华中科技大学
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《电力系统分析》（I）

主讲教师：孙海顺

E-mail：haishunsun@hust.edu.cn

第五章 电力系统三相短路的暂态过程

本章主要内容

讨论电力系统突然短路时的电磁暂态现象及其分析方法。

包括：（1）恒定电势源电路突然三相短路；

（2）同步发电机突然短路暂态过程的物理分析

（3）同步发电机常用暂态参数的定义

（4）定转子绕组短路电流起始值的计算

基本原理：超导体闭合回路磁链守恒原则

第五章 电力系统三相短路的暂态过程

5-1 短路的一般概念

5-2 恒定电势源电路的三相短路

5-3 同步电机突然三相短路的物理分析

5-4 无阻尼绕组同步电机三相短路电流计算

5-5 有阻尼绕组同步电机的突然三相短路

5-1 短路的一般概念

1. 短路的原因、类型及后果

$f^{(3)}$　　$f^{(1)}$　　$f^{(2)}$　　$f^{(1,1)}$

2. 短路计算的目的

(1) 电动力稳定度——冲击电流

(2) 热稳定度——短路电流周期分量

(3) 设备容量校验——短路电流有效值

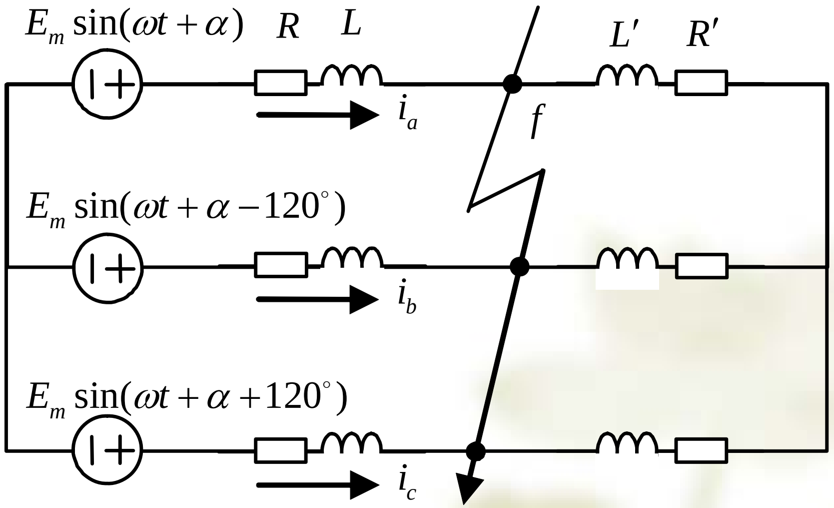
(4) 继电保护和自动装置整定——短路电流周期分量

(5) 输电线路对通信的干扰——零序电流分量

5-2 恒定电势源电路的三相短路

1. 短路的暂态过程——短路前稳态

三相对称，以a相为例



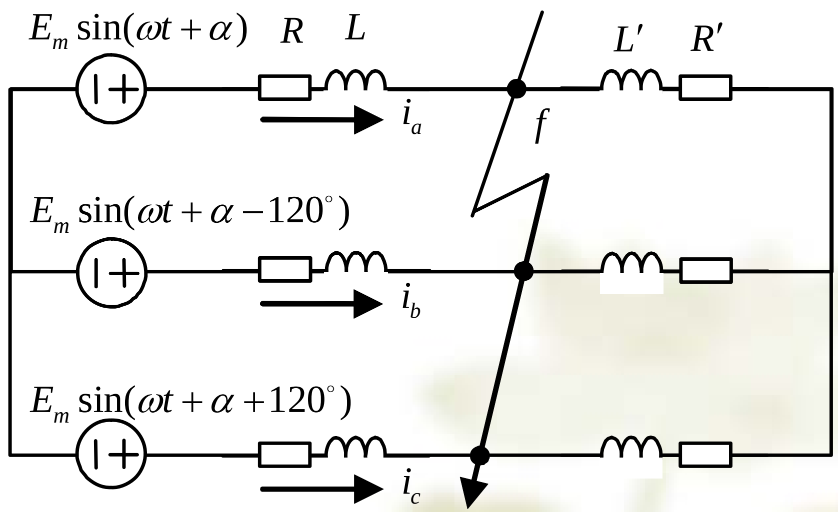
$$e = E_m \sin(\omega t + \alpha)$$
$$i = I_m \sin(\omega t + \alpha - \varphi')$$

$$I_m = \frac{E_m}{\sqrt{(R+R')^2 + \omega^2 (L+L')^2}}; \quad \varphi' = arctg\frac{\omega\left(L+L'\right)}{R+R'}$$

5-2 恒定电势源电路的三相短路

1. 短路的暂态过程——短路状态

三相对称，以a相为例



$$Ri + L\frac{di}{dt} = E_m \sin(\omega t + \alpha)$$

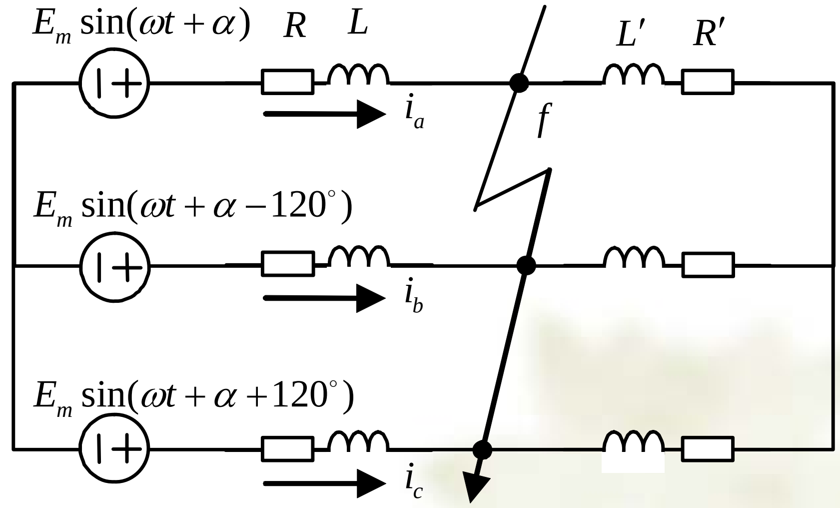
$$i_p = I_{pm} \sin(\omega t + \alpha - \varphi)$$

$$i_{ap} = Ce^{\lambda t} = C\exp\left(-t/T_a\right)$$

$$I_{pm} = \frac{E_m}{\sqrt{R^2 + (\omega L)^2}}; \quad \varphi = arctg\left(\frac{\omega L}{R}\right); \quad \lambda = -\frac{R}{L}; \quad T_a = \frac{L}{R}$$

5-2 恒定电势源电路的三相短路

1. 短路的暂态过程——短路状态



$$Ri + L\frac{di}{dt} = E_m \sin(\omega t+\alpha)$$

$$i_p = I_{pm}\sin(\omega t+\alpha-\varphi)$$

$$i_{ap} = Ce^{\lambda t} = C\exp\left(-t/T_a\right)$$

$$i = i_p + i_{ap} = I_{pm}\sin(\omega t+\alpha-\varphi) + C\exp\left(-t/T_a\right)$$

α：合闸角

t=0

$$I_m\sin(\alpha-\varphi') = I_{pm}\sin(\alpha-\varphi) + C$$

$C = i_{ap0}$

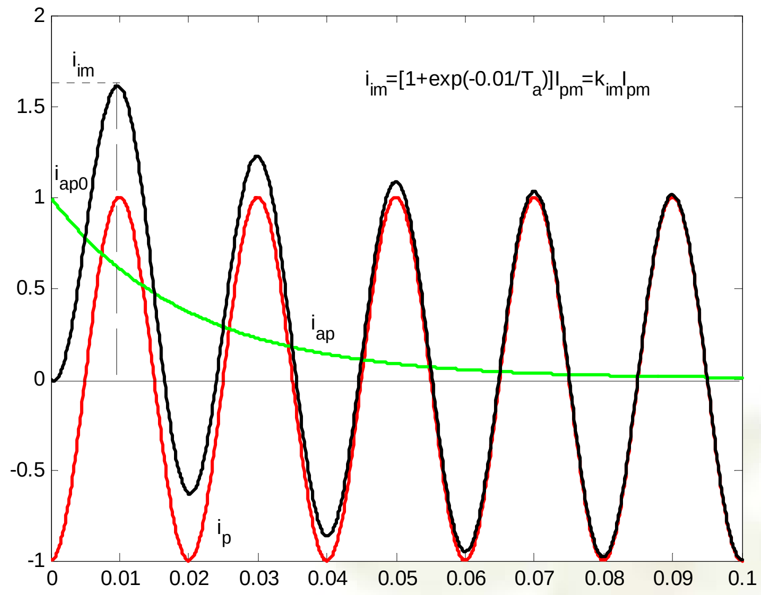
$$i = I_{pm}\sin(\omega t+\alpha-\varphi) + \left[I_m\sin(\alpha-\varphi') - I_{pm}\sin(\alpha-\varphi)\right]\exp\left(-t/T_a\right)$$

5-2 恒定电势源电路的三相短路

主要结论：

（1）定义短路发生时刻系统A相电势源电压相位α为**合闸角**；

（2）短路电流包含**周期分量**和**直流分量**；



（3）短路电流周期分量**幅值恒定**；

（4）直流分量为**衰减分量**，其初始值大小与短路**合闸角**有关；

空载，$\varphi = 90^\circ$：$i_{ap0} = I_{pm}\cos\alpha, \alpha = 0^\circ$时最大；$\alpha = 90^\circ$时为零；

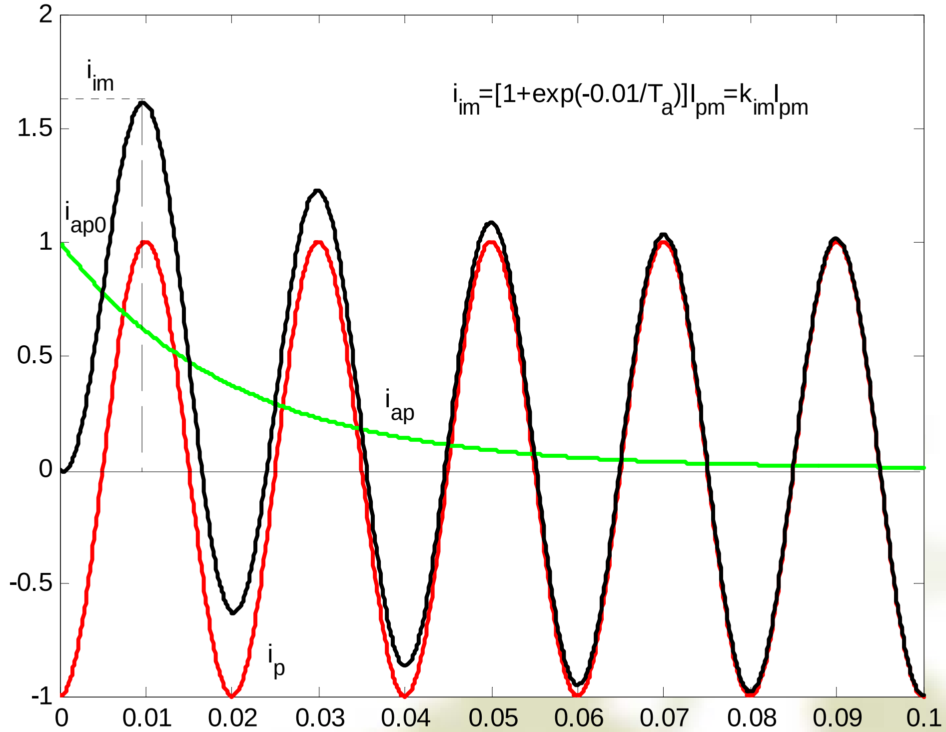
$$i = I_{pm}\sin(\omega t + \alpha - \varphi) + \left[I_m \sin(\alpha - \varphi') - I_{pm}\sin(\alpha - \varphi) \right] \exp\left(-t/T_a\right)$$

5-2 恒定电势源电路的三相短路

2. 短路冲击电流

短路电流最大可能瞬时值：

- 空载；
- 纯感性电路；
- 合闸角0°；
- 短路后半个周波时刻；



$$i = I_{pm}\left[1+\exp\left(-0.01/T_a\right)\right] = k_{im}I_{pm}$$

$$i = -I_{pm}\cos\omega t + I_{pm}\exp\left(-t/T_a\right)$$

$$\left(\alpha-\varphi\right) = -90^\circ, \varphi = 90^\circ, \alpha = 0^\circ$$

$$i = I_{pm}\sin(\omega t+\alpha-\varphi)+\left[I_m\sin(\alpha-\varphi')-I_{pm}\sin(\alpha-\varphi)\right]\exp\left(-t/T_a\right)$$

5-2 恒定电势源电路的三相短路

2. 短路冲击电流——冲击系数kim

发电机端母线： $k_{im}=1.9$

发电厂高压母线： $k_{im}=1.85$

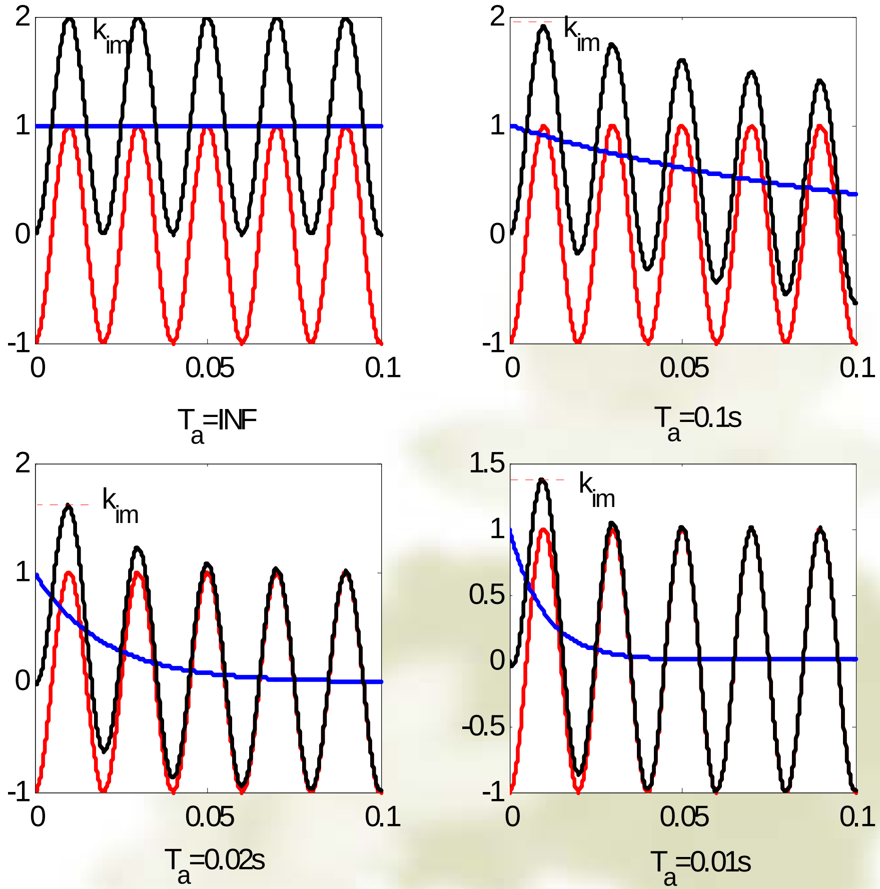
其他地点： $k_{im}=1.8$

$$k_{im}=1+\exp\left(-0.01/T_a\right)$$

$$1.0\le k_{im}\le 2.0$$

$$T_a=L/R$$

$$i=I_{pm}\left[1+\exp\left(-0.01/T_a\right)\right]=k_{im}I_{pm}$$



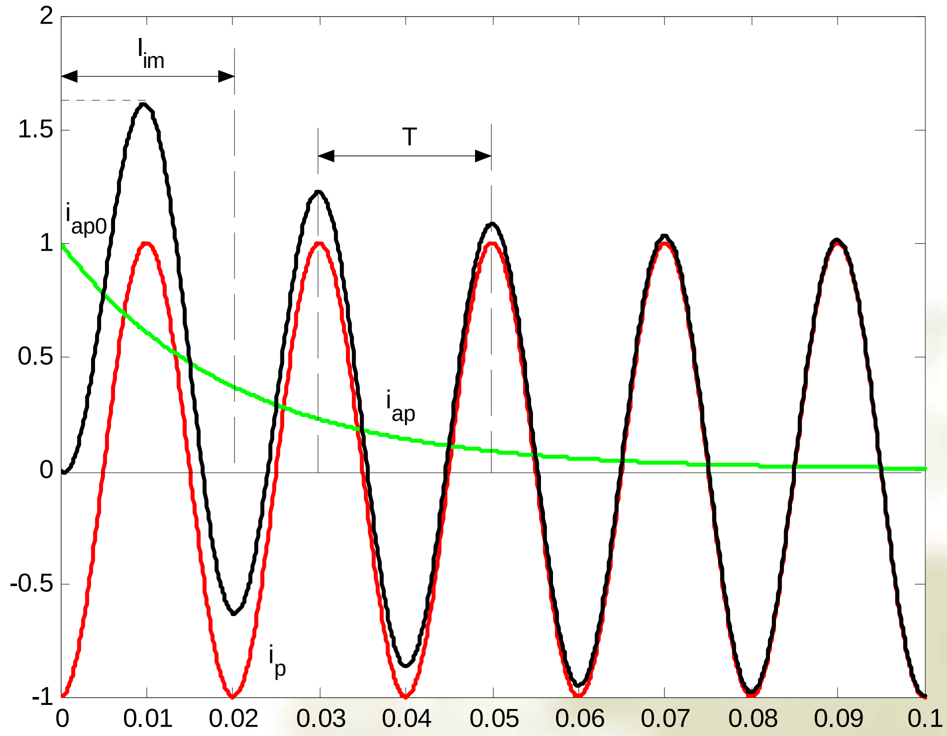
5-2 恒定电势源电路的三相短路

3. 短路电流有效值——定义、近似计算、最大值

$$I_t = \sqrt{\frac{1}{T}\int_{t-T/2}^{t+T/2} i_t^2 dt} = \sqrt{\frac{1}{T}\int_{t-T/2}^{t+T/2} \left(i_{pt} + i_{apt}\right)^2 dt}$$

$$I_t = \sqrt{I_{pt}^2 + I_{apt}^2}$$

$$I_{im} = \sqrt{I_p^2 + \left[\left(k_{im} - 1\right)\sqrt{2} I_p\right]^2}$$



5-2 恒定电势源电路的三相短路

4. 短路容量——定义、标幺值

短路电流有效值与短路处正常工作电压的乘积

$$S_t = \sqrt{3} V_{av} I_t$$

标幺值

$$S_{t*} = \frac{\sqrt{3} V_{av} I_t}{\sqrt{3} V_B I_B} = \frac{I_t}{I_B} = I_{t*}$$

