sigma}x_{D\sigma}}\right)}{\left(x_\sigma + \dfrac{x_{ad}x_{f\sigma}}{x_{f\sigma} + x_{ad}}\right)}$$

$$= \frac{1}{R_f}\left(\frac{x_f(x_{D\sigma} + x_{ad}) - x_{ad}^2}{x_f}\right)\frac{\left(x_\sigma + \dfrac{x_{ad}x_{f\sigma}x_{D\sigma}}{x_{ad}x_{f\sigma} + x_{ad}x_{D\sigma} + x_{f\sigma}x_{D\sigma}}\right)}{\left(x_\sigma + \dfrac{x_{ad}x_{f\sigma}}{x_f}\right)}$$

$$= \frac{1}{R_f}\left(\frac{(x_{f\sigma} + x_{ad})(x_{D\sigma} + x_{ad}) - x_{ad}^2}{x_f}\right)\frac{\left(x_\sigma + \dfrac{x_{ad}x_{f\sigma}x_{D\sigma}}{x_{ad}x_{f\sigma} + x_{ad}x_{D\sigma} + x_{f\sigma}x_{D\sigma}}\right)}{\left(\dfrac{x_\sigma x_f + x_{ad}x_{f\sigma}}{x_f}\right)}$$

$$= \frac{1}{R_f}\left(\frac{x_{f\sigma}x_{D\sigma} + x_{ad}x_{D\sigma} + x_{f\sigma}x_{ad}}{x_\sigma x_f + x_{ad}x_{f\sigma}}\right)\left(\frac{x_\sigma x_{ad}x_{f\sigma} + x_\sigma x_{ad}x_{D\sigma} + x_\sigma x_{f\sigma}x_{D\sigma} + x_{ad}x_{f\sigma}x_{D\sigma}}{x_{ad}x_{f\sigma} + x_{ad}x_{D\sigma} + x_{f\sigma}x_{D\sigma}}\right)$$

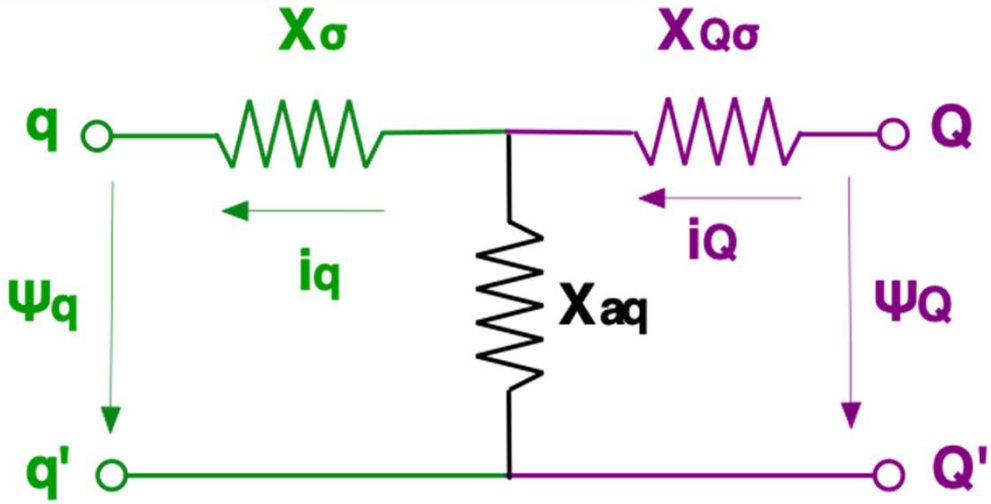
$$= \frac{1}{R_f}\left(\frac{x_\sigma x_{ad}x_{f\sigma} + x_\sigma x_{ad}x_{D\sigma} + x_\sigma x_{f\sigma}x_{D\sigma} + x_{ad}x_{f\sigma}x_{D\sigma}}{x_\sigma(x_{f\sigma} + x_{ad}) + x_{ad}x_{f\sigma}}\right)$$

$$= \frac{1}{R_f}\left(\frac{x_\sigma x_{ad}x_{f\sigma} + x_\sigma x_{ad}x_{D\sigma} + x_\sigma x_{f\sigma}x_{D\sigma} + x_{ad}x_{f\sigma}x_{D\sigma}}{x_\sigma x_{f\sigma} + x_\sigma x_{ad} + x_{ad}x_{f\sigma}}\right)$$

$$= \frac{1}{R_f}\left(x_{D\sigma} + \frac{x_\sigma x_{ad}x_{f\sigma}}{x_\sigma x_{f\sigma} + x_\sigma x_{ad} + x_{ad}x_{f\sigma}}\right)$$