一般采用短路电流周期分量的初始有效值（I_p）与短路处平均额定电压（V_{av}）的乘积

5-3 同步电机突然三相短路的物理分析

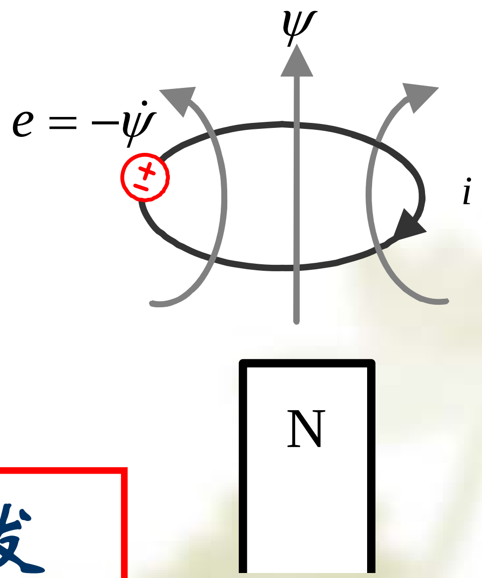
1. 超导体闭合回路磁链守恒原则

$$\frac{d\psi}{dt} + Ri = 0$$

R=0

$$\frac{d\psi}{dt} = 0$$

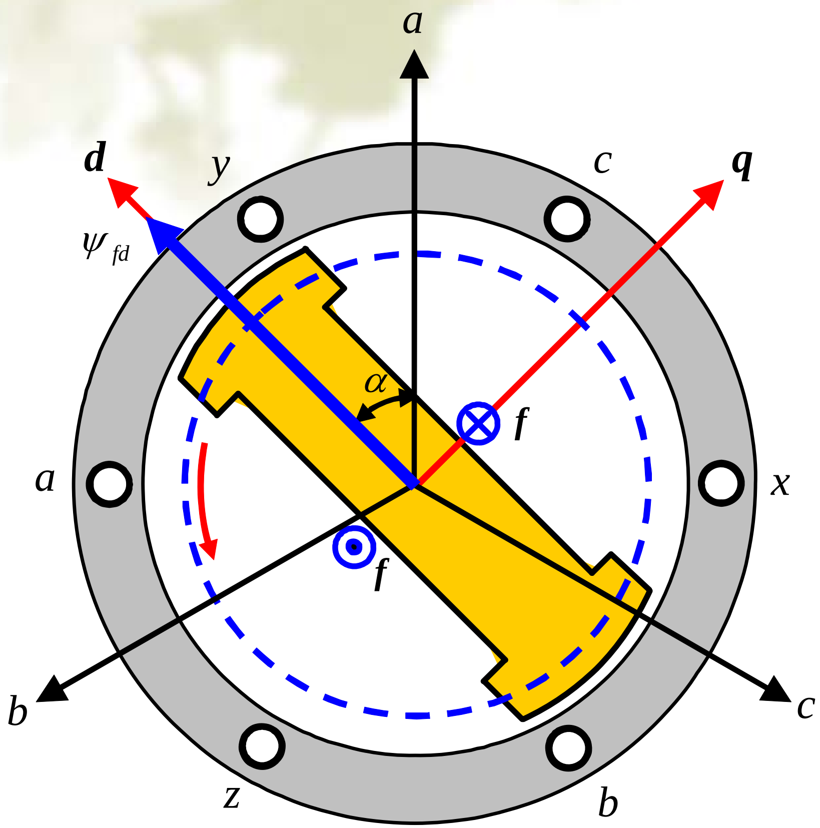
$$Li + \psi = \psi_0$$

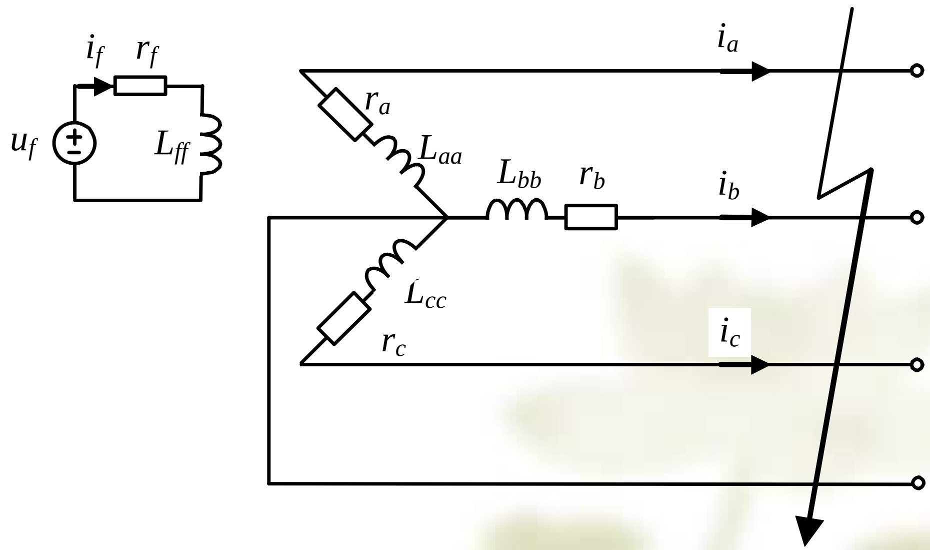


楞次定则：任何闭合线圈在发生突然变化的瞬间，都能维持磁链不变。

5-3 同步电机突然三相短路的物理分析

2. 无阻尼绕组同步电机突然三相短路的物理分析

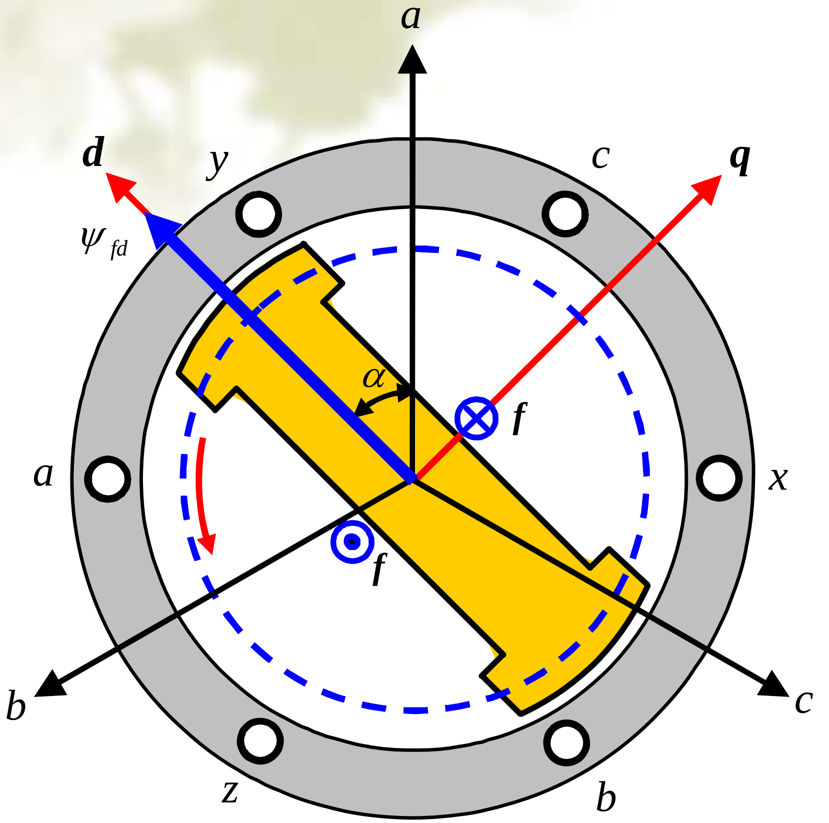


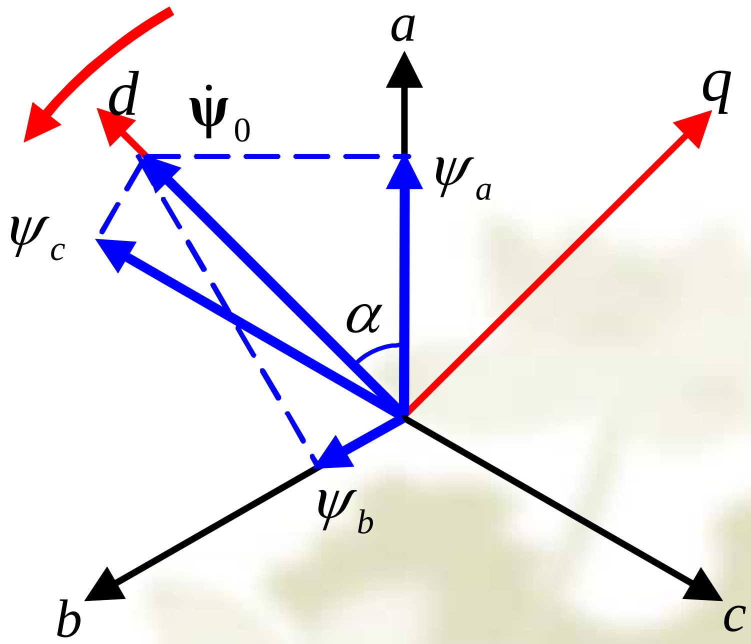


短路发生的瞬间，定转子各相线组磁链维持为短路前初值不变

2. 无阻尼绕组同步电机突然三相短路的物理分析

(1) 短路前定子各相绕组磁链——仅有励磁电流作用

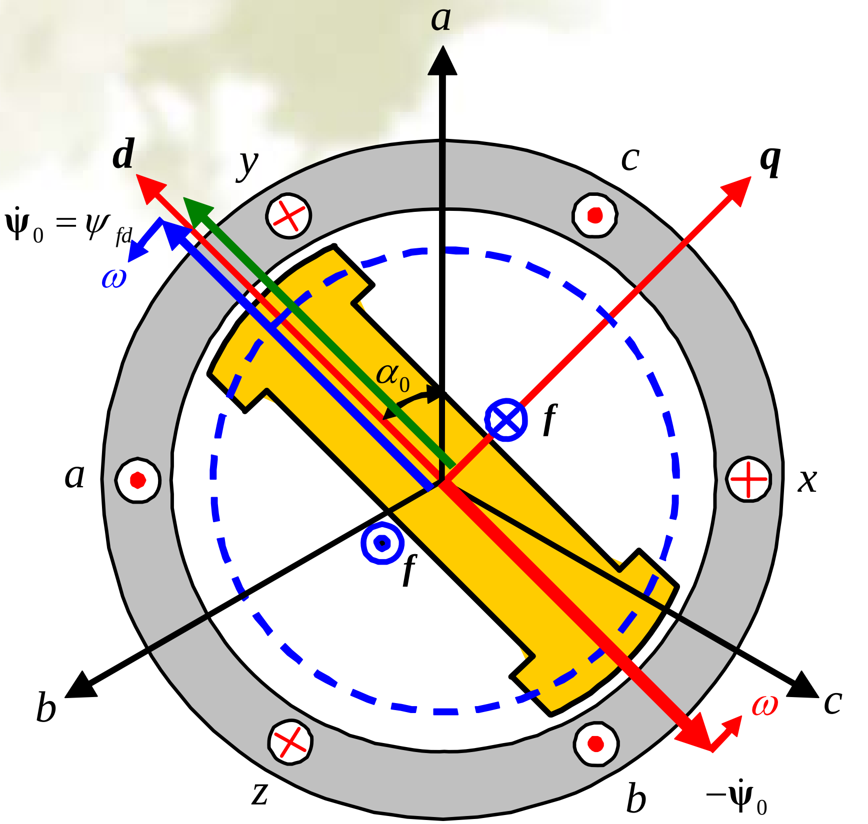




$$\psi_a = \boldsymbol{\psi}_0 \cos\left(\omega t + \alpha_0\right),\ \psi_b = \boldsymbol{\psi}_0 \cos\left(\omega t + \alpha_0 - 120^\circ\right),\ \psi_c = \boldsymbol{\psi}_0 \cos\left(\omega t + \alpha_0 + 120^\circ\right)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(2) 短路瞬间定子绕组磁链守恒——定子电流+励磁电流



短路发生的瞬间，定子各相绕组磁链维持为短路前瞬间初值不变

$$\psi_{a0} = \Delta\psi_a + \Psi_0 \cos(\omega t + \alpha_0)$$

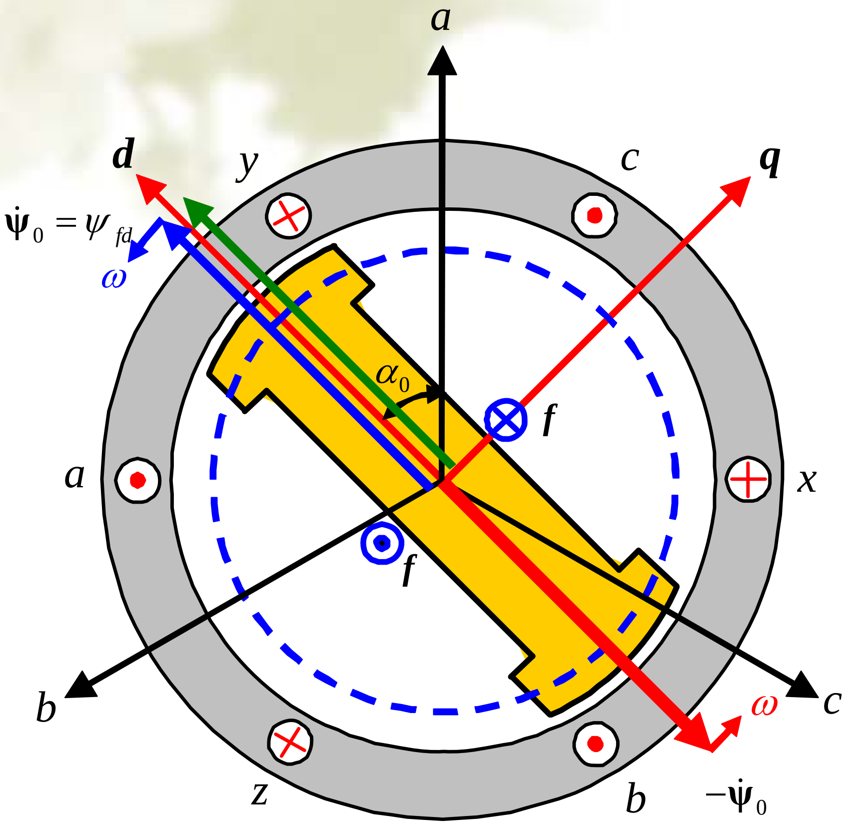
$$\psi_{b0} = \Delta\psi_b + \Psi_0 \cos(\omega t + \alpha_0 - 120^\circ)$$

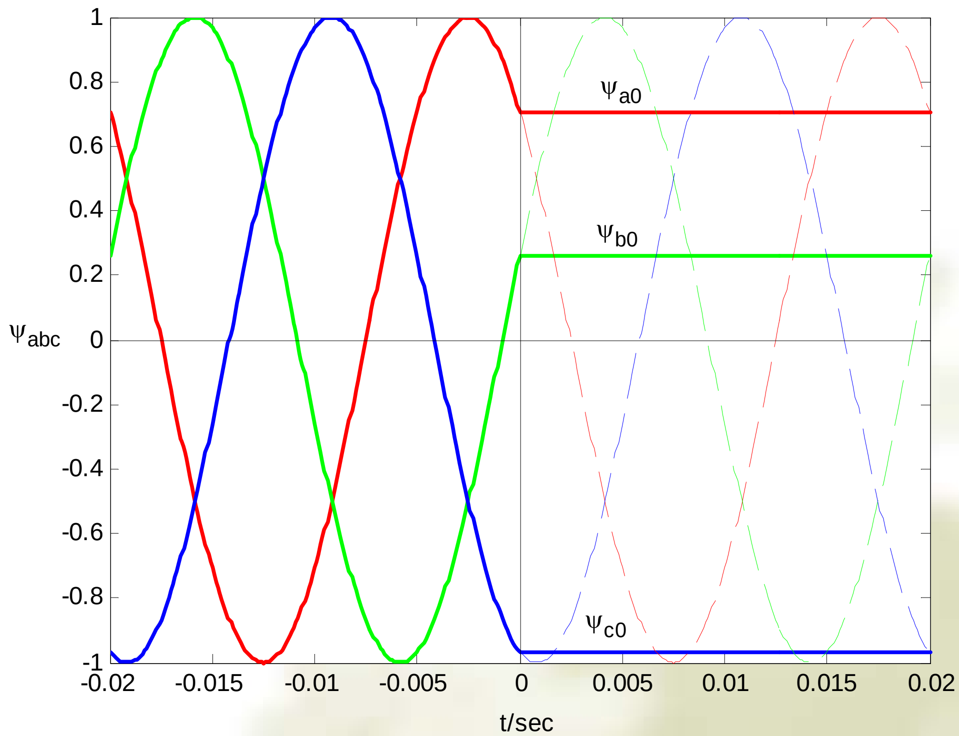
$$\psi_{c0} = \Delta\psi_c + \Psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

$$\psi_{a0} = \Psi_0 \cos\alpha_0, \quad \psi_{b0} = \Psi_0 \cos(\alpha_0 - 120^\circ), \quad \psi_{c0} = \Psi_0 \cos(\alpha_0 + 120^\circ)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(2) 短路瞬间定子绕组磁链守恒——定子电流+励磁电流



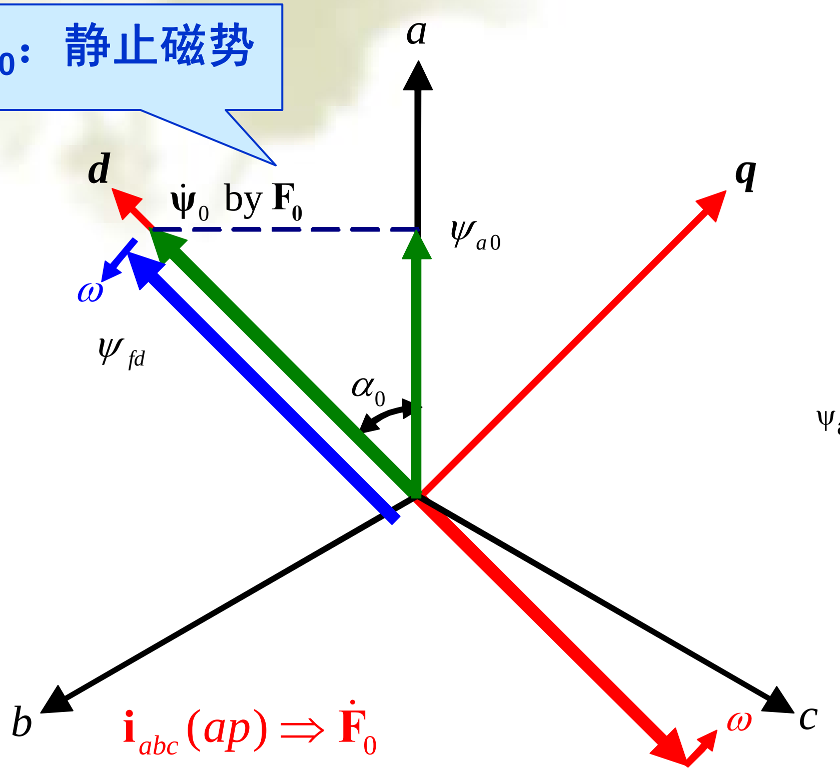


$$\psi_{a0} = \boldsymbol{\psi}_0 \cos\alpha_0,\ \ \psi_{b0} = \boldsymbol{\psi}_0 \cos\left(\alpha_0 - 120^\circ\right),\ \ \psi_{c0} = \boldsymbol{\psi}_0 \cos\left(\alpha_0 + 120^\circ\right)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

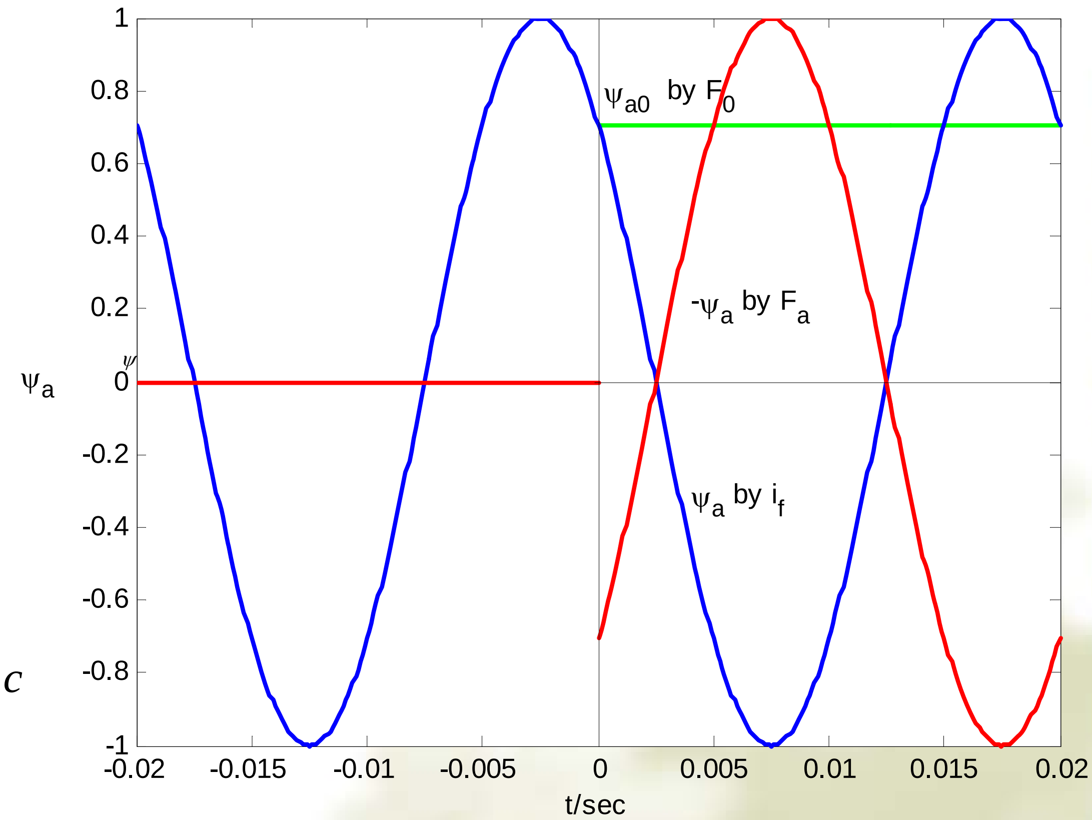
(2) 短路瞬间定子绕组磁链守恒——定子直流+基频电流

F0：静止磁势



$\mathbf{i}_{abc}(ap) \Rightarrow \dot{\mathbf{F}}_0$

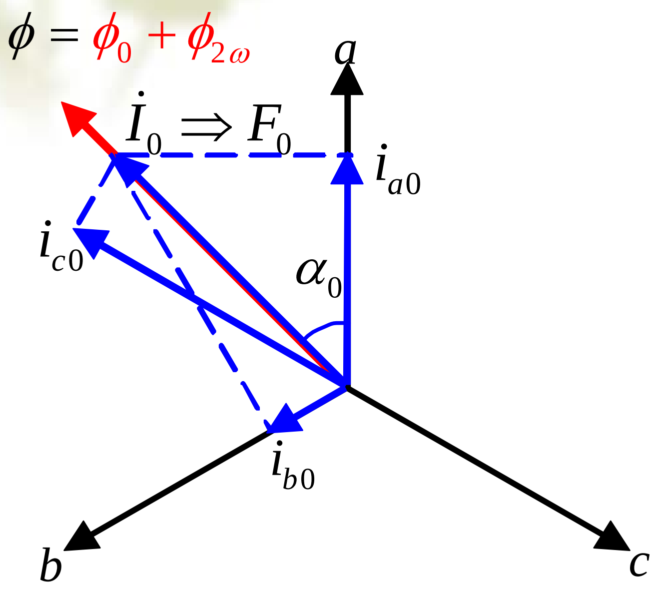
$\mathbf{i}_{abc}(\omega) \Rightarrow \dot{\mathbf{I}}(-i_d) \Rightarrow \dot{\mathbf{F}}_a$

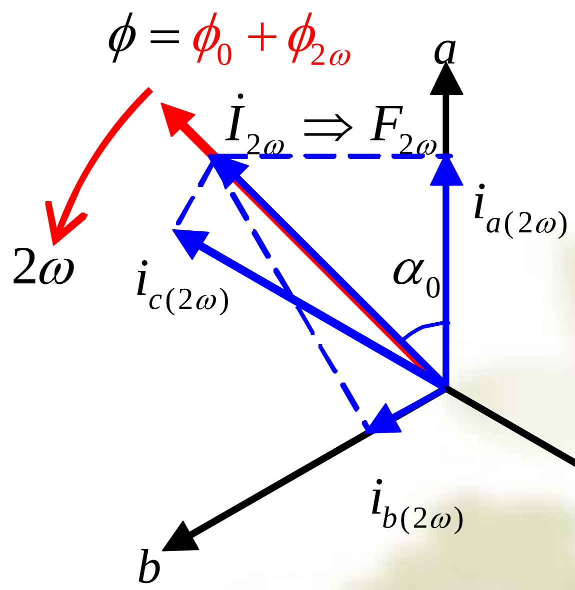


$$\psi_{a0} = \Delta\psi_a + \boldsymbol{\psi}_0 \cos(\omega t + \alpha_0) = [\psi_{a0} \text{ by } F_0]_{ap} + [\psi_a \text{ by } F_a]_{\omega} + \boldsymbol{\psi}_0 \cos(\omega t + \alpha_0)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(2) 短路瞬间定子绕组磁链守恒——定子直流+倍频电流





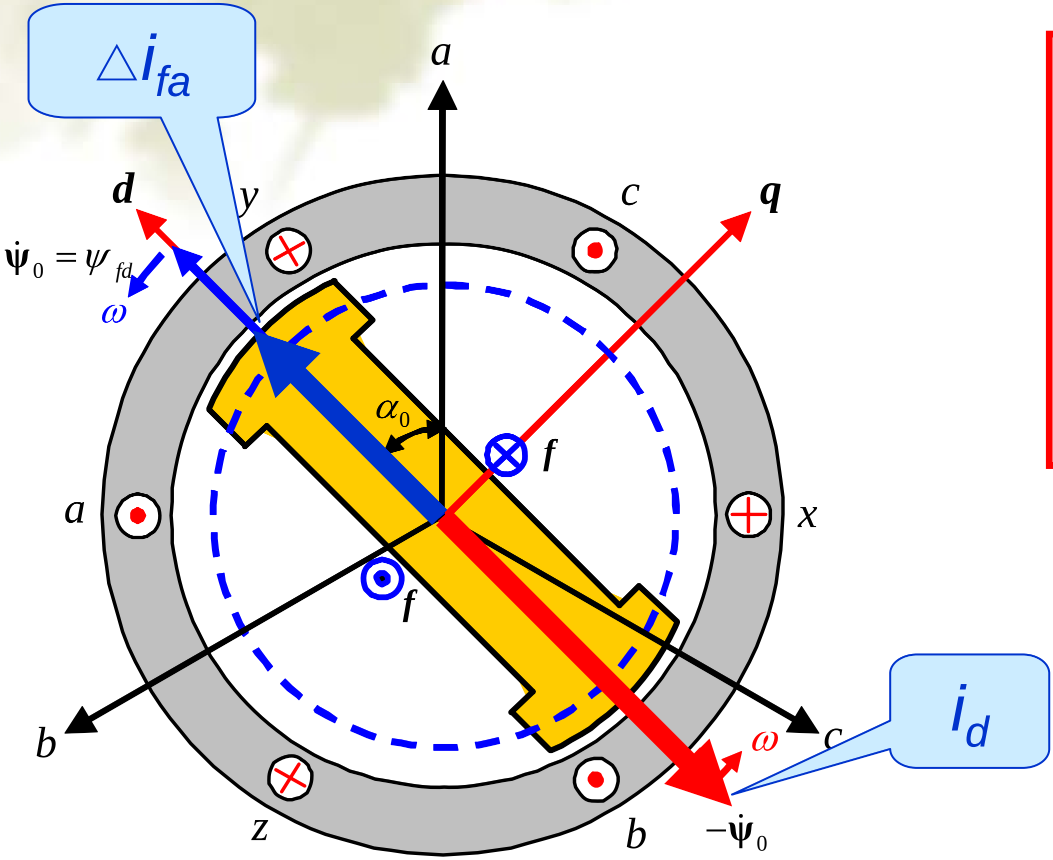
$$i_{abc(ap)} \Rightarrow F_0 \Rightarrow \phi_0' + \phi_{2\omega}' \Rightarrow \psi_0' + \psi_{2\omega}'$$

$$i_{abc(2\omega)} \Rightarrow F_0 \Rightarrow \phi_0'' + \phi_{2\omega}'' \Rightarrow \psi_0'' + \psi_{2\omega}''$$

$$\psi_{a0} = \Delta\psi_a + \Psi_0\cos(\omega t + \alpha_0), \psi_{b0} = \Delta\psi_b + \Psi_0\cos(\omega t + \alpha_0 - 120^\circ), \psi_{c0} = \Delta\psi_c + \Psi_0\cos(\omega t + \alpha_0 + 120^\circ)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(2) 短路瞬间转子绕组磁链守恒——励磁电流直流分量



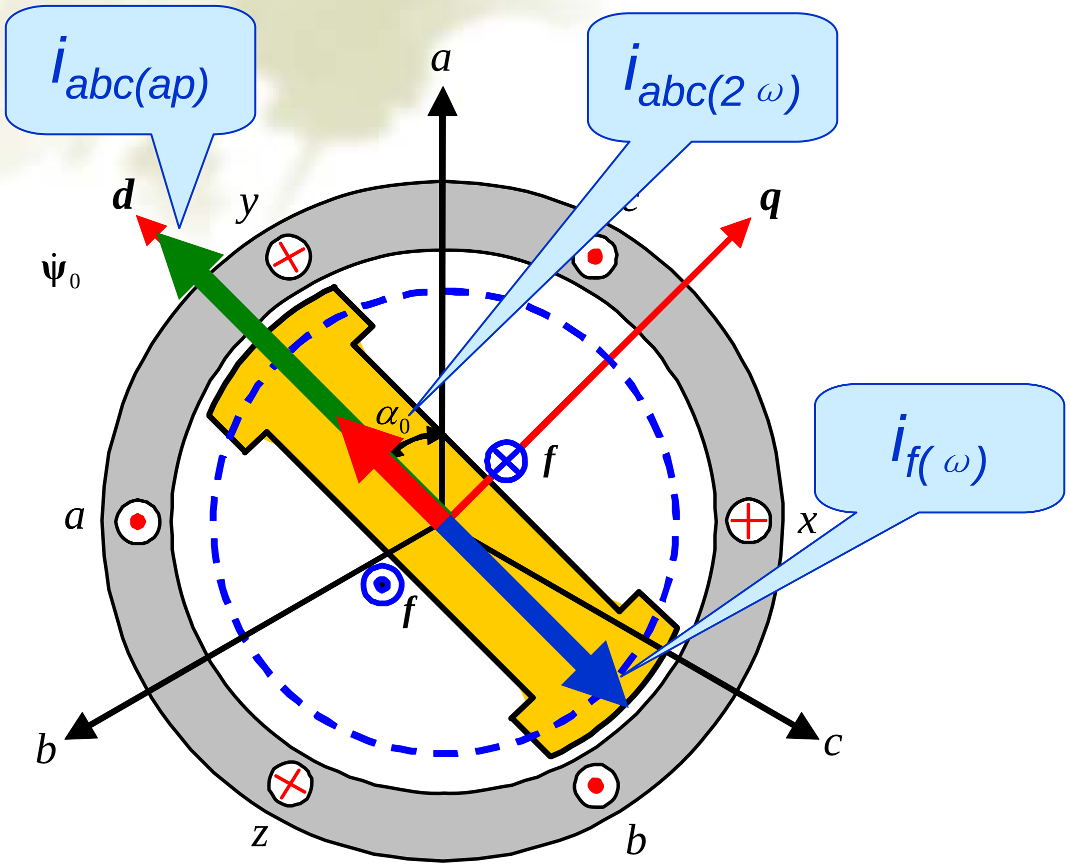
$$\psi_{f0} = \Delta\psi_f + \psi_{f[0]} \Rightarrow \Delta\psi_f = 0$$

为了维持磁链守恒，励磁绕组将产生附加直流电流分量，抵消定子基频电流的电枢反应；

励磁绕组附加直流电流反过来又激起更大的定子基频电流，以保持定子磁链守恒；

2. 无阻尼绕组同步电机突然三相短路的物理分析

(2) 短路瞬间转子绕组磁链守恒——励磁电流基频分量



$$\psi_{f0} = \Delta\psi_f + \psi_{f[0]} \Rightarrow \Delta\psi_f = 0$$

定子非周期电流产生空间静止磁势，会在转子绕组中感生**基频电流**

该励磁电流**基频分量**抵消**定子直流和倍频电流**作用下产生的交变磁链；

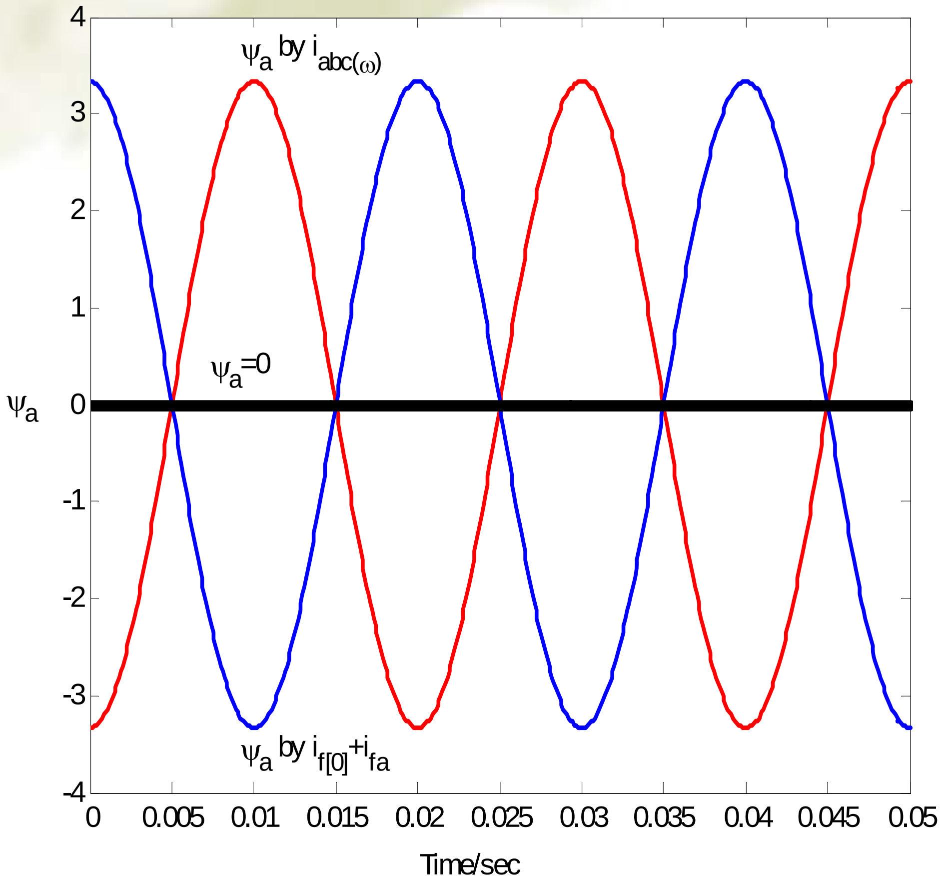
2. 无阻尼绕组同步电机突然三相短路的物理分析

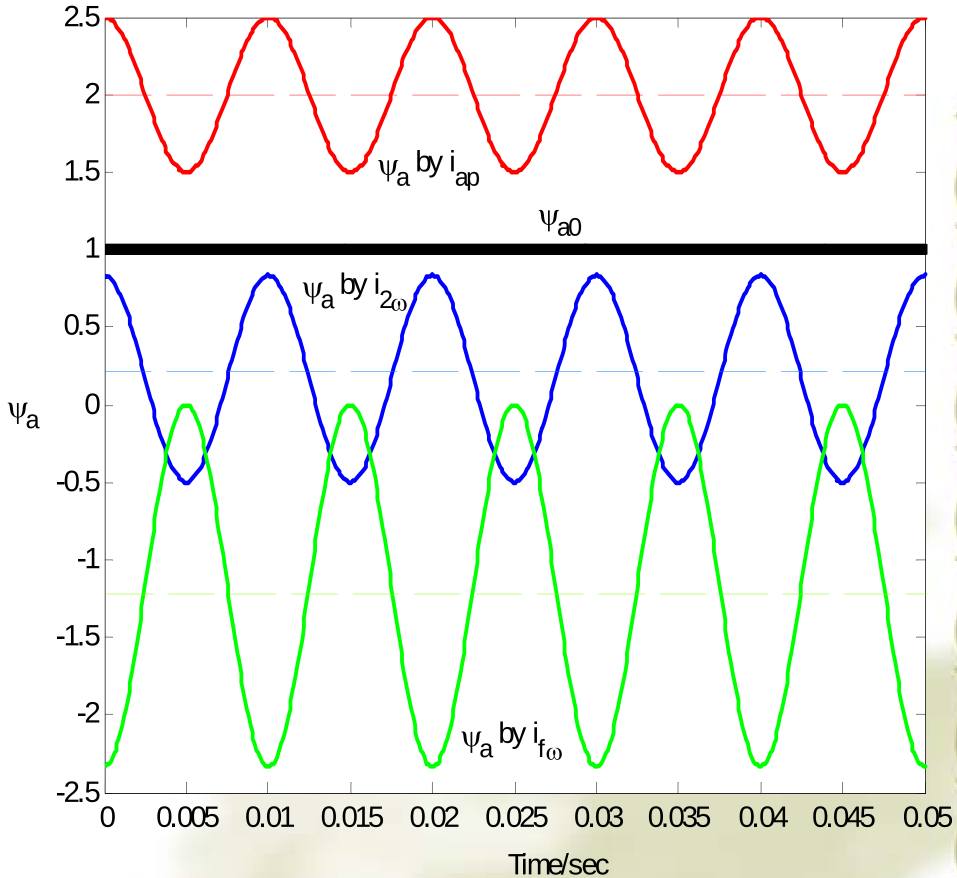
(3) 定转子绕组各种电流分量及其相互关系

	t=0-	t=0+					
$\mathbf{i}_{abc}$	0		$\mathbf{i}_{abc(\omega)}$	↑	$\mathbf{i}_{abc(ap)}$		$\mathbf{i}_{abc(2\omega)}$
Ψ_{abc}	Ψ_{abc0}	$\Psi_{(\omega)}^{i_f}$	$\Psi_{(\omega)}^{\mathbf{i}_{abc}}$	$\Psi_{(\omega)}^{\Delta i_{fa}}$	$\Psi_{(-)}^{ap}$ $\Psi_{(2\omega)}^{ap}$	$\Psi_{(-)}^{i_{f\omega}}$ $\Psi_{2\omega}^{i_{f\omega}}$	$\Psi_{(-)}^{2\omega}$ $\Psi_{(2\omega)}^{2\omega}$
ψ_f	$\psi_{f[0]}$	$\psi_{f[0]}$	$\psi_{(-)}^{\mathbf{i}_{abc}}$	$\psi_{(-)}^{\Delta i_{fa}}$	$\Psi_{(\omega)}^{ap}$	$\Psi_{(\omega)}^{i_{f\omega}}$	$\Psi_{(\omega)}^{2\omega}$
i_f	$i_{f[0]}$	$i_{f[0]}$		Δi_{fa}		$\Delta i_{f\omega}$	

2. 无阻尼绕组同步电机突然三相短路的物理分析

(3) 定转子绕组各种电流分量及其相互关系





$$\psi_a = \psi_{(\omega)}^{i_{f[0]}+\Delta i_{fa},\mathbf{i}_{abc(\omega)}} + \psi_{(-)}^{\mathbf{i}_{abc(ap)},\mathbf{i}_{abc(2\omega)},\Delta i_{f\omega}} + \psi_{(2\omega)}^{\mathbf{i}_{abc(ap)},\mathbf{i}_{abc(2\omega)},\Delta i_{f\omega}} = \psi_{a0}$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(3) 定转子绕组各种电流分量及其相互关系

	强制分量	自由分量		
定子绕组	稳态短路电流	基频自由电流	非周期电流	倍频电流
	$i_{abc(\infty)}$	$\Delta i_{abc(\omega)} = i_{abc(\omega)} - i_{abc(\infty)}$	$i_{abc(ap)}$	$i_{abc(2\omega)}$
	$i_{f[0]}$	Δi_{fa}	$\Delta i_{f\omega}$	
转子绕组	稳态励磁电流	自由直流	基频电流	

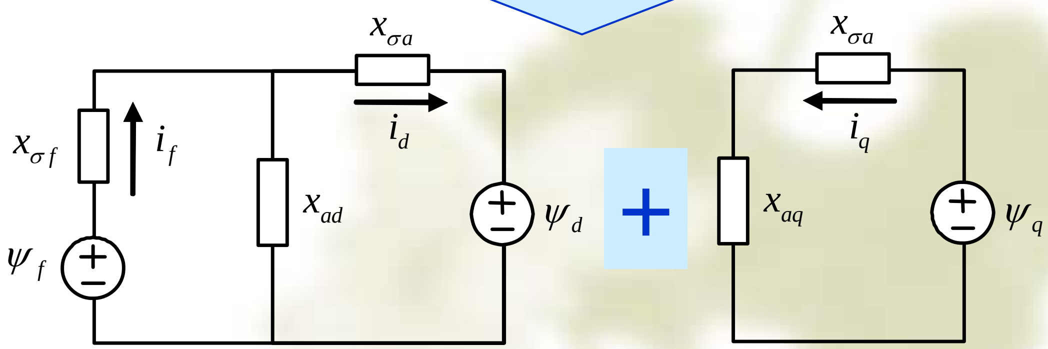
5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——磁链平衡等值电路

$$
\begin{aligned}
\psi_d &= -x_d i_d + x_{ad} i_f \\
\psi_q &= x_q i_q \\
\psi_f &= -x_{ad} i_d + x_f i_f
\end{aligned}
$$

$$
\begin{aligned}
\psi_d &= -x_{\sigma a} i_d + x_{ad}\left(i_f - i_d\right) \\
\psi_q &= x_q i_q \\
\psi_f &= x_{ad}\left(i_f - i_d\right) + x_{\sigma f} i_f
\end{aligned}
$$

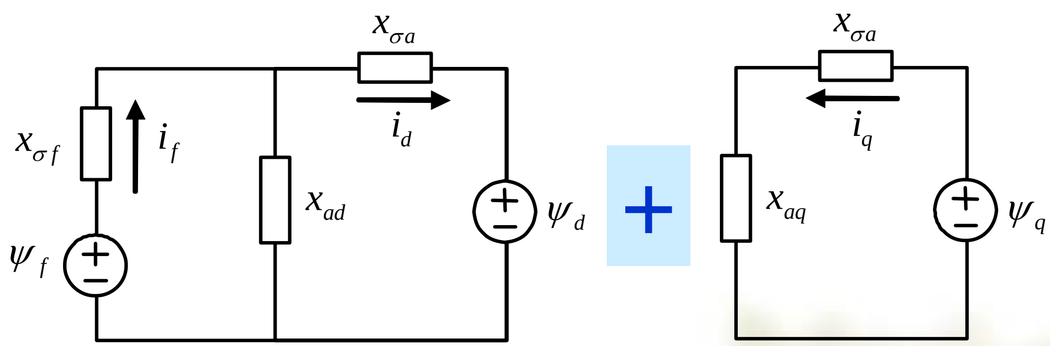
$$
\begin{cases}
\psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\
\psi_q = x_q i_q + x_{aq} i_Q \\
\psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\
\psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \\
\psi_Q = x_{aq} i_q + x_Q i_Q
\end{cases}
$$



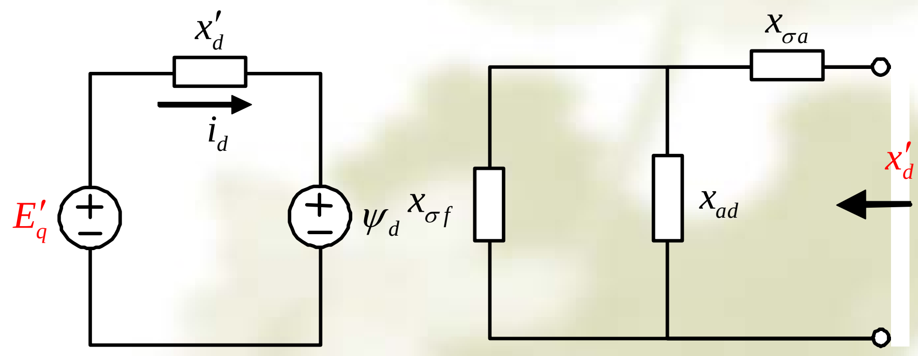
5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——暂态电抗和暂态电势

$$
\begin{aligned}
\psi_d &= -x_d i_d + x_{ad} i_f \\
\psi_q &= x_q i_q \\
\psi_f &= -x_{ad} i_d + x_f i_f
\end{aligned}
$$



$$
\begin{aligned}
\psi_d &= E'_q - x'_d i_d \\
\psi_q &= x_q i_q
\end{aligned}
$$



$$
E'_q = \frac{x_{ad}}{x_f}\psi_f , \quad x'_d = x_{\sigma a} + \frac{x_{\sigma f} x_{ad}}{x_{\sigma f} + x_{ad}}
$$

短路瞬间暂态电势保持不变

5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——短路状态磁链平衡关系

$i_{abc(\omega)} \Leftrightarrow i'_d, i'_q$

$\left.\begin{matrix} i_{abc(ap)} \\ i_{abc(2\omega)} \end{matrix}\right\} i_{d\omega}, i_{q\omega}$

$i_{f[0]}$

Δi_{fa}

$\Delta i_{f\omega}$

$$\psi_{d\omega} = -x_d\left(i'_d + i_{d\omega}\right) + x_{ad}\left(i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}\right)$$

$$\psi_{q\omega} = x_q\left(i'_q + i_{q\omega}\right)$$

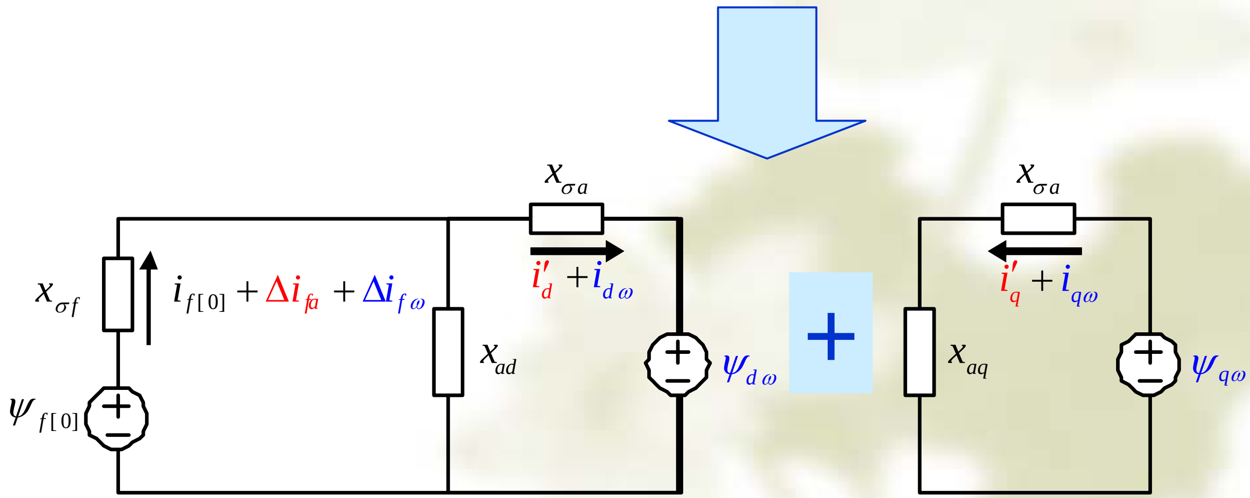
$$\psi_{f[0]} = -x_{ad}\left(i'_d + i_{d\omega}\right) + x_f\left(i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}\right)$$

$$\psi_{a0} = \psi_0 \cos\alpha_0$$

$$\psi_{b0} = \psi_0 \cos(\alpha_0 - 120^\circ)$$

$$\psi_{c0} = \psi_0 \cos(\alpha_0 + 120^\circ)$$

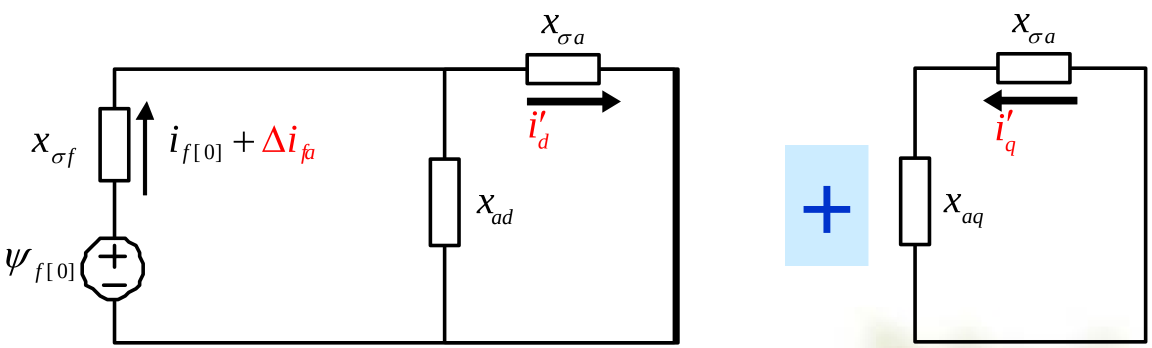
$$\begin{cases} \psi_{d\omega} = \psi_0 \cos\omega t \\ \psi_{q\omega} = \psi_0 \sin\omega t \end{cases}$$