派克变换的应用实例之五——有关的时间常数计算

- q轴



- 定子绕组短路、励磁绕组短路时，Q阻尼绕组的间常数

$$T_q''=\left(x_{Q\sigma}+\frac{x_{aq}x_\sigma}{x_{aq}+x_\sigma}\right)\Big/R_Q$$

$$T_q''\approx T_Q\frac{x_q''}{x_q}$$

$$T_Q=\frac{x_Q}{R_Q}$$

派克变换的应用实例之五——有关的时间常数计算

$$T_q''=\left(x_{Q\sigma}+\frac{x_{aq}x_\sigma}{x_{aq}+x_\sigma}\right)\Big/R_Q$$

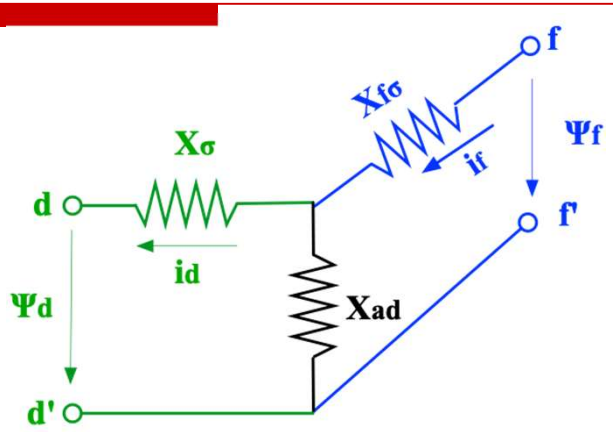
$$T_q''\approx T_Q\frac{x_q''}{x_q}$$

$$\begin{aligned}T_q''&=\frac{1}{R_Q}\left(x_{Q\sigma}+\frac{x_\sigma x_{aq}}{x_\sigma+x_{aq}}\right)=\frac{1}{R_Q}\left(\frac{x_{Q\sigma}(x_\sigma+x_{aq})+x_\sigma x_{aq}}{x_\sigma+x_{aq}}\right)\\&=\frac{1}{R_Q}\left(\frac{x_{Q\sigma}x_\sigma+x_{Q\sigma}x_{aq}+x_\sigma x_{aq}}{x_q}\right)=\frac{1}{R_Q}\left(\frac{x_\sigma(x_{Q\sigma}+x_{aq})+x_{Q\sigma}x_{aq}}{x_q}\right)\\&=\frac{1}{R_Q}\left(\frac{x_\sigma x_Q+x_{Q\sigma}x_{aq}}{x_q}\right)=\frac{x_Q}{R_Q}\frac{\left(x_\sigma+\frac{x_{Q\sigma}x_{aq}}{x_Q}\right)}{x_q}=T_Q\frac{\left(x_\sigma+\frac{x_{Q\sigma}x_{aq}}{x_{Q\sigma}+x_{aq}}\right)}{x_q}\\&=T_Q\frac{x_q''}{x_q}\end{aligned}$$

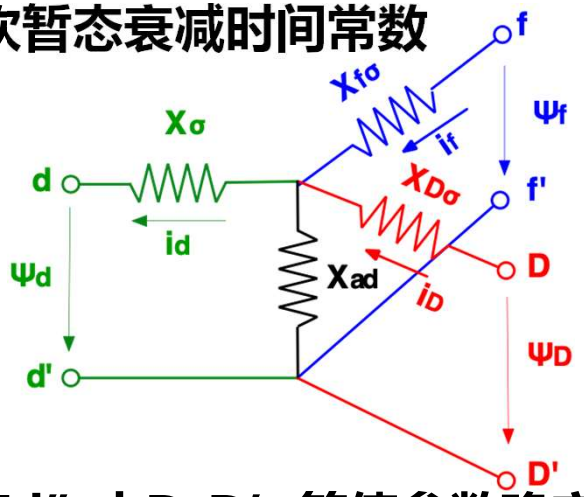
派克变换的应用实例之五——有关的时间常数计算

- 暂态衰减时间常数
  - Td ‘由f-f’ 等值参数确定

$$T_d' = \left(x_{f\sigma} + \frac{x_{ad} x_\sigma}{x_{ad} + x_\sigma} \right) \Big/ R_f$$