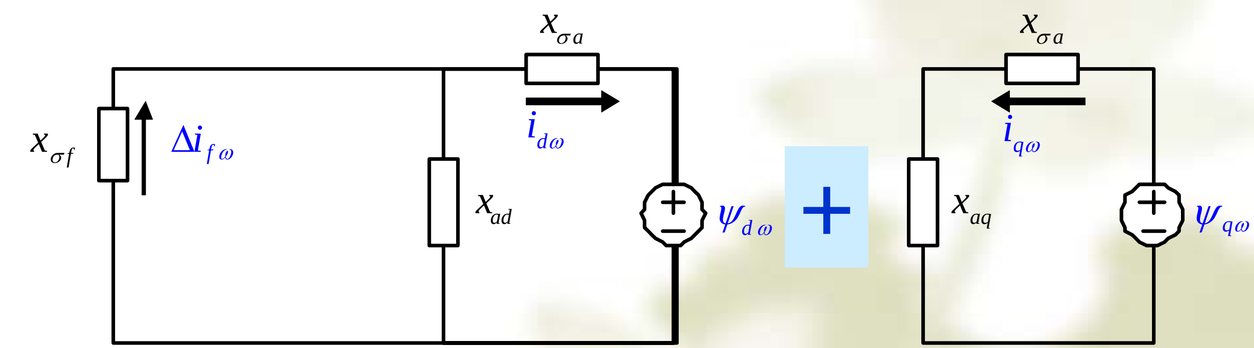


5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——短路状态磁链平衡关系

$$\left.\begin{matrix} i_{abc(\omega)} \Leftrightarrow i'_d, i'_q \\ i_{f[0]} + \Delta i_{fa} \end{matrix}\right\} \Rightarrow \begin{cases} \psi_{abc} = 0 \\ \psi_f = \psi_{f[0]} \end{cases}$$





$$\left.\begin{matrix} i_{abc(ap)} \\ i_{abc(2\omega)} \\ \Delta i_{f\omega} \end{matrix}\right\} \Leftrightarrow \begin{cases} i_{d\omega} \\ i_{q\omega} \\ \Delta i_{f\omega} \end{cases}$$

$$\begin{cases} \psi_{abc} = \psi_{abc[0]} \\ \psi_f = 0 \end{cases}$$

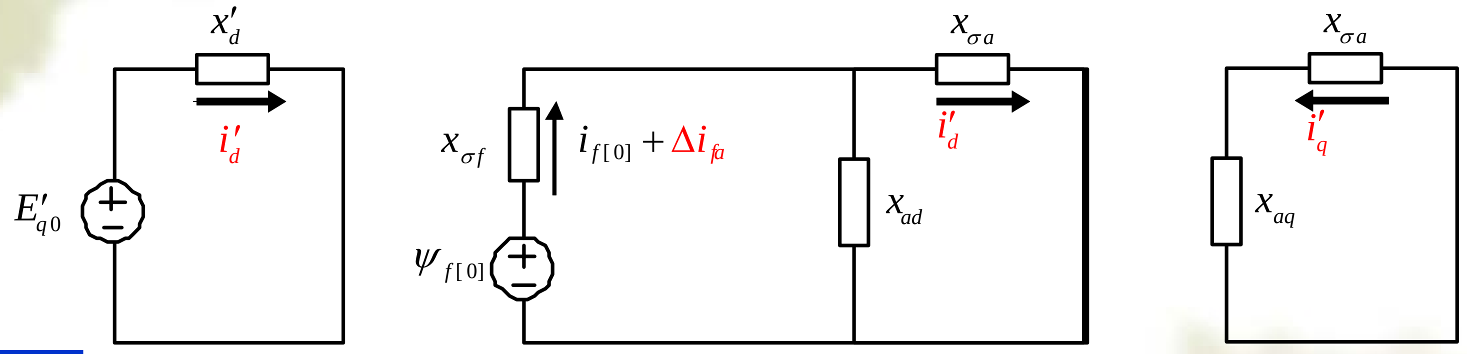
$$\Psi_{abc[0]} \Rightarrow \psi_{d\omega}, \psi_{q\omega}$$

5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——定子起始暂态电流

$$i'_d = \frac{E'_{q[0]}}{x'_d}$$

$$i'_q = 0$$

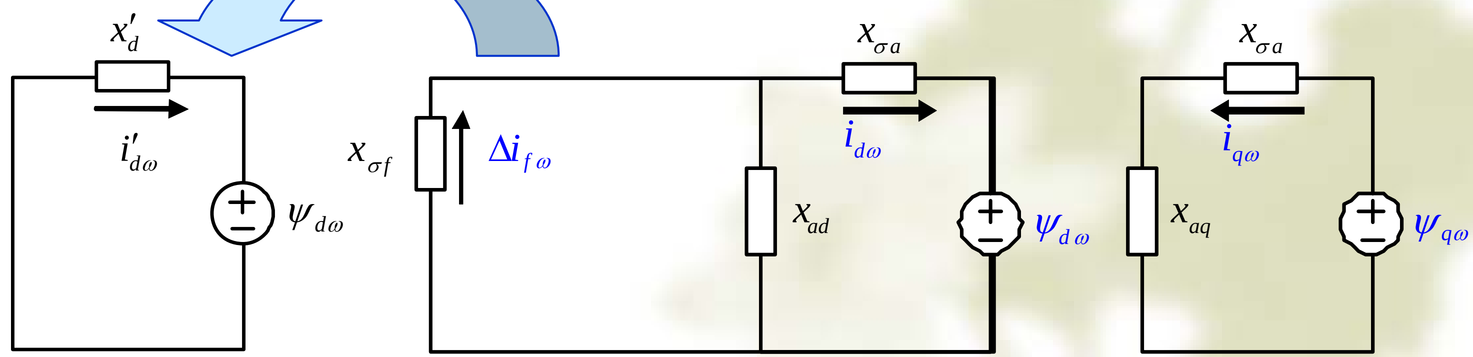


$$E'_{q0} = \frac{x_{ad}}{x_f}\psi_{f[0]}$$

$$\Psi_{abc[0]} \Rightarrow \psi_{d\omega}, \psi_{q\omega}$$

$$i_{d\omega} = -\frac{\psi_{d\omega}}{x'_d}$$

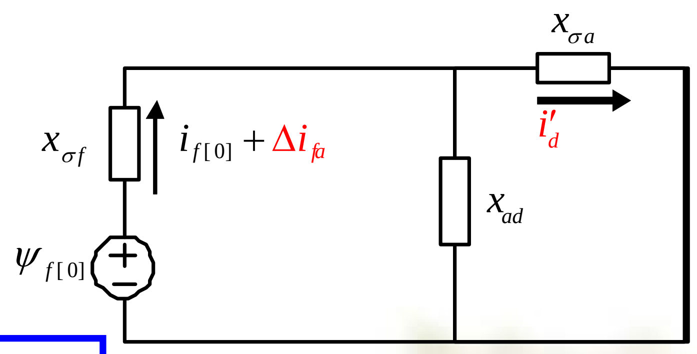
$$i_{q\omega} = \frac{\psi_{q\omega}}{x_q}$$



5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——计算转子电流

$$\Delta i_{fa} = \frac{x_d i_d' - E_{q[0]}}{x_{ad}} = \frac{x_d}{x_{ad}}\left(\frac{E_{q[0]}'}{x_d'} - \frac{E_{q[0]}}{x_d}\right)$$



$$0 = -x_d i_d' + x_{ad}\left(i_{f[0]} + \Delta i_{fa}\right)$$

$$0 = x_q i_q'$$

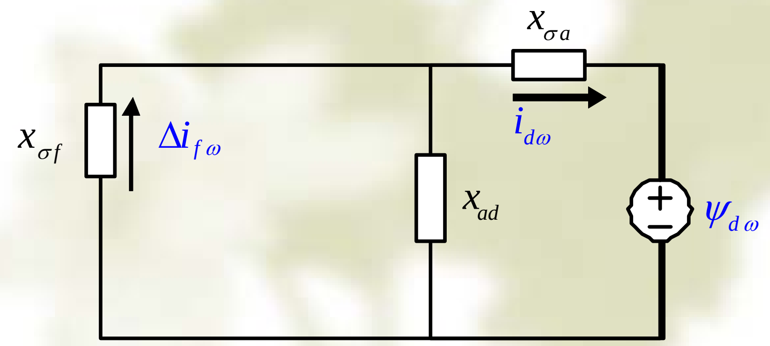
$$\psi_{f[0]} = -x_{ad} i_d' + x_f\left(i_{f[0]} + \Delta i_{fa}\right)$$

$$E_{q[0]} = x_{ad} i_{f[0]}$$

$$i_d' = \frac{E_{q[0]}'}{x_d'}$$

$$\begin{cases} \psi_{d\omega} = \psi_0 \cos \omega t \\ \psi_{q\omega} = \psi_0 \sin \omega t \end{cases}$$

$$\Delta i_{f\omega} = \frac{x_{ad}}{x_f} i_{d\omega} = -\frac{x_{ad}}{x_f} \times \frac{\psi_{d\omega}}{x_d'}$$



5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——计算稳态短路电流

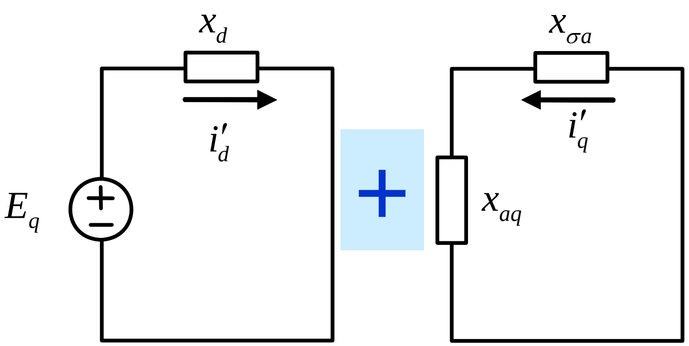
$$i_{d\infty}=\frac{x_{ad}i_{f[0]}}{x_d}=\frac{E_{q[0]}}{x_d}$$

$$0=-x_d i'_d+x_{ad}\left(i_{f[0]}+\Delta i_{fa}\right)$$

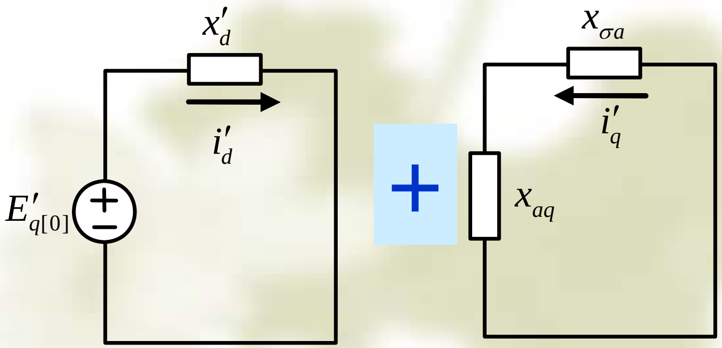
$$0=x_q i'_q$$

$$\psi_{f[0]}=-x_{ad}i'_d+x_f\left(i_{f[0]}+\Delta i_{fa}\right)$$

$$i'_d=\frac{E_{q0}}{x_d},\ E_{q0}\neq E_{q[0]}$$



$$i'_d=\frac{E'_{q[0]}}{x'_d}$$



5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算—Summary

$$
\begin{aligned}
i_d &= i_{d\infty} + \left(i_d' - i_{d\infty}\right) + i_{d\omega} \\
i_q &= i_q' + i_{q\omega} = i_{q\omega} \\
i_f &= i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}
\end{aligned}
$$

$\Rightarrow$

$$
\begin{aligned}
i_a &= -i_d \cos\alpha + i_q \sin\alpha \\
i_b &= -i_d \cos\left(\alpha - 120^\circ\right) + i_q \sin\left(\alpha - 120^\circ\right) \\
i_c &= -i_d \cos\left(\alpha + 120^\circ\right) + i_q \sin\left(\alpha + 120^\circ\right)
\end{aligned}
$$

$$
i_{d\infty} = \frac{E_{q[0]}}{x_d},\quad \Delta i_d' = i_d' - i_{d\infty} = \frac{E_{q0}'}{x_d'} - \frac{E_{q[0]}}{x_d},\quad \Delta i_{fa} = \frac{x_d}{x_{ad}} \times \left(\frac{E_{q0}'}{x_d'} - \frac{E_{q[0]}}{x_d}\right)
$$

$$
i_{d\omega} = -\frac{\psi_{d\omega}}{x_d'},\quad i_{q\omega} = \frac{\psi_{q\omega}}{x_q},\quad \Delta i_{f\omega} = -\frac{x_{ad}}{x_f} \times \frac{\psi_{d\omega}}{x_d'}
$$

根据短路前稳态确定

E_{q0}'，$E_{q[0]}$，$\psi_{d\omega}$，$\psi_{q\omega}$

5-4 无阻尼绕组同步电机三相短路电流计算

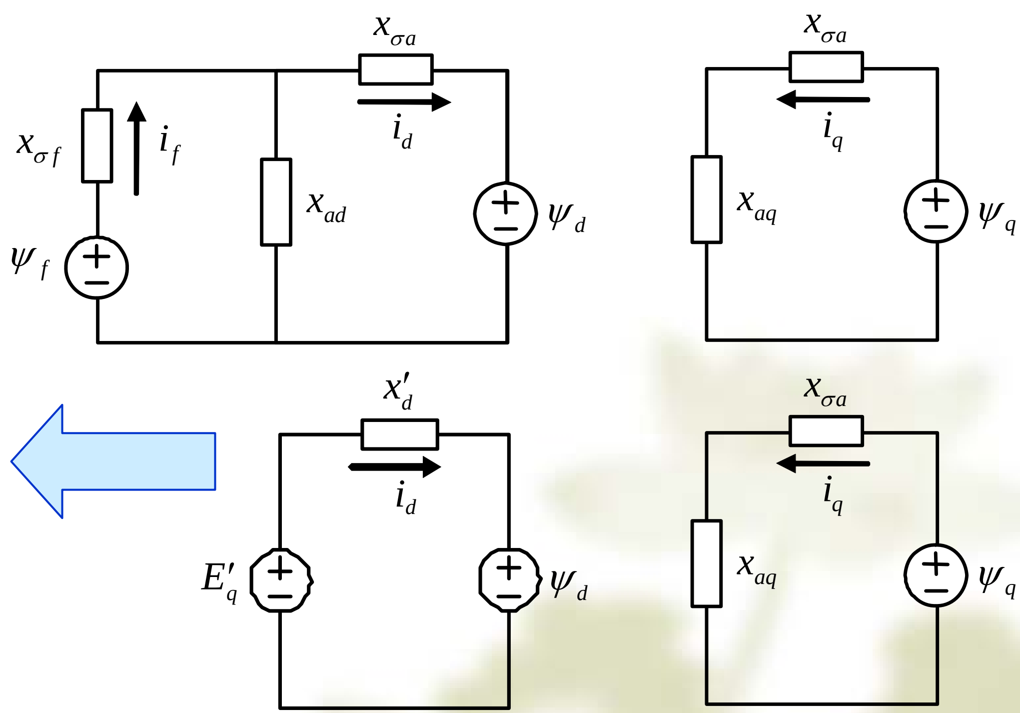
1. 短路电流各分量计算——初始磁链和暂态电势

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

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

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

$$\psi_d = E'_q - x'_d i_d \qquad \psi_q = x_q i_q$$



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

$$u_{d[0]} = \psi_{q[0]} \qquad u_{q[0]} = \psi_{d[0]}$$

$$u_{q[0]} = E'_{q[0]} - x'_d i_{d[0]} \qquad u_{d[0]} = x_q i_{q[0]}$$

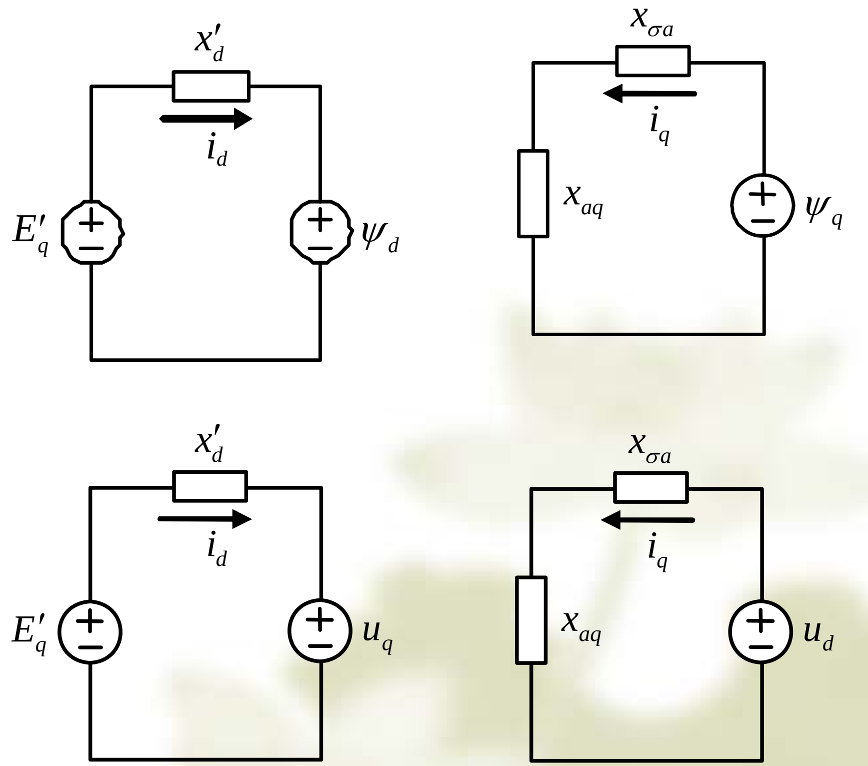
$$\psi_0 = V_{[0]}$$

$$E'_{q0} = E'_{q[0]} \Leftarrow \dot{V}_{[0]}, \dot{I}_{[0]}$$

5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型——暂态参数表示的电势方程

$$E_q' = \frac{x_{ad}}{x_f}\psi_f, x_d' = x_{\sigma a} + \frac{x_{\sigma f} x_{ad}}{x_{\sigma f} + x_{ad}}$$



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

$$\psi_d = E_q' - x_d' i_d \qquad \psi_q = x_q i_q$$

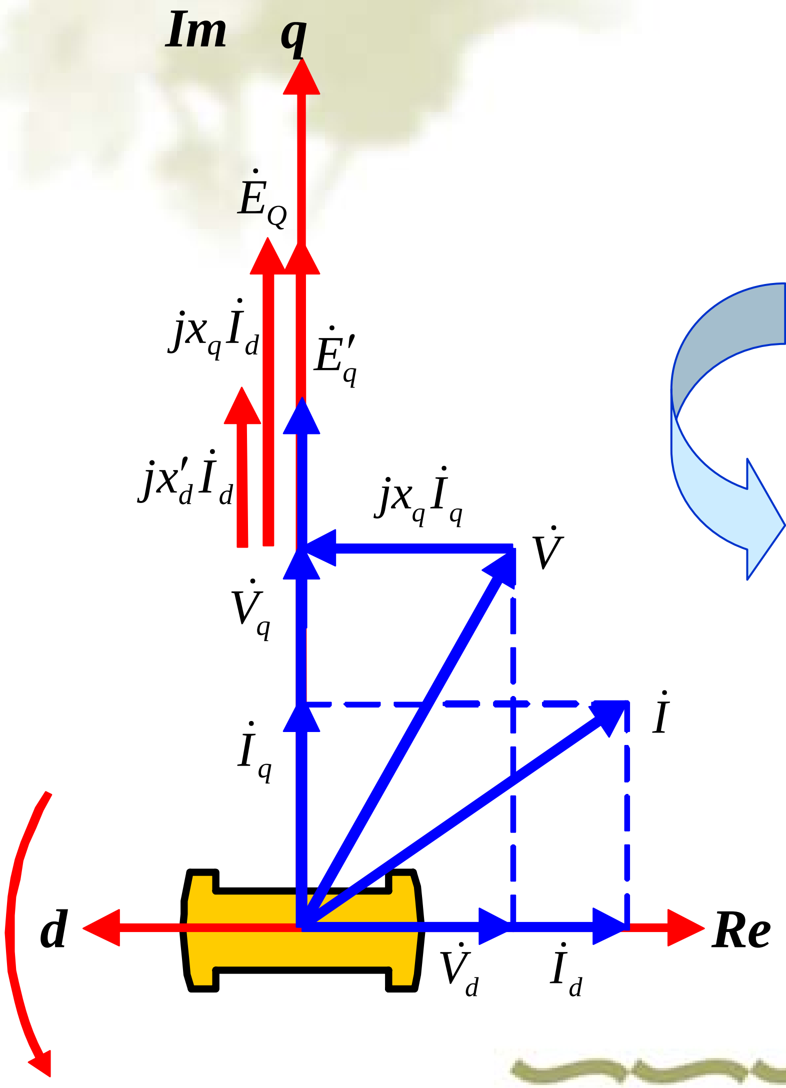
$$u_d = \dot{\psi}_d + \omega\psi_q - r i_d$$

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

$$u_q = E_q' - x_d' i_d, \quad u_d = x_q i_q$$

5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型——相量方程式和相量图



$$\begin{cases} u_d = x_q i_q \\ u_q = E'_q - x'_d i_d \end{cases}$$

$$\dot{E}'_q = jE'_q, \dot{V}_d = u_d, \dot{I}_d = i_d$$
$$\dot{I}_q = ji_q, \dot{V}_q = ju_q$$

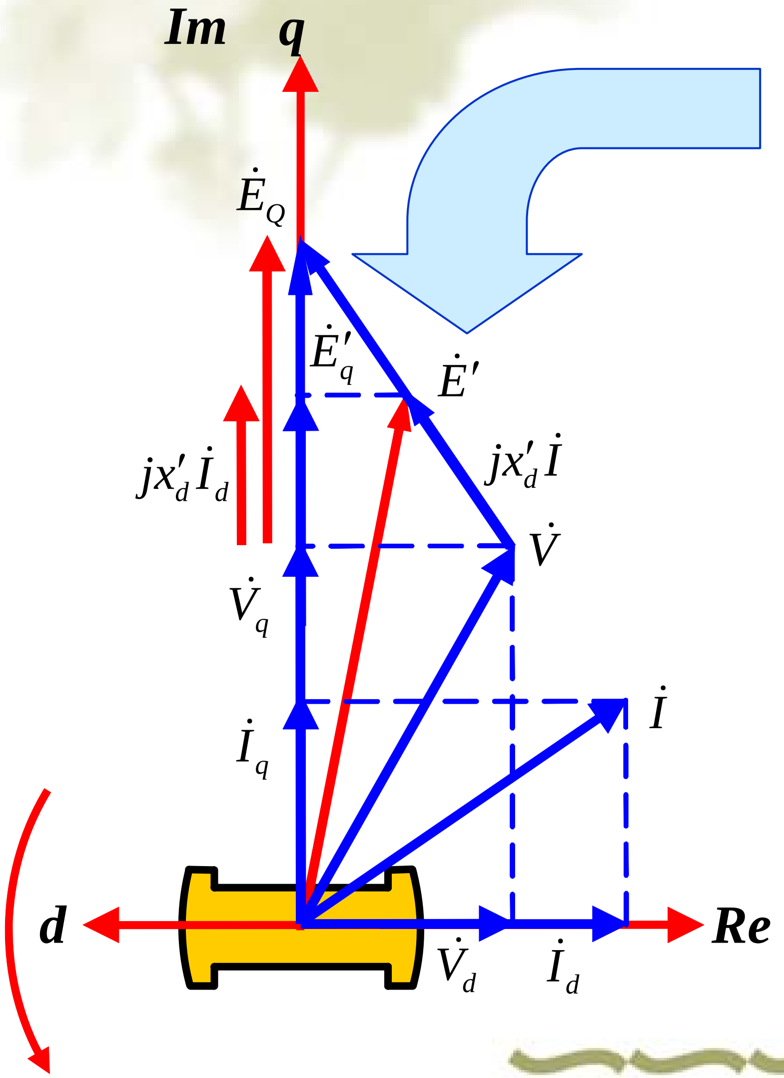
$$\begin{cases} u_d = -jx_q \times ji_q \\ ju_q = jE'_q - jx'_d i_d \end{cases}$$

$$\begin{cases} \dot{V}_d = -jx_q\dot{I}_q \\ \dot{V}_q = \dot{E}'_q - jx'_d\dot{I}_d \end{cases}$$

$$\dot{V} = \dot{E}'_q - jx'_d\dot{I}_d - jx_q\dot{I}_q = \dot{E}_Q - jx_q\dot{I}$$
$$\dot{E}_Q = \dot{E}'_q - j(x'_d - x_q)\dot{I}_d$$

5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型——暂态电抗后的暂态电势



暂态电抗后的电势——计算电势

$$\dot{V} = \dot{E}' - jx'_d\dot{I}$$

$$\begin{cases} u_d = -jx_q \times ji_q \\ ju_q = jE'_q - jx'_d i_d \end{cases}$$

$$\begin{cases} \dot{V}_d = -jx_q\dot{I}_q \\ \dot{V}_q = \dot{E}'_q - jx'_d\dot{I}_d \end{cases}$$

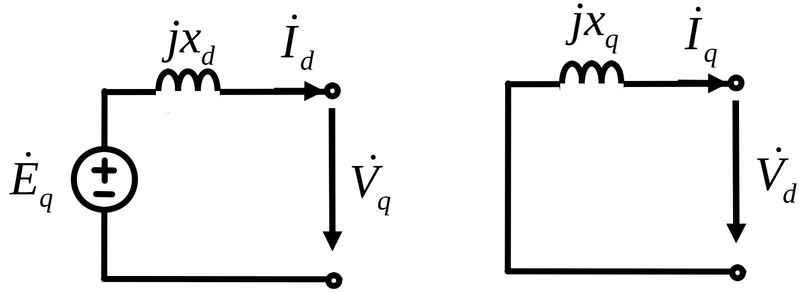
$$\dot{V} = \dot{E}'_q - jx'_d\dot{I}_d - jx_q\dot{I}_q = \dot{E}' - jx'_d\dot{I}$$

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

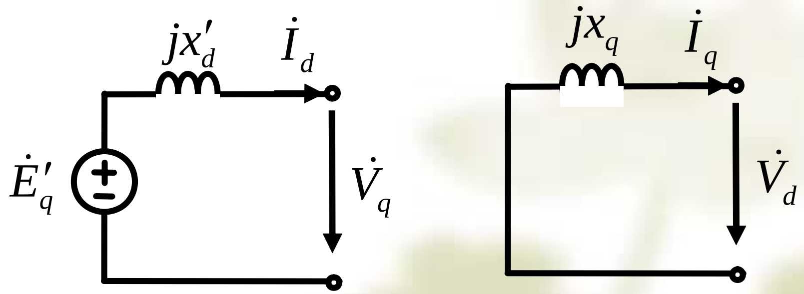
5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型——等值电路

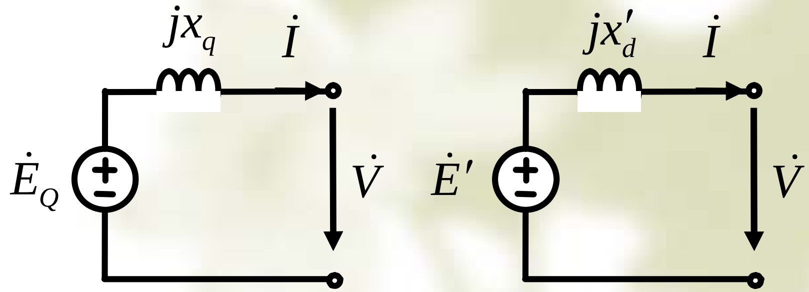
$$\begin{cases}\dot{V}_d = -jx_q\dot{I}_q \\ \dot{V}_q = \dot{E}_q - jx_d\dot{I}_d\end{cases}$$



$$\begin{cases}\dot{V}_d = -jx_q\dot{I}_q \\ \dot{V}_q = \dot{E}'_q - jx'_d\dot{I}_d\end{cases}$$



$$\dot{V} = \dot{E}_Q - jx_q\dot{I}$$
$$\dot{V} = \dot{E}' - jx'_d\dot{I}$$



5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型——Summary

同步电机结构参数：

x_d， x_q， x'_d

可以实测或者计算

同步电机运行参数：

E_q， E'_q， E_Q， E'

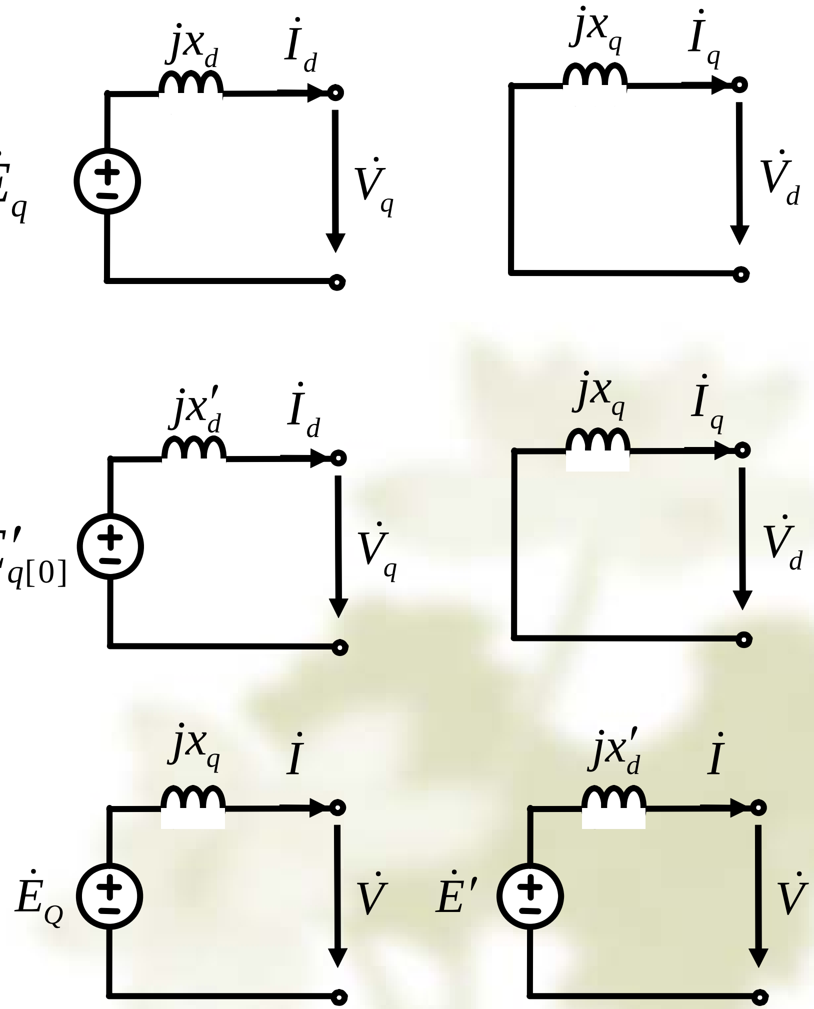
根据运行状态计算

$\dot{V},\dot{I} \Rightarrow E_Q,\delta+\varphi \Rightarrow I_d,I_q \Rightarrow E_{q[0]},E'_{q[0]}$

$\dot{V},\dot{I} \Rightarrow E'$

$x_{ad}i_f = \dot{E}_q$

$\dfrac{x_{ad}}{x_f}\psi_{f[0]} = \dot{E}'_{q[0]}$



5-4 无阻尼绕组同步电机三相短路电流计算

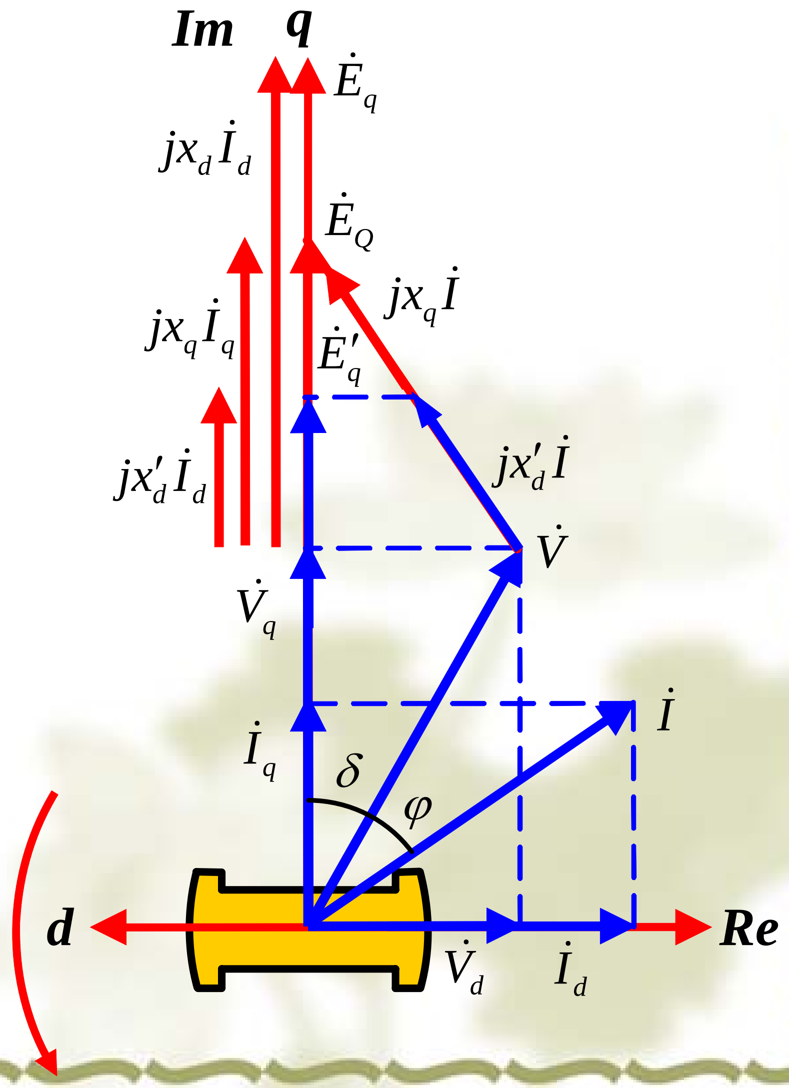
3. 短路电流计算——确定计算初值 E'_{q0}和$E_{q[0]}$

$E'_{q0} = E'_{q[0]}$，而$E'_{q[0]}$和$E_{q[0]}$均可由短路前发电机运行状态确定，例3-2，例5-1

$$i_d = \frac{E'_q - u_q}{x'_d} = \frac{E_q - u_q}{x_d} = \frac{E_q - V\cos\delta}{x_d}$$

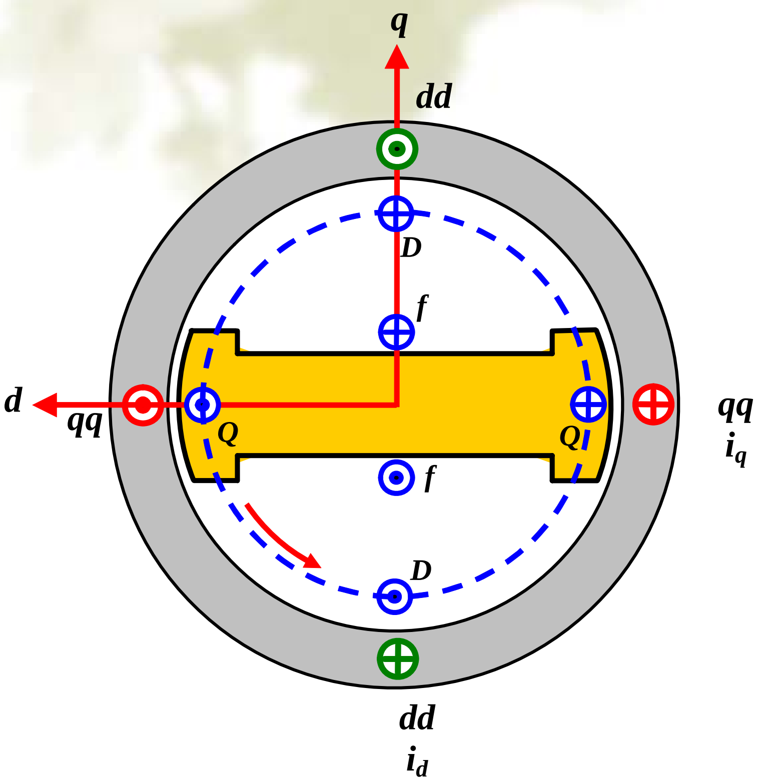
$$\Rightarrow \frac{E'_{q0}}{x'_d} - \frac{E_{q[0]}}{x_d} = \left(\frac{1}{x'_d} - \frac{1}{x_d}\right) V_{[0]} \cos\delta_0$$

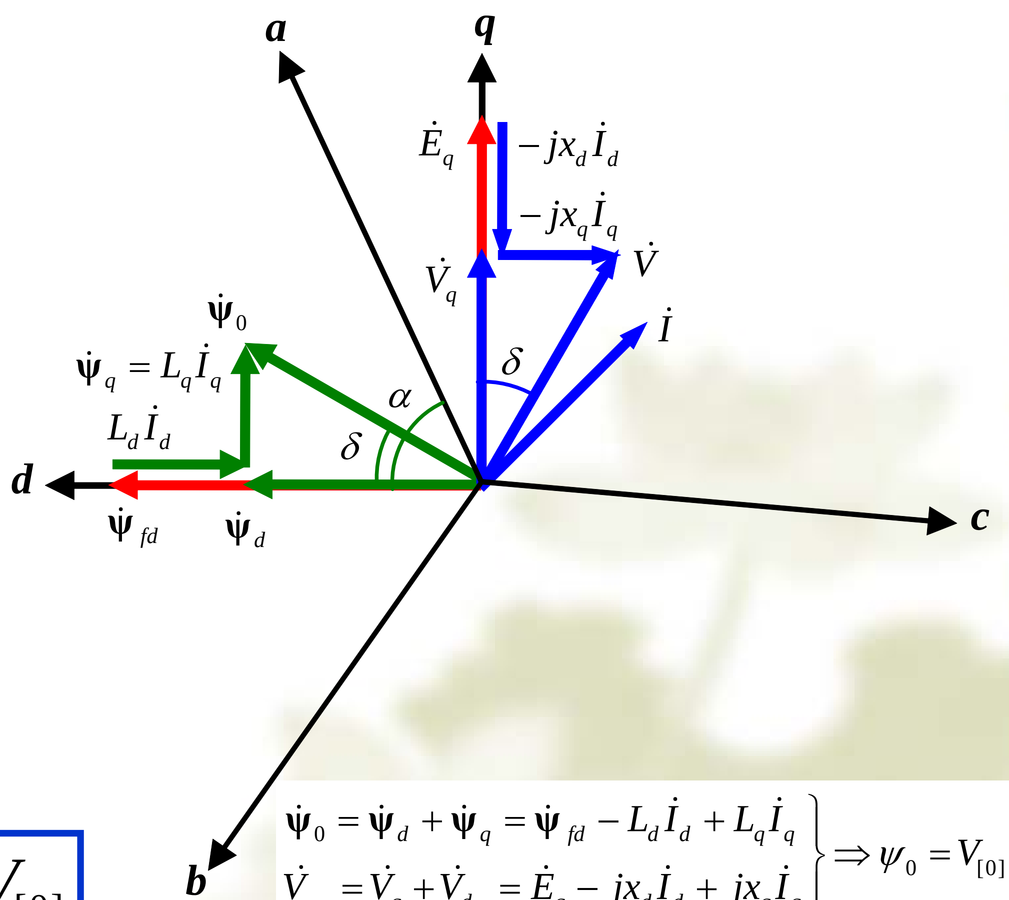
空载情况下，$E'_{q0} = E'_{q[0]} = E_{q[0]} = V_{[0]}$



5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——确定计算初值 $\Psi_{abc[0]} \Rightarrow \psi_{d\omega}, \psi_{q\omega}$



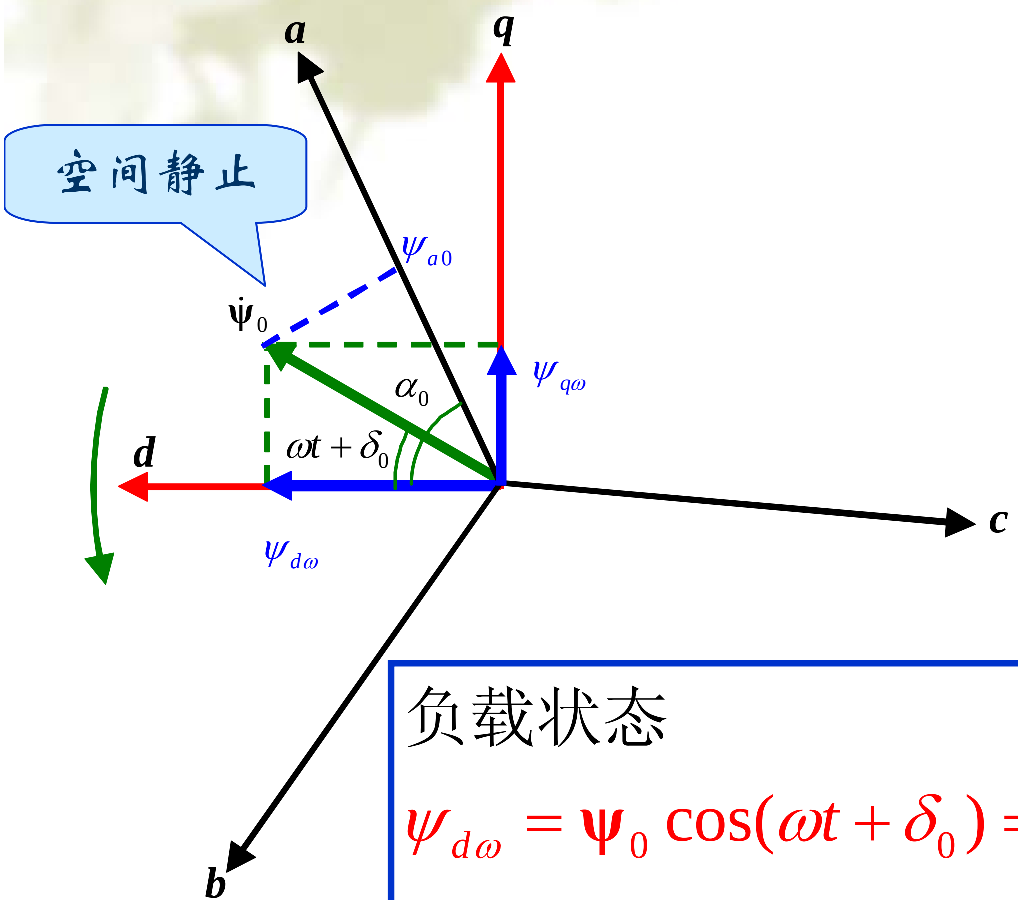


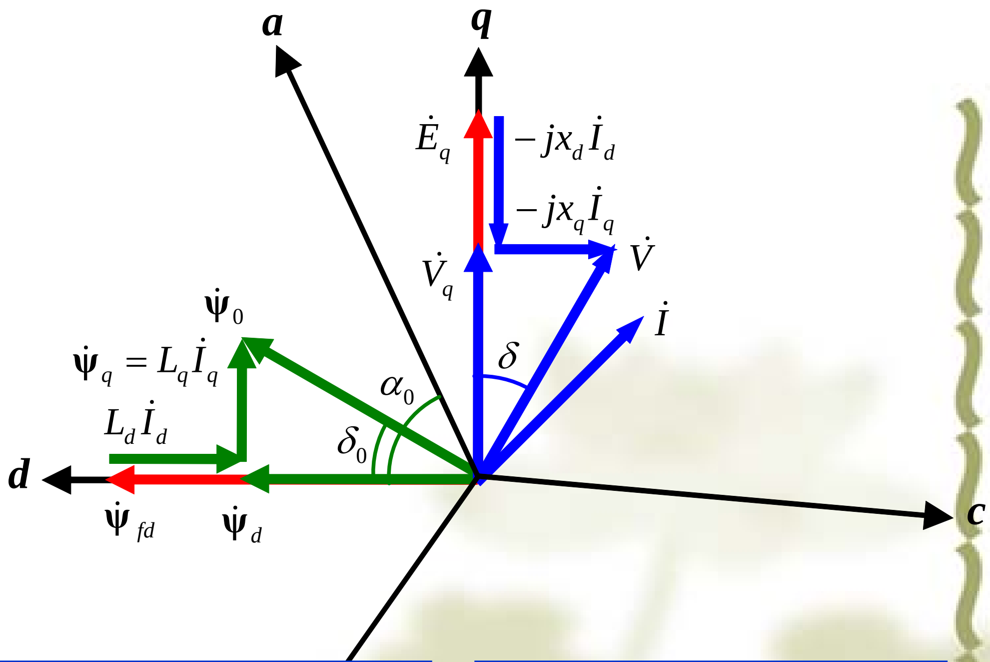
$$\left.\begin{aligned}\dot{\Psi}_0 &= \dot{\Psi}_d + \dot{\Psi}_q = \dot{\Psi}_{fd} - L_d\dot{I}_d + L_q\dot{I}_q \\ \dot{V} &= \dot{V}_q + \dot{V}_d = \dot{E}_q - jx_d\dot{I}_d + jx_q\dot{I}_q\end{aligned}\right\} \Rightarrow \psi_0 = V_{[0]}$$

$$u_{d[0]} = \psi_{q[0]}, u_{q[0]} = \psi_{d[0]} \Rightarrow \psi_{[0]} = V_{[0]}$$

5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——确定计算初值 $\Psi_{abc[0]} \Rightarrow \psi_{d\omega}, \psi_{q\omega}$





负载状态

$$\psi_{d\omega} = \Psi_0 \cos(\omega t + \delta_0) = V_{[0]} \cos(\omega t + \delta_0)$$

$$\psi_{q\omega} = \Psi_0 \sin(\omega t + \delta_0) = V_{[0]} \sin(\omega t + \delta_0)$$

空载状态

$$\psi_{d\omega} = E'_{q0} \cos \omega t$$

$$\psi_{q\omega} = E'_{q0} \sin \omega t$$

5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——全电流计算式（不计衰减）

$$i_a = -\frac{E_{q[0]}}{x_d}\cos(\omega t+\alpha_0) - \left(\frac{E'_{q0}}{x'_d} - \frac{E_{q[0]}}{x_d}\right)\cos(\omega t+\alpha_0) + \frac{V_{[0]}}{2}\left(\frac{1}{x'_d} + \frac{1}{x_q}\right)\cos(\alpha_0 - \delta_0) + \frac{V_{[0]}}{2}\left(\frac{1}{x'_d} - \frac{1}{x_q}\right)\cos(2\omega t + \alpha_0 + \delta_0)$$