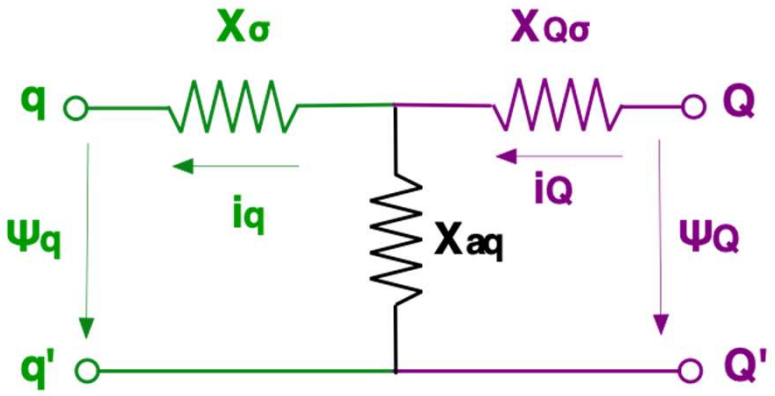


- 次暂态衰减时间常数



  - Td” 由D-D’ 等值参数确定

$$T_d'' = \left(x_{D\sigma} + \frac{x_{ad} x_\sigma x_{f\sigma}}{x_{ad} x_\sigma + x_{ad} x_{f\sigma} + x_\sigma x_{f\sigma}} \right) \Big/ R_D$$

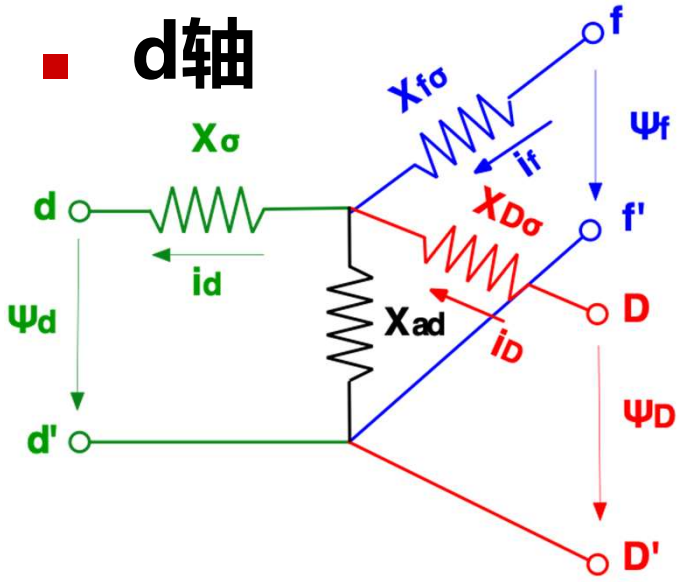


  - Tq” 由Q-Q ‘等值参数确定

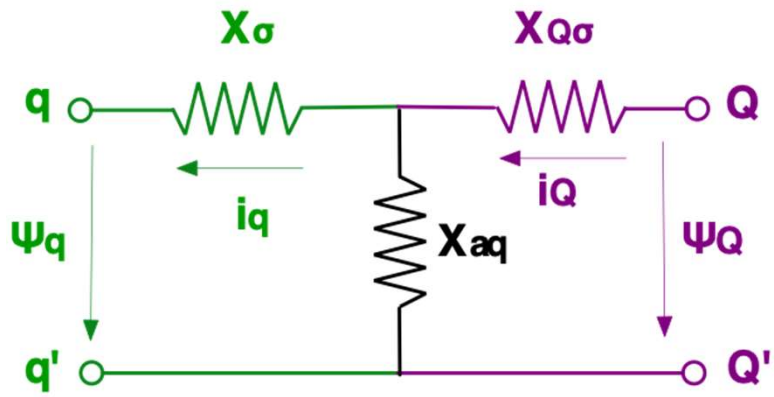
$$T_q'' = \left(x_{Q\sigma} + \frac{x_{aq} x_\sigma}{x_{aq} + x_\sigma} \right) \Big/ R_Q$$