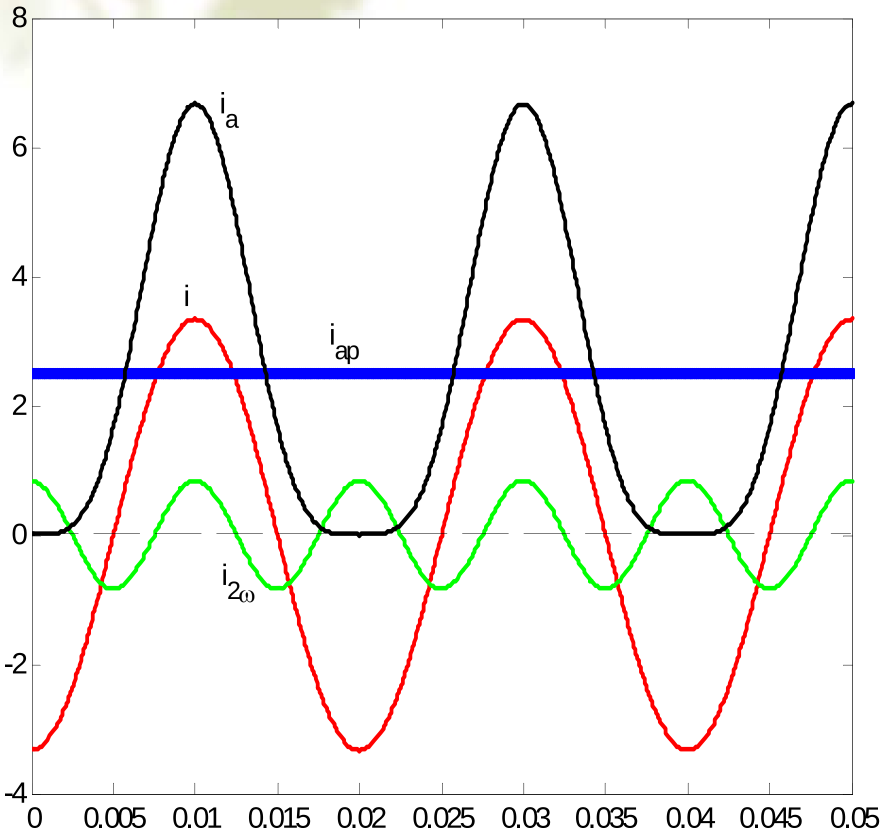
$$i_f = i_{f[0]} + \frac{(x_d - x'_d)}{x_{ad} x'_d} V_{[0]}\cos\delta_0 - \frac{(x_d - x'_d)}{x_{ad} x'_d} V_{[0]}\cos(\omega t + \delta_0)$$

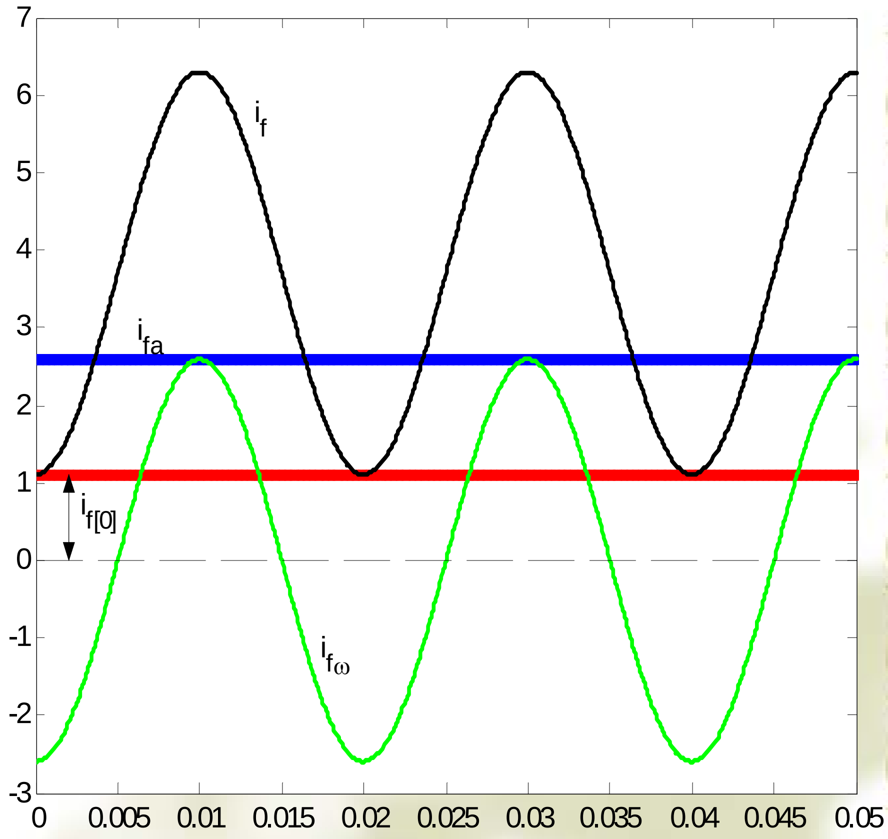
外接电抗x_e短路，则$x_d + x_e \to x_d, x_q + x_e \to x_q,$

$x'_d + x_e \to x'_d, V_{[0]}$为短路点的电压初值

5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——确定全电流波形（不计衰减）





5-4 无阻尼绕组同步电机三相短路电流计算

4. 自由电流的衰减——简化原则

(1) 在短路瞬间为了保持本绕组磁链不变而出现的自由电流，如果它产生的磁通相对本绕组静止，那么这个自由电流即依本绕组时间常数衰减。一切同该自由电流发生依存关系的其他自由电流(本绕组或外绕组的)均按同一时间常数衰减

(2) 某绕组的时间常数即是该绕组的电感 (考虑其他绕组的互感耦合) 和电阻之比，而忽略其他绕组电阻的影响。

5-4 无阻尼绕组同步电机三相短路电流计算

4. 自由电流的衰减——时间常数

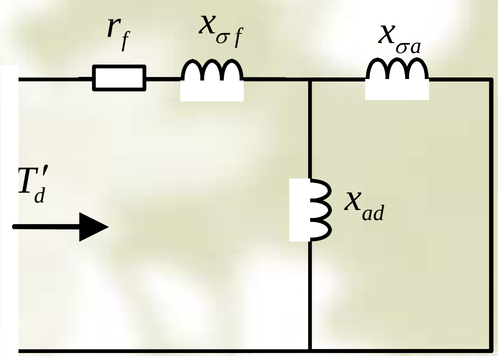
$i_{abc(ap)} \Rightarrow \dot{\psi}_0$, 相对定子绕组静止，因此$i_{abc(ap)}, i_{abc(2\omega)}, \Delta i_{f\omega}$依定子绕组时间常数衰减，

即有 $\rightarrow T_a = \dfrac{2x_d' x_q}{\omega(x_d' + x_q)} \Big/ r$

$\omega = 2\pi f (rad/s), x_d', x_q (p.u.)$

$\Delta i_{fa} \Rightarrow \psi_{fd}$相对转子绕组静止，因此$\Delta i_{abc(\omega)}, \Delta i_{fa}$依励磁绕组时间常数衰减，

即$T_d' = T_{d0}' \dfrac{x_d'}{x_d}, T_{d0}' = \dfrac{x_f}{\omega r_f}$



5-4 无阻尼绕组同步电机三相短路电流计算

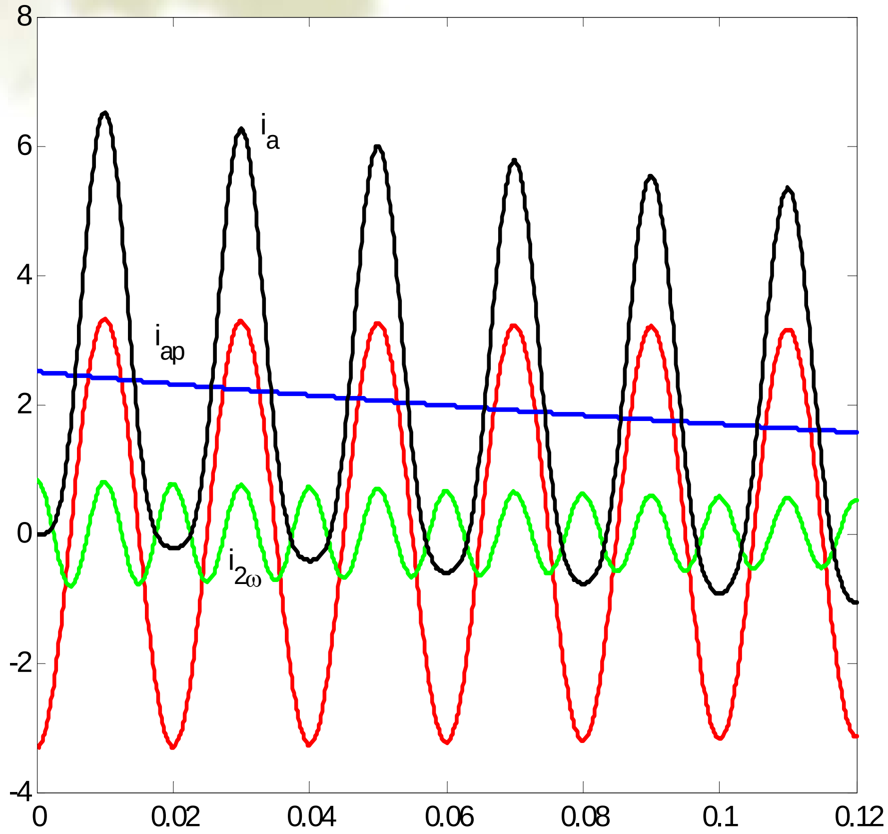
3. 自由电流的衰减——全电流算式

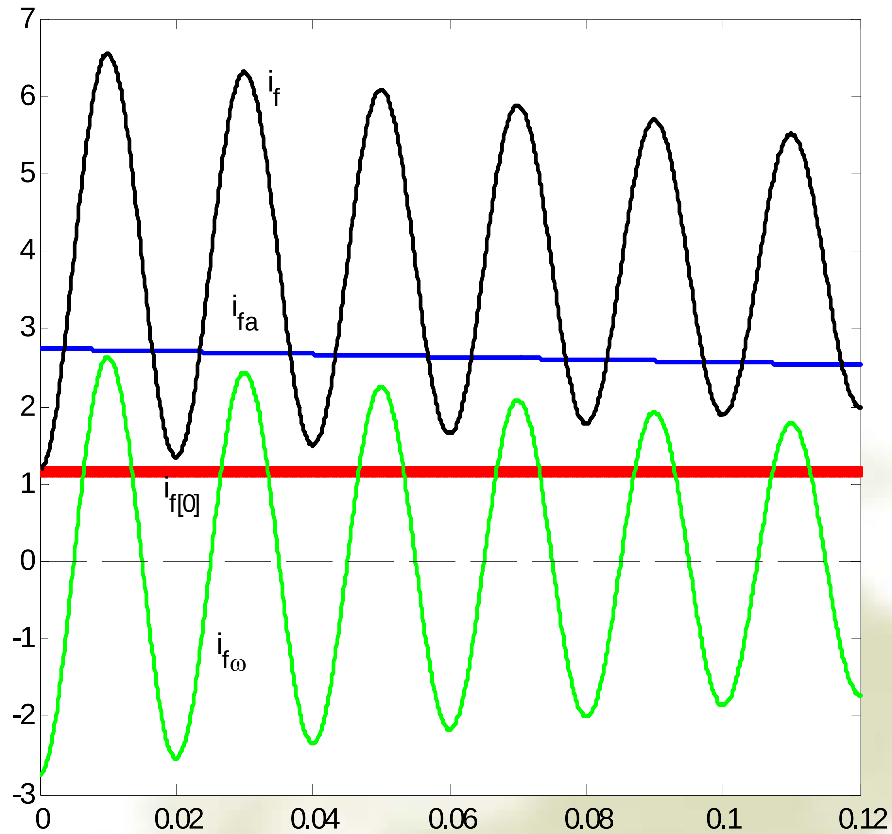
$$i_a = -\frac{E_{q[0]}}{x_d}\cos(\omega t+\alpha_0) - \left(\frac{E'_{q0}}{x'_d} - \frac{E_{q[0]}}{x_d}\right)\cos(\omega t+\alpha_0)\exp\left(-\frac{t}{T'_d}\right)$$
$$+\frac{V_{[0]}}{2}\left(\frac{1}{x'_d}+\frac{1}{x_q}\right)\exp\left(-\frac{t}{T_a}\right)\cos(\alpha_0-\delta_0)$$
$$+\frac{V_{[0]}}{2}\left(\frac{1}{x'_d}-\frac{1}{x_q}\right)\exp\left(-\frac{t}{T_a}\right)\cos(2\omega t+\alpha_0+\delta_0)$$

$$i_f = i_{f[0]} + \frac{(x_d - x'_d)}{x_{ad}x'_d}V_{[0]}\cos\delta_0\exp\left(-\frac{t}{T'_d}\right) - \frac{(x_d - x'_d)}{x_{ad}x'_d}V_{[0]}\exp\left(-\frac{t}{T_a}\right)\cos(\omega t+\delta_0)$$

5-4 无阻尼绕组同步电机三相短路电流计算

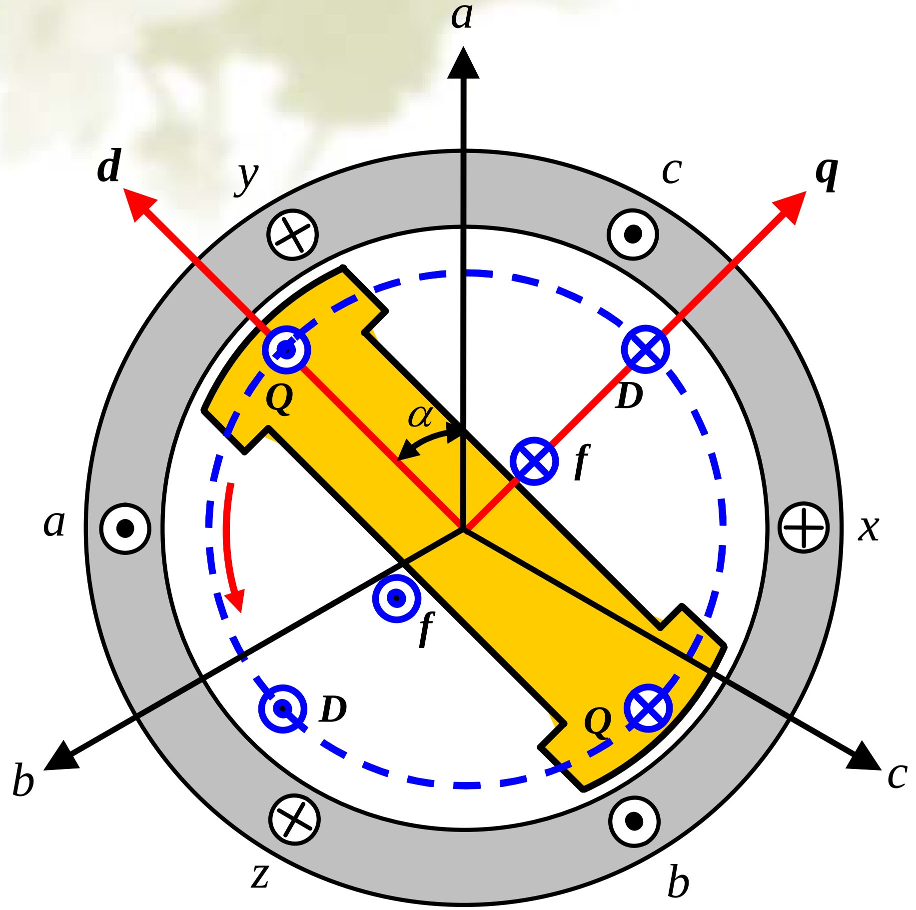
3. 自由电流的衰减——全电流波形

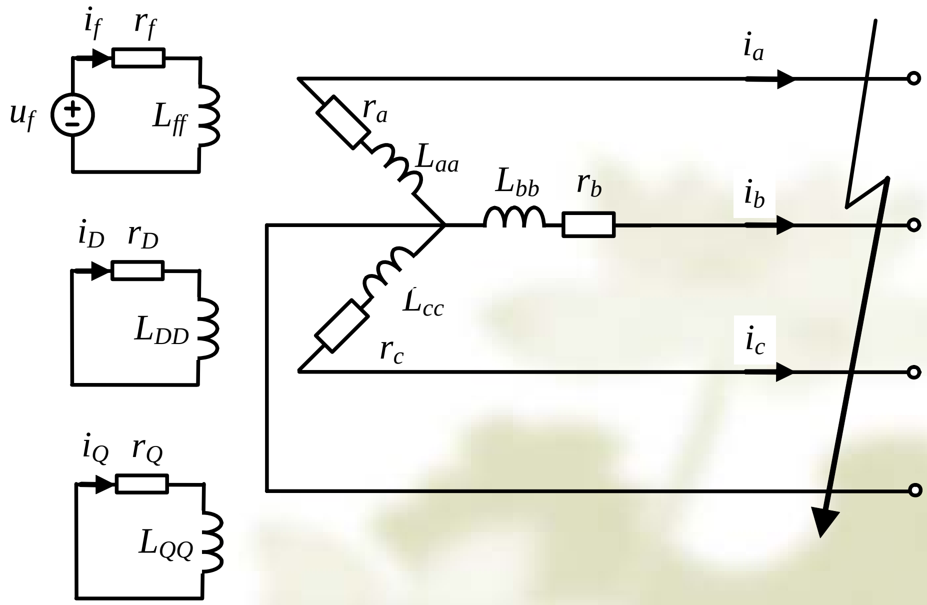




5-5 有阻尼绕组同步电机的突然三相短路

1. 突然短路的物理过程





5-5 有阻尼绕组同步电机的突然三相短路

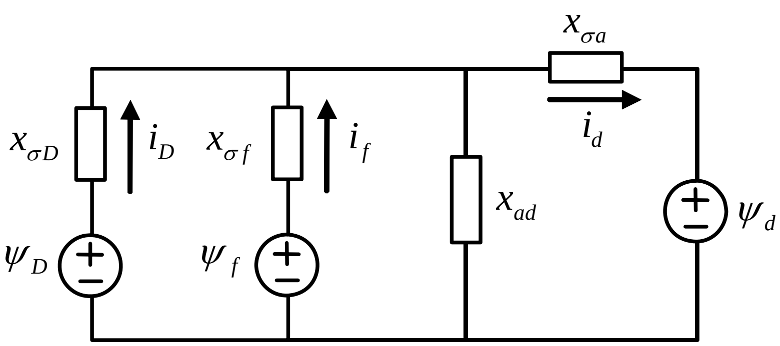
1. 突然短路的物理过程

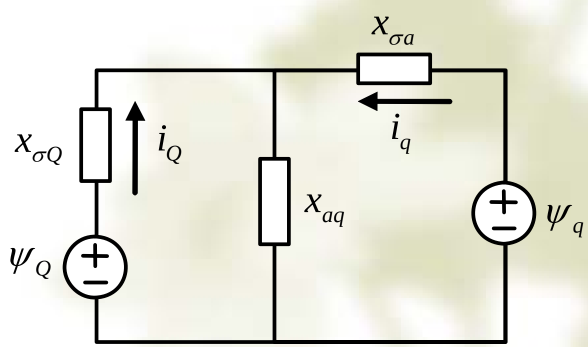
	强制分量	自由分量		
定子绕组	稳态短路电流	基频自由电流	非周期电流	倍频电流
	$i_{abc(\infty)}$	$\Delta i_{abc(\omega)} = i_{abc(\omega)} - i_{abc(\infty)}$	$i_{abc(ap)}$	$i_{abc(2\omega)}$
	$i_{f[0]}$	Δi_{fa}　Δi_{Da}　Δi_{Qa}	$\Delta i_{f\omega}$　$\Delta i_{D\omega}$　$\Delta i_{Q\omega}$	
转子绕组	稳态励磁电流	自由直流	基频电流	

2. 次暂态电抗和次暂态电势

(1) 磁链平衡等值电路

$$\begin{cases}\psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\ \psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\ \psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \\ \psi_q = x_q i_q + x_{aq} i_Q \\ \psi_Q = x_{aq} i_q + x_Q i_Q\end{cases} \Rightarrow \begin{cases}\psi_d = x_{ad}(i_f + i_D - i_d) - x_{\sigma a} i_d \\ \psi_f = x_{ad}(i_f + i_D - i_d) + x_{\sigma f} i_f \\ \psi_D = x_{ad}(i_f + i_D - i_d) + x_{\sigma D} i_D \\ \psi_q = x_{\sigma a} i_q + x_{aq}(i_q + i_Q) \\ \psi_Q = x_{\sigma Q} i_Q + x_{aq}(i_q + i_Q)\end{cases}$$

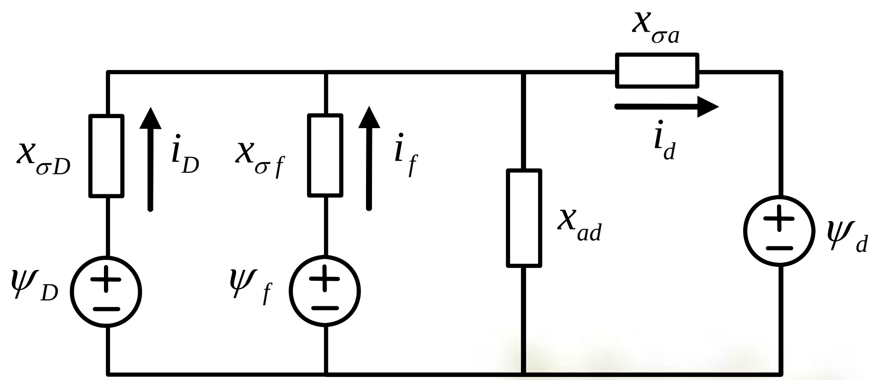




2. 次暂态电抗和次暂态电势

(2) 纵轴次暂态电抗和横轴次暂态电势

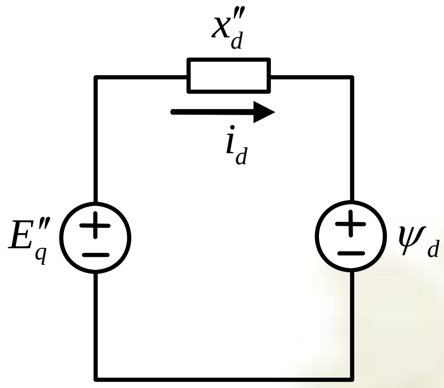
$$\begin{cases} \psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\ \psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\ \psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \end{cases}$$

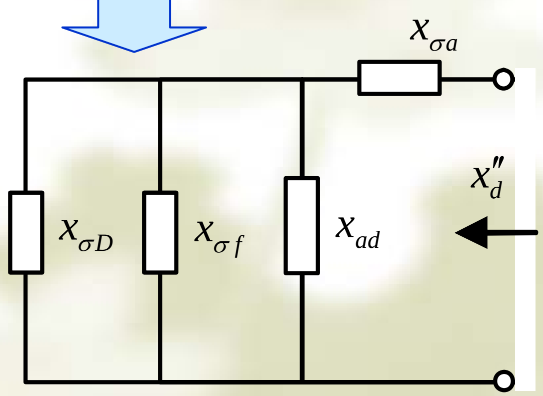


横轴次暂态电势

$$E_q'' = \left(\frac{\psi_f}{x_{\sigma f}} + \frac{\psi_D}{x_{\sigma D}} \right) \times x_{ad} \,//\, x_{\sigma f} \,//\, x_{\sigma D}$$

短路瞬间不发生突变



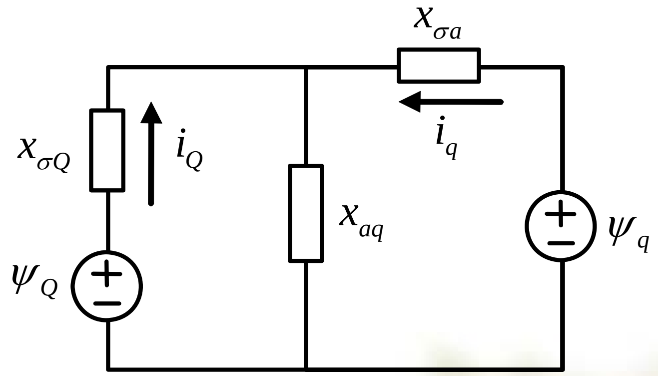


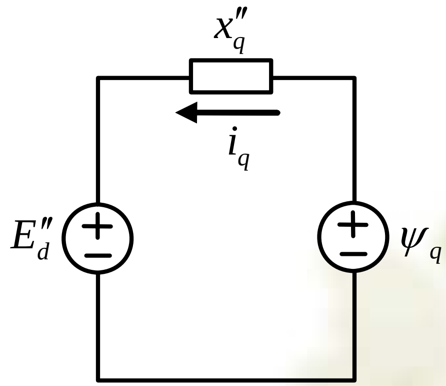
纵轴次暂态电抗 $x_d'' = x_{\sigma a} + x_{ad} \,//\, x_{\sigma f} \,//\, x_{\sigma D}$

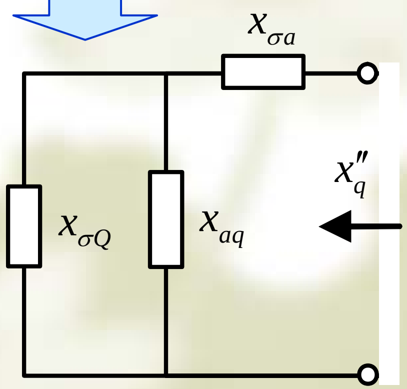
2. 次暂态电抗和次暂态电势

(3) 横轴次暂态电抗和纵轴次暂态电势

$$\begin{cases}\psi_q = x_q i_q + x_{aq} i_Q \\ \psi_Q = x_{aq} i_q + x_Q i_Q\end{cases}$$







纵横轴次暂态电势

$$E_d'' = \frac{x_{aq}}{x_Q}\psi_Q$$

短路瞬间不发生突变

横轴次暂态电抗 $x_q'' = x_{\sigma a} + x_{aq} // x_{\sigma Q}$

3. 有阻尼绕组电机的短路电流

(1) 短路状态磁链平衡关系

$i_{abc(\omega)} \Leftrightarrow i''_d, i''_q$

$\left.\begin{array}{l} i_{abc(ap)} \\ i_{abc(2\omega)} \end{array}\right\} i_{d\omega}, i_{q\omega}$

$i_{f[0]}$

Δi_{fa}

$\Delta i_{f\omega}$

Δi_{Da}

$\Delta i_{D\omega}$

Δi_{Qa}

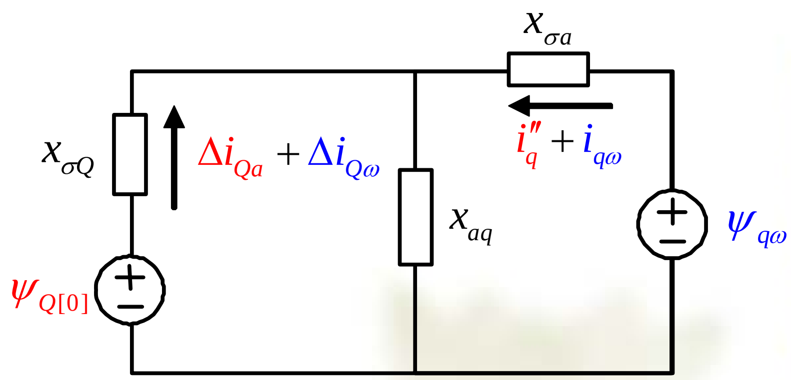
$\Delta i_{Q\omega}$

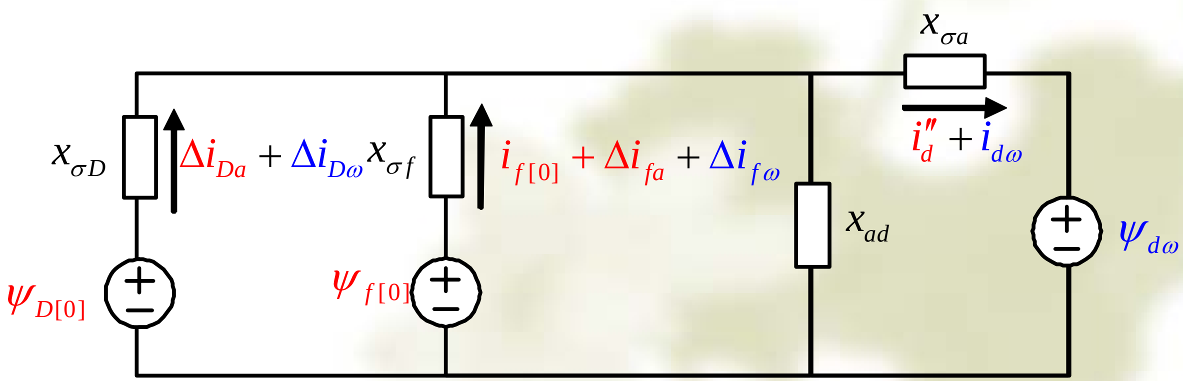
$$\psi_{a0} = \psi_0 \cos(\alpha_0 - \delta_0)$$

$$\psi_{b0} = \psi_0 \cos(\alpha_0 - \delta_0 - 120^\circ)$$

$$\psi_{c0} = \psi_0 \cos(\alpha_0 - \delta_0 + 120^\circ)$$

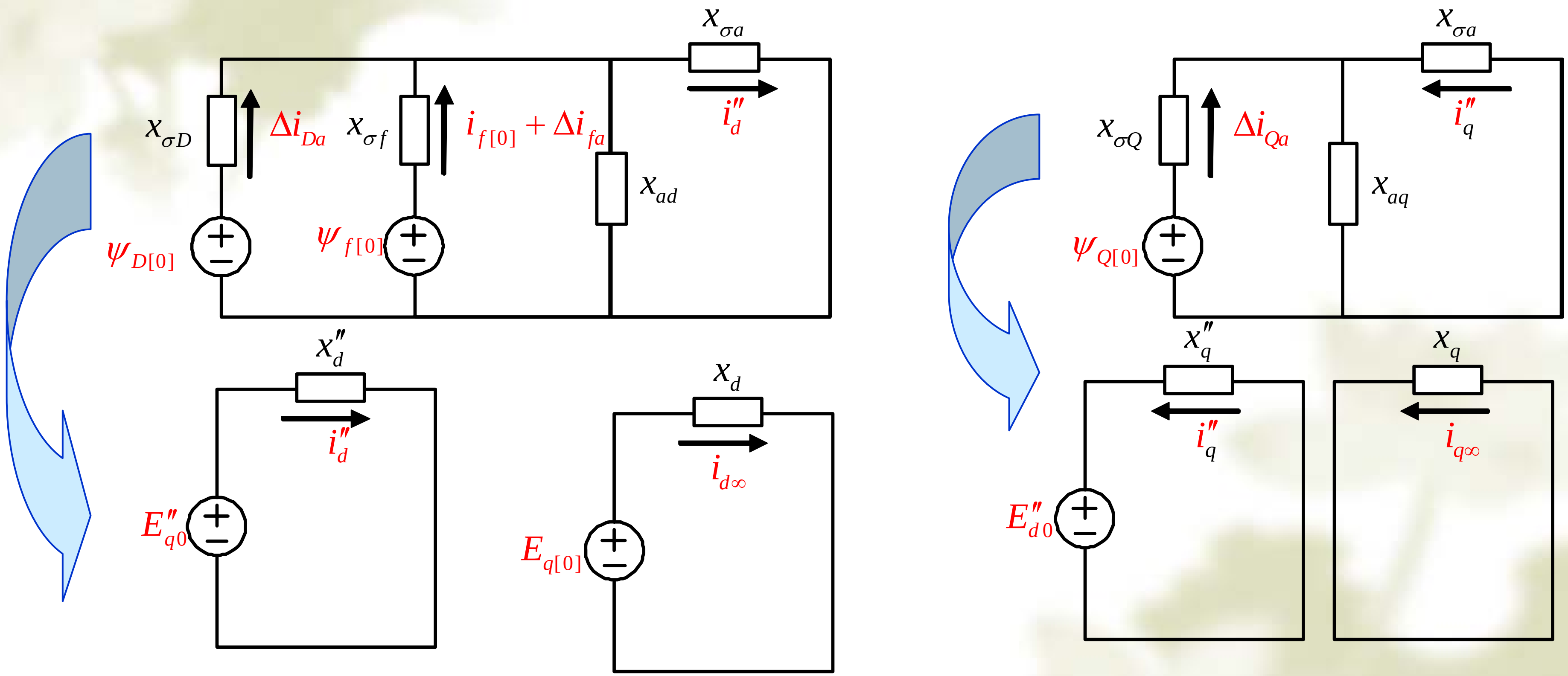
$$\begin{cases} \psi_{d\omega} = \psi_0 \cos(\omega t + \delta_0) \\ \psi_{q\omega} = \psi_0 \sin(\omega t + \delta_0) \end{cases}$$





3. 有阻尼绕组电机的短路电流

(2) 利用磁链平衡等值电路计算次暂态电流



$$i''_d = E''_{q0} / x''_d, \quad i_{d\infty} = E_{q[0]} / x_d$$

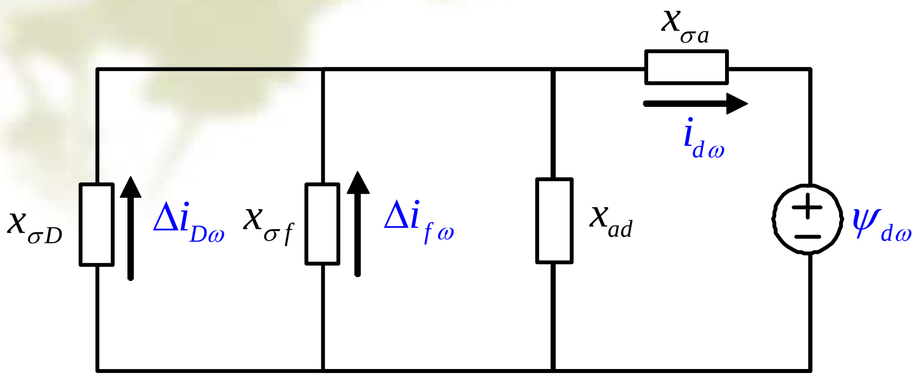
$$E''_{q0} = V_{[0]} \cos\delta_0 + x''_d i_{d[0]}$$

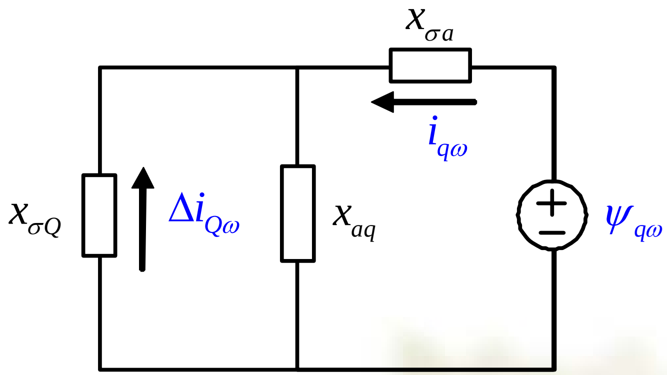
$$i''_q = -E''_{d0} / x''_q, \quad i_{q\infty} = 0$$

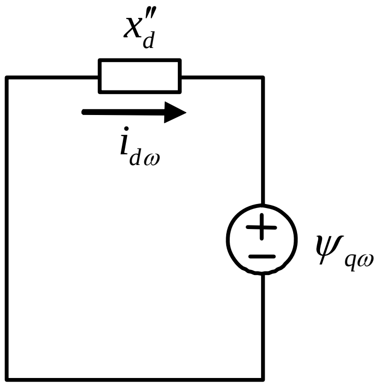
$$E''_{d0} = u_{d[0]} - i_{q[0]} x''_q = (x_q - x''_q) / x_q \, V_{[0]} \sin\delta_0$$

3. 有阻尼绕组电机的短路电流

(3) 利用磁链平衡等值电路计算短路电流非周期分量

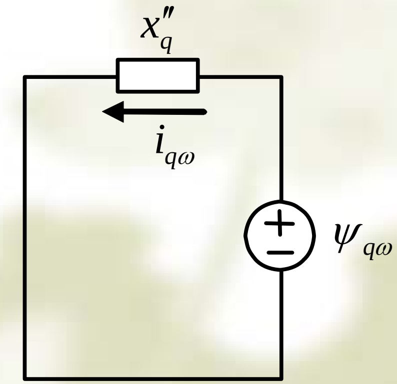






$$\psi_{d\omega} = V_{[0]}\cos(\omega t + \delta_0)$$

$$\psi_{d\omega} = V_{[0]}\cos(\omega t + \delta_0)$$



$$i_{d\omega} = -\frac{\psi_{d\omega}}{x''_d} = -\frac{V_{[0]}}{x''_d}\cos(\omega t + \delta_0)$$

$$i_{q\omega} = \frac{\psi_{q\omega}}{x''_q} = \frac{V_{[0]}}{x''_q}\sin(\omega t + \delta_0)$$

3. 有阻尼绕组电机的短路电流

(4) 各种电流分量计算式—Summary

$$i''_d = E''_{q0}/x''_d,\ i_{d\infty} = E_{q[0]}/x_d,\ i'_d = E'_{q[0]}/x'_d$$

$$i''_q = -E''_{d0}/x''_q,\ i_{q\infty} = 0$$

$$i_{d\omega} = -V_{[0]}\cos(\omega t+\delta_0)/x''_d$$

$$i_{q\omega} = V_{[0]}\sin(\omega t+\delta_0)/x''_q$$

$$\Delta i_{fa} = \frac{x_{ad}x_{\sigma D}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]}\cos\delta_0}{x''_d}$$

$$\Delta i_{Da} = \frac{x_{ad}x_{\sigma f}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]}\cos\delta_0}{x''_d}$$

$$\Delta i_{Qa} = -\frac{x_q - x''_q}{x_{aq}x''_q} \times V_{[0]}\sin\delta_0$$

$$\Delta i_{f\omega} = -\frac{x_{ad}x_{\sigma D}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]}\cos(\omega t+\delta_0)}{x''_d}$$

$$\Delta i_{D\omega} = -\frac{x_{ad}x_{\sigma f}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]}\cos(\omega t+\delta_0)}{x''_d}$$

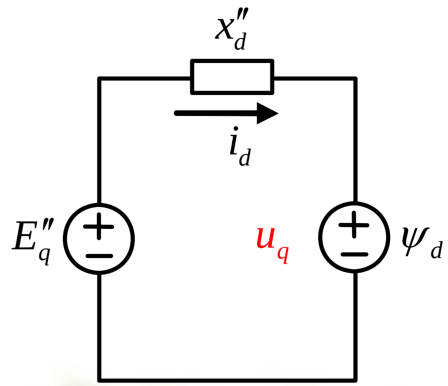
$$\Delta i_{Q\omega} = -\frac{x_q - x''_q}{x_{aq}x''_q} \times \frac{V_{[0]}\cos(\omega t+\delta_0)}{x''_d}$$

4.同步电机 次暂态模型

(1) 次暂态参数表示的电势方程

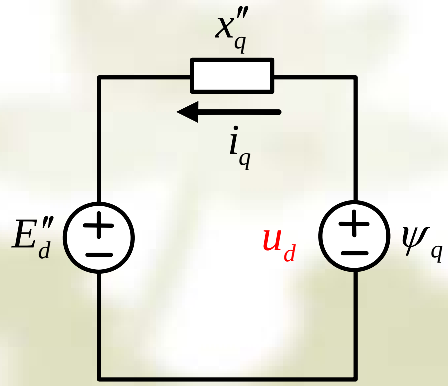
$$E''_q = \left(\frac{\psi_f}{x_{\sigma f}} + \frac{\psi_D}{x_{\sigma D}}\right) \times x_{ad} // x_{\sigma f} // x_{\sigma D}$$

$$E''_d = \frac{x_{aq}}{x_Q}\psi_Q$$



$$x''_d = x_{\sigma a} + x_{ad} // x_{\sigma f} // x_{\sigma D}$$

$$x''_q = x_{\sigma a} + x_{aq} // x_{\sigma Q}$$



$$u_d = \dot{\psi}_d + \omega\psi_q - ri_d$$
$$u_q = -\dot{\psi}_q + \omega\psi_d - ri_q$$

不考虑$\dot{\psi}_d$和$\dot{\psi}_q$

$\omega = 1.0$，忽略r

$$u_d = \psi_q$$
$$u_q = \psi_d$$

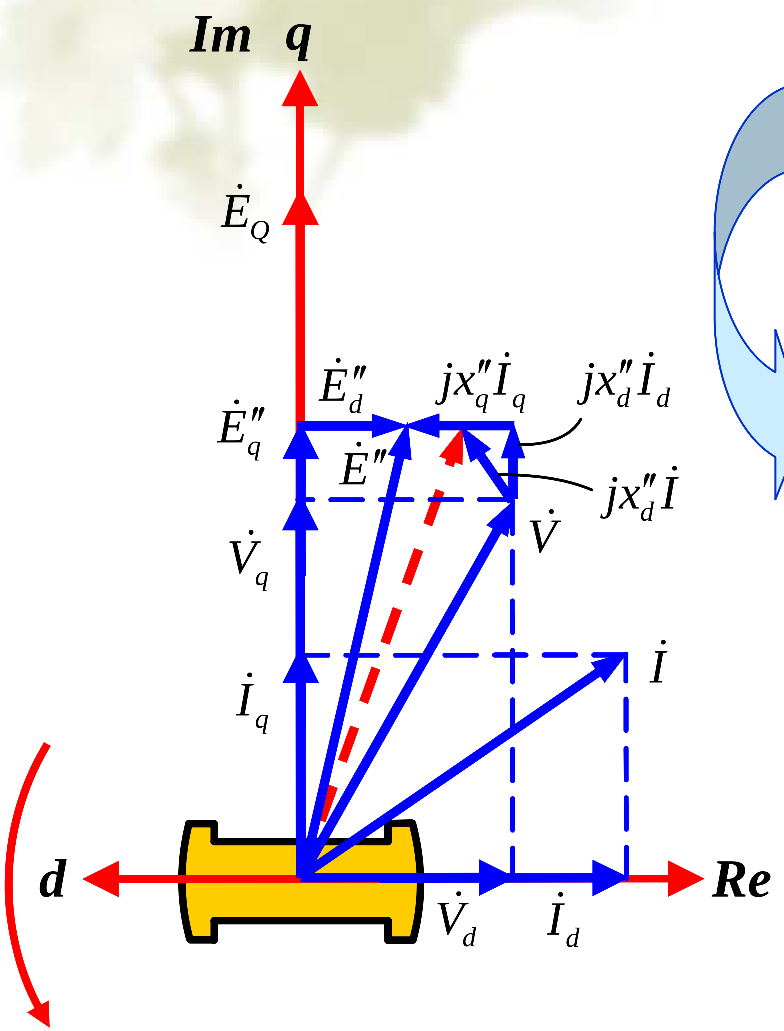
$$\psi_d = E''_q - x''_d i_d$$
$$\psi_q = E''_d - x''_q i_q$$

电势方程

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

4.同步电机 次暂态模型

(2) 次暂态参数表示的相量方程及相量图



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

$$\dot{E}''_q = jE''_q, \dot{V}_d = u_d, \dot{I}_d = i_d$$
$$\dot{E}''_d = jE''_d, \dot{I}_q = ji_q, \dot{V}_q = ju_q$$

$$ju_q = jE''_q - jx''_d i_d$$
$$u_d = E''_d - jx''_q j i_q$$

$$\dot{V}_q = \dot{E}''_q - jx''_d \dot{I}_d$$
$$\dot{V}_d = \dot{E}''_d - jx''_q \dot{I}_q$$

$$\dot{V} = (\dot{E}''_q + \dot{E}''_d) - jx''_d\dot{I}_d - jx''_q\dot{I}_q$$
$$= \dot{E}'' - jx''_d\dot{I}_d - jx''_q\dot{I}_q \approx \dot{E}'' - jx''_d\dot{I}$$

$\dot{E}'' = \dot{E}''_q + \dot{E}''_d$: 次暂态电势, $x''_d \approx x''_q$

4.同步电机 次暂态模型

(3) 同步电机稳态、暂态和次暂态参数及等值电路

同步电机结构参数：

$x_d, x_q, x'_d, x''_d, x''_q$

同步电机运行参数：

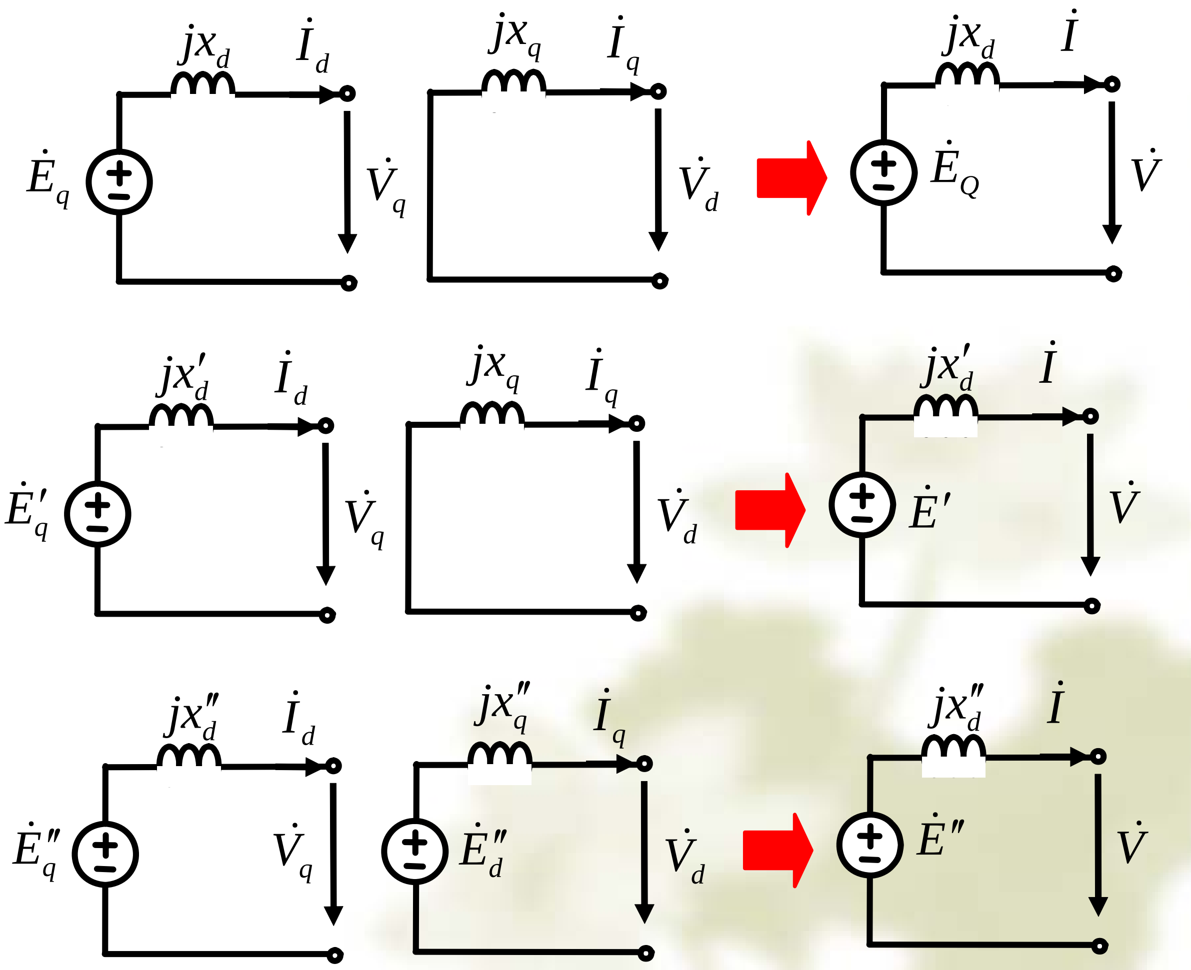
$E_Q, E_q, E'_q, E''_q, E''_d$

$\dot{V}, \dot{I}, x_q \Rightarrow E_Q, \delta+\varphi$

$\Rightarrow V_d, V_q, I_d, I_q + x_d$

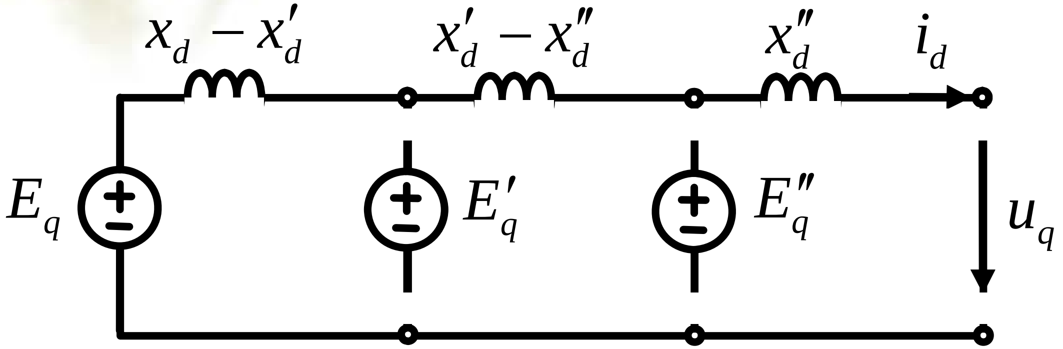
$x'_d \Rightarrow E_q, E'_q, E''_q, E''_d$