派克变换的应用实例之五——有关的时间常数计算

- d轴



- q轴



- 励磁绕组短路、定子绕组的时间常数：
  - 无阻尼绕组时

$$T_a = \frac{2x'_d x_q}{R(x'_d + x_q)}$$

  - 阻尼绕组短路 （R_D、R_Q =0） 时

$$T_a = \frac{2x''_d x''_q}{R(x''_d + x''_q)}$$

自动调节励磁装置对短路电流的影响

- 当同步发电机端电压波动时，自动调节励磁装置将自动的调节励磁电压，以改变励磁电流，由此改变发电机的空载电动势，以便维持发电机端电压在允许范围内。

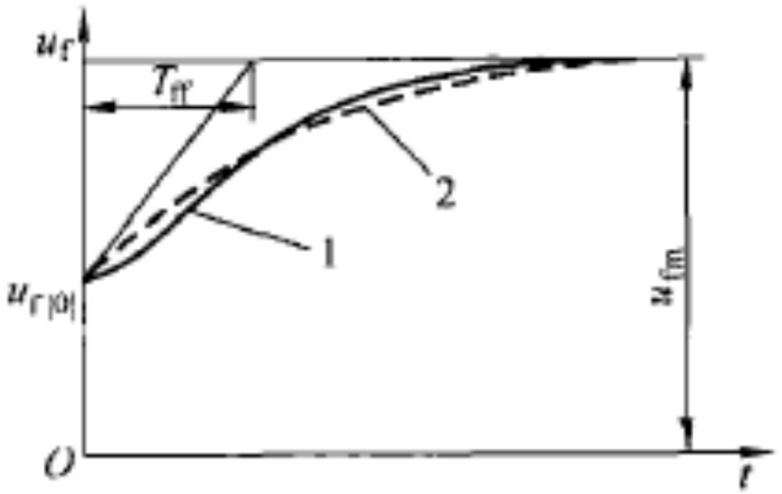


图 1-37　u_f 的变化曲线

- 当同步发电机端附近突然短路，强行励磁会对短路电流产生明显影响，其他控制由于限幅环节的作用，对短路电流影响不大。
- 由于励磁机励磁绕组具有电感，它的电流不可能突然增大，以致与之对应的励磁机电压也不可能突然升高。
- 开始上升较慢，后来上升较快。

自动调节励磁装置对短路电流的影响

- 如果在励磁电压升高过程中发电机端电压恢复到额定电压，强行励磁装置中的低压继电器就会返回，励磁电压也就不会再继续升高。

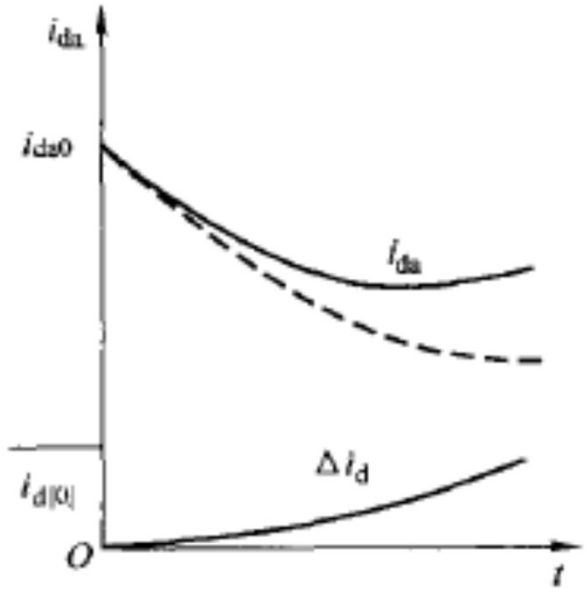


图 1-40　强行励磁对 i_{da} 变化的影响

- 对应的a相电流中的附加分量为

$$\Delta i_a = \frac{\Delta E_{qm}}{X_d}\left(1 - \frac{T_d' e^{\frac{-t}{T_d'}} - T_{ff} e^{\frac{-t}{T_{ff}}}}{T_d' - T_{ff}}\right)\cos(\omega t + \theta_0)$$

$$= \frac{\Delta E_{qm}}{X_d} F(t)\cos(\omega t + \theta_0)$$

主观题 1分

Setting

同学们，恭喜你，本课程最难的部分你已经学完了。接下来，我们在进入机电暂态的内容之前，需要一次期中考试，往年都是纸质版闭卷考试，今年情况特殊，现征集意见或建议：

1、对本部分内容的意见或者建议。

2、对期中考试形式的意见或建议。

3、其他与本课程有关的意见或建议。

Answer