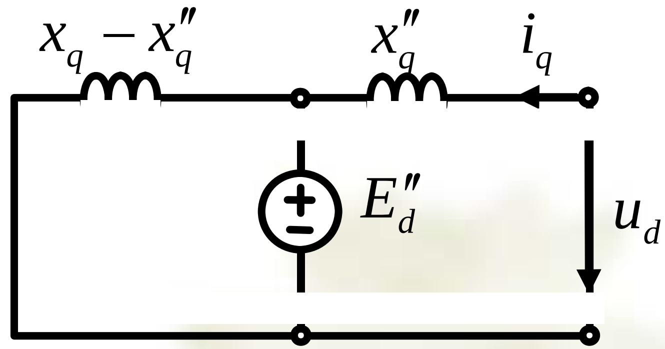
$\dot{V}, \dot{I}, x'_d, x''_d \Rightarrow \dot{E}', \dot{E}''$



4.同步电机次暂态模型

(4) 同步电机稳态、暂态和次暂态参数之间关系





$$i_d = \frac{E_q - V\cos\delta}{x_d} = \frac{E_q' - V\cos\delta}{x_d'} = \frac{E_q'' - V\cos\delta}{x_d''}$$

$$i_q = \frac{V\sin\delta}{x_q} = \frac{E_d'' - V\sin\delta}{x_q''}$$

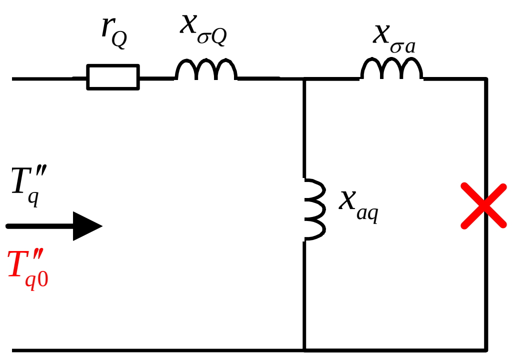
5. 自由电流的衰减

(1) 横轴次暂态电流和非周期分量

$$i_q = i''_q \exp\left(-\frac{t}{T''_q}\right) + i_{q\omega} \exp\left(-\frac{t}{T_a}\right)$$

$$i_Q = \Delta i_{Qa} \exp\left(-\frac{t}{T''_q}\right) + \Delta i_{Q\omega} \exp\left(-\frac{t}{T_a}\right)$$

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



横轴次暂态开路时间常数：$T''_{q0} = \dfrac{x_Q}{\omega r_Q}$

横轴次暂态短路时间常数：$T''_q = \dfrac{x''_q}{x_q} T''_{q0}$

5. 自由电流的衰减

(2) 纵轴次暂态、暂态电流分量和非周期分量

$$i_d = i_{d\infty} + \Delta i_d'' \exp\left(-\frac{t}{T_d''}\right) + \Delta i_d' \exp\left(-\frac{t}{T_d'}\right) + i_{d\omega} \exp\left(-\frac{t}{T_a}\right)$$

$$i_f = i_{f[0]} + \Delta i_{fa}'' \exp\left(-\frac{t}{T_d''}\right) + \Delta i_{fa}' \exp\left(-\frac{t}{T_d'}\right) + \Delta i_{f\omega} \exp\left(-\frac{t}{T_a}\right)$$

$$i_D = \Delta i_{Da} \exp\left(-\frac{t}{T_d''}\right) + \Delta i_{D\omega} \exp\left(-\frac{t}{T_a}\right)$$

$$\Delta i_d'' = \frac{E_{q0}''}{x_d''} - \frac{E_{q[0]}'}{x_d'}$$

$$\Delta i_d' = \frac{E_{q[0]}'}{x_d'} - \frac{E_{q[0]}}{x_d}$$

$$i_d = i_{d\infty} + \left(i_d'' - i_d'\right) + \left(i_d' - i_{d\infty}\right) + i_{d\omega}$$

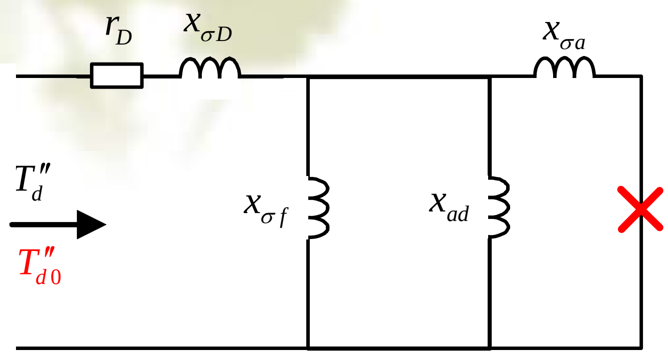
$$i_f = i_{f[0]} + \left(\Delta i_{fa} - \Delta i_{fa}'\right) + \Delta i_{fa}' + \Delta i_{f\omega}$$

$$i_D = \Delta i_{Da} + \Delta i_{D\omega}$$

$$\Delta i_{fa}' = \frac{x_d - x_d'}{x_{ad} x_d'} V_{[0]} \cos\delta_0$$

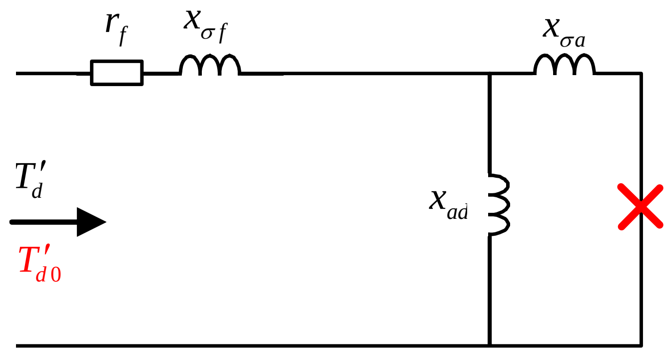
5. 自由电流的衰减

(2) 纵轴次暂态、暂态电流分量和非周期分量



纵轴次暂态开路时间常数：T''_{d0}

纵轴次暂态短路时间常数：$T''_d = \dfrac{x''_d}{x'_d} T''_{d0}$



纵轴暂态开路时间常数：$T'_{d0} = \dfrac{x_f}{\omega r_f}$

纵轴暂态短路时间常数：$T'_d = \dfrac{x'_d}{x_d} T'_{d0}$

6. 短路全电流

(1) 定子电流纵轴和横轴分量

$$i_d = \frac{E_{q[0]}}{x_d} + \left(\frac{E''_{q0}}{x''_d} - \frac{E'_{q[0]}}{x'_d}\right)\exp\left(-\frac{t}{T''_d}\right) + \left(\frac{E'_{q[0]}}{x'_d} - \frac{E_{q[0]}}{x_d}\right)\exp\left(-\frac{t}{T'_d}\right) - \frac{V_{[0]}}{x''_q}\exp\left(-\frac{t}{T_a}\right)\cos(\omega t + \delta_0)$$

$$i_q = -\frac{E''_{d0}}{x''_q}\exp\left(-\frac{t}{T''_q}\right) + \frac{V_{[0]}}{x''_q}\exp\left(-\frac{t}{T_a}\right)\sin(\omega t + \delta_0)$$

$$i_a = -i_d \cos(\omega t + \alpha_0) + i_q \sin(\omega t + \alpha_0)$$

6. 短路全电流

(2) A相定子电流

$$i_a = -\frac{E_{q[0]}}{x_d}\cos(\omega t+\alpha_0) - \left(\frac{E''_{q0}}{x''_d} - \frac{E'_{q[0]}}{x'_d}\right)\exp\left(-\frac{t}{T''_d}\right)\cos(\omega t+\alpha_0)$$

$$-\left(\frac{E'_{q[0]}}{x'_d} - \frac{E_{q[0]}}{x_d}\right)\exp\left(-\frac{t}{T'_d}\right)\cos(\omega t+\alpha_0) - \frac{E''_{d0}}{x''_q}\exp\left(-\frac{t}{T''_q}\right)\sin(\omega t+\alpha_0)$$

$$+\frac{V_{[0]}}{2}\left(\frac{1}{x''_d}+\frac{1}{x''_q}\right)\exp\left(-\frac{t}{T_a}\right)\cos(\delta_0-\alpha_0)$$

$$+\frac{V_{[0]}}{2}\left(\frac{1}{x''_d}-\frac{1}{x''_q}\right)\exp\left(-\frac{t}{T_a}\right)\cos(2\omega t+\delta_0+\alpha_0)$$

6. 短路全电流

(3) 励磁电流

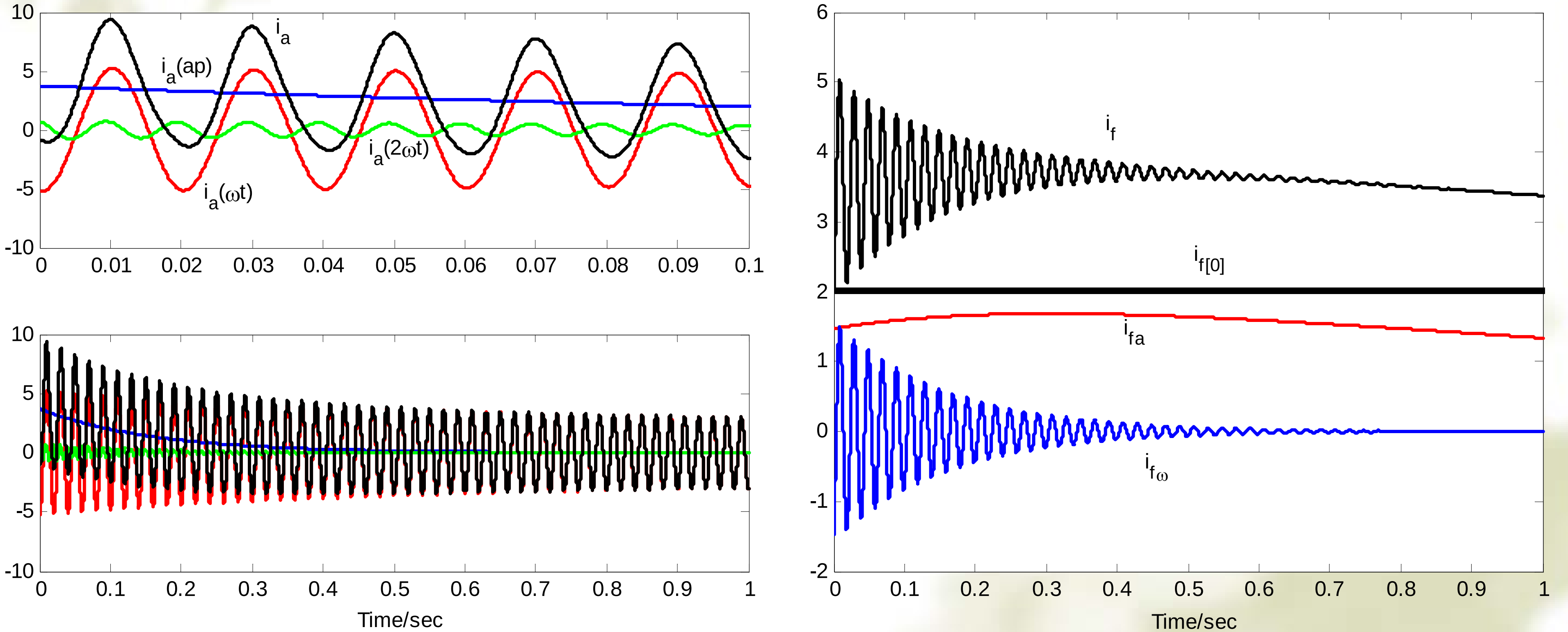
$$i_f = i_{f[0]} + \left[\frac{x_{ad} x_{\sigma D}}{\left(x_f x_D - x_{ad}^2 \right) x_d''} - \frac{x_d - x_d'}{x_{ad} x_d'} \right] V_{[0]} \cos\delta_0 \exp\left(-\frac{t}{T_d''} \right)$$

$$+ \frac{x_d - x_d'}{x_{ad} x_d'} V_{[0]} \cos\delta_0 \exp\left(-\frac{t}{T_d'} \right)$$

$$- \frac{x_{ad} x_{\sigma D}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]} \cos(\omega t + \delta_0)}{x_d''} \exp\left(-\frac{t}{T_a} \right)$$

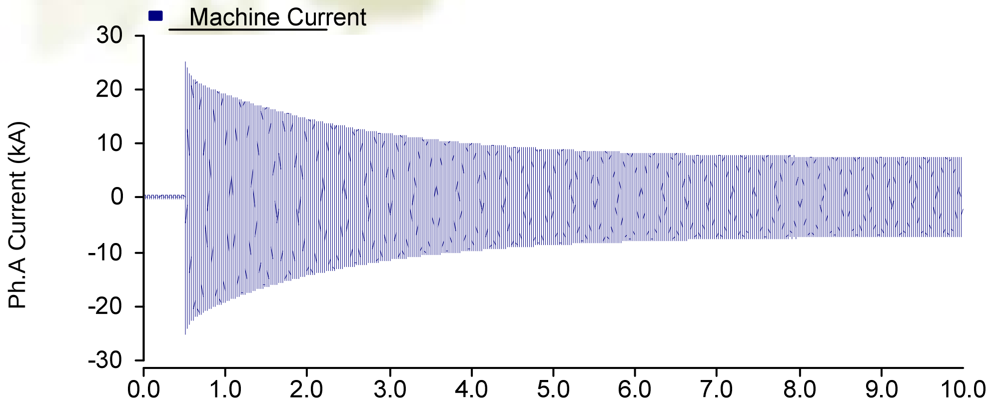
6. 短路全电流

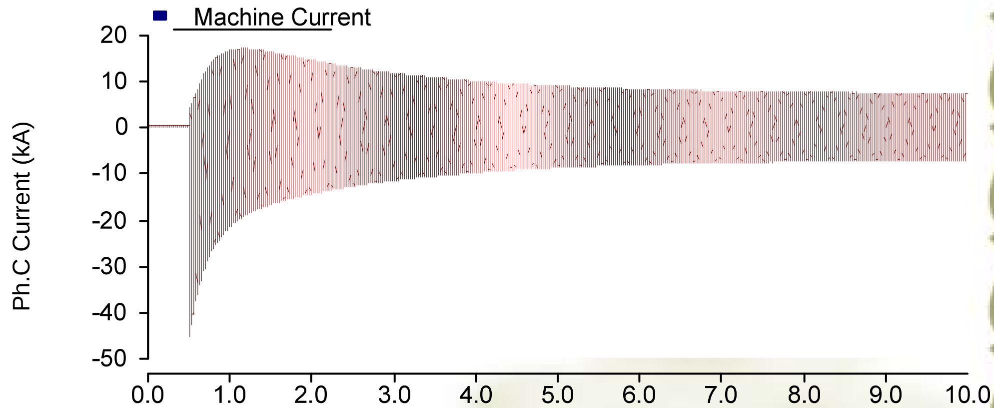
(3) 电流波形

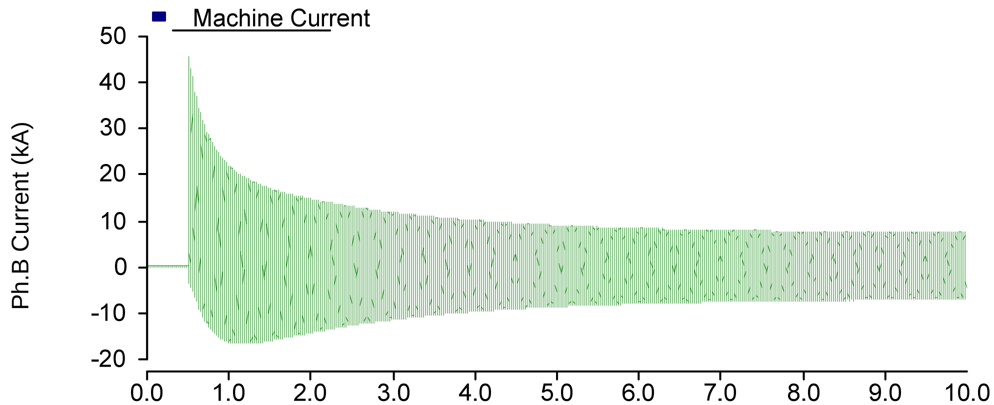


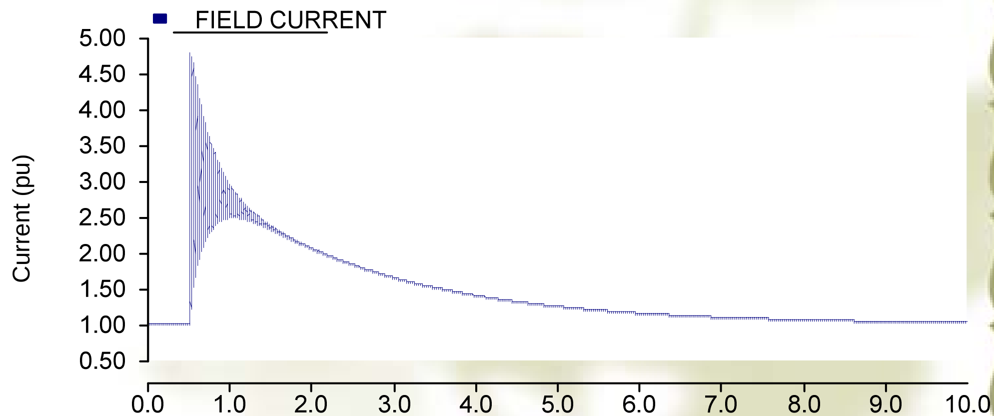
6. 短路全电流

(3) 电流波形







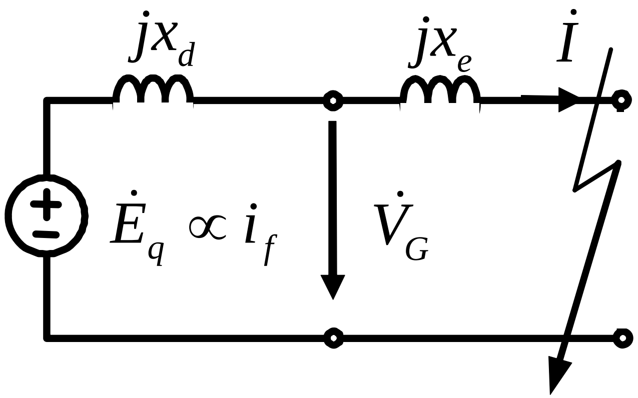


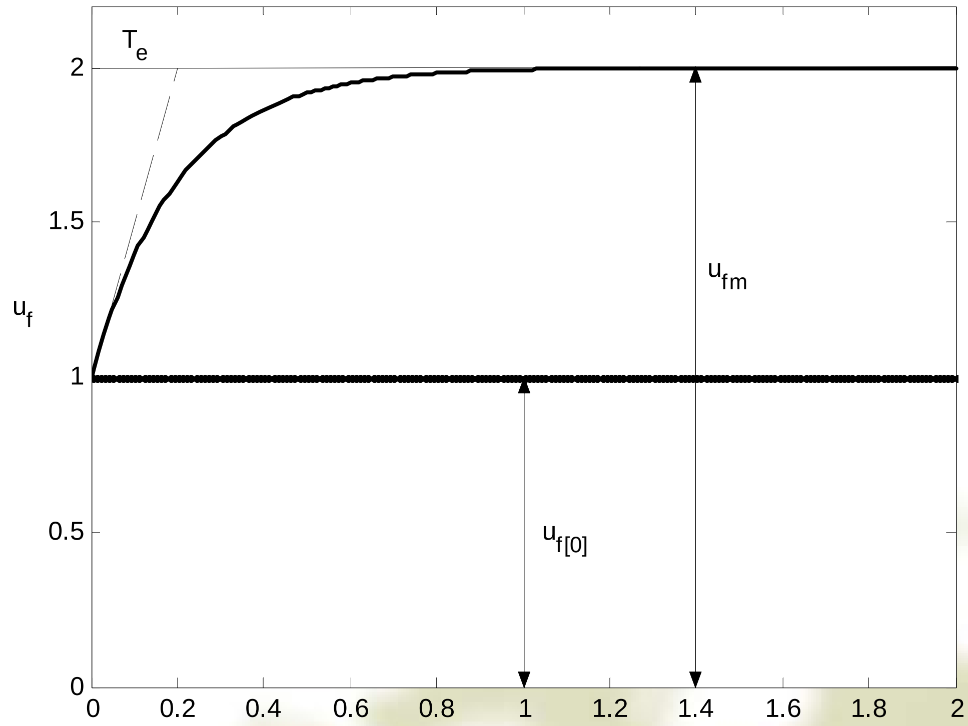
5-6 强行励磁对短路暂态过程的影响

(1) 强励： i_f—E_q—V_G

(2) 临界电抗X_{cr}： V_{GN}

(3) 短路稳态电流 I_∞





最大稳态短路电流

$$I = V_{GN} / x_e$$

本章小结

❖ 短路电流周期分量、冲击电流、有效值、短路容量的定义

❖ 同步电机突然三相短路的各种电流分量（强制分量和自由分量，周期分量和非周期分量）及相互之间的对应关系和磁链平衡关系

❖ 同步电机暂态和次暂态参数的定义和计算，相应的等值电路和相量图

❖ 同步电机三相短路电流计算的基本原理和方法——由磁链平衡关系计算各分量，确定自由电流的衰减时间常数

Ex 5-3，5-7(1前一问)(2)

To Be Continued