

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

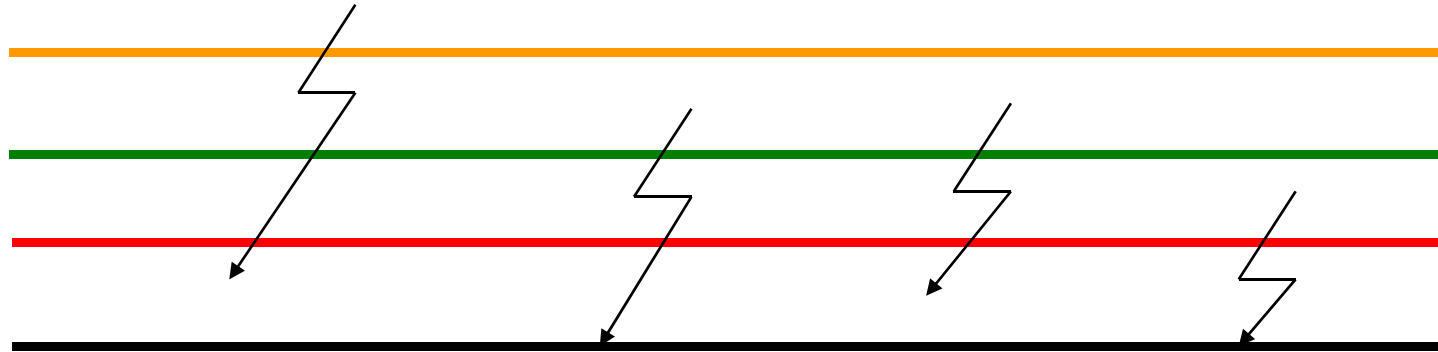
5-5 有阻尼绕组同步电机的突然三相短路

5-6 强行励磁对短路暂态过程的影响

5-1 短路的一般概念

1. 短路的原因、类型及后果

短路： 不正常的相相或相地发生通路



❖ 三相短路（对称） $f^{(3)}$
❖ 两相短路接地 $f^{(1,1)}$

❖ 两相短路 $f^{(2)}$
❖ 单相短路 $f^{(1)}$

5-1 短路的一般概念

1. 短路的原因、类型及后果

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

短路的原因

1. 元件损坏
2. 气象条件恶化
3. 违规操作
4. 其它

短路的概率

1. $f^{(1)}$ 最多
2. $f^{(3)}$ 最少，但最严重

5-1 短路的一般概念

1. 短路的原因、类型及后果

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

2. 短路计算的目

- (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

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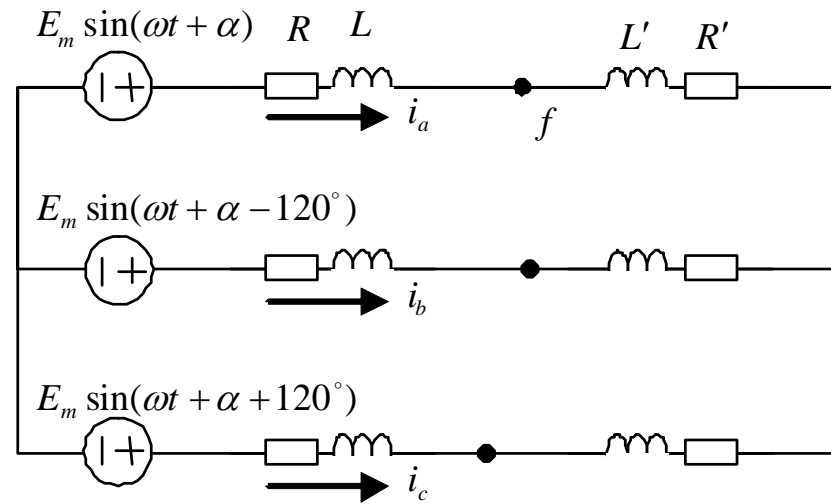
5-6 强行励磁对短路暂态过程的影响

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

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



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

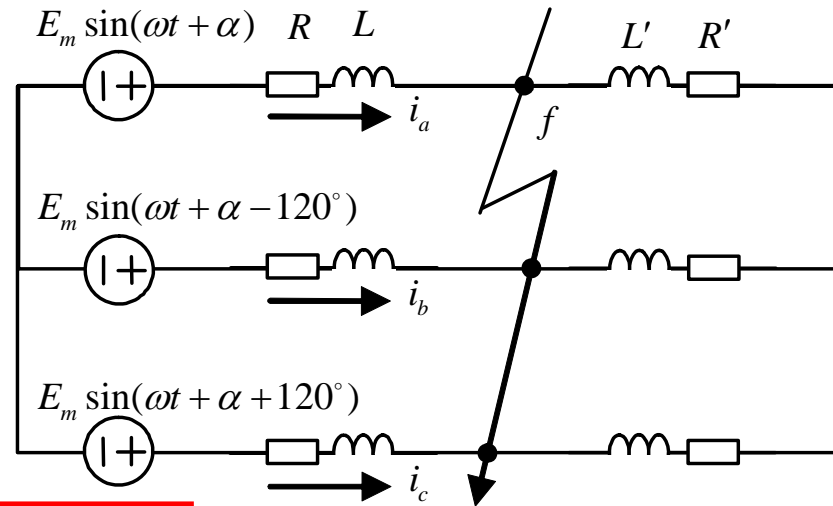
5-2 恒定电势源电路的三相短路

1. 短路的暂态过程——短路后足够长时间后的稳态

三相对称，以a相为例

$$e = E_m \sin(\omega t + \alpha)$$

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



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

电感电流不会突变，如何从 I_m 过渡到 I_{pm} ？

5-2 恒定电势源电路的三相短路

1. 短路的暂态过程——短路暂态过程中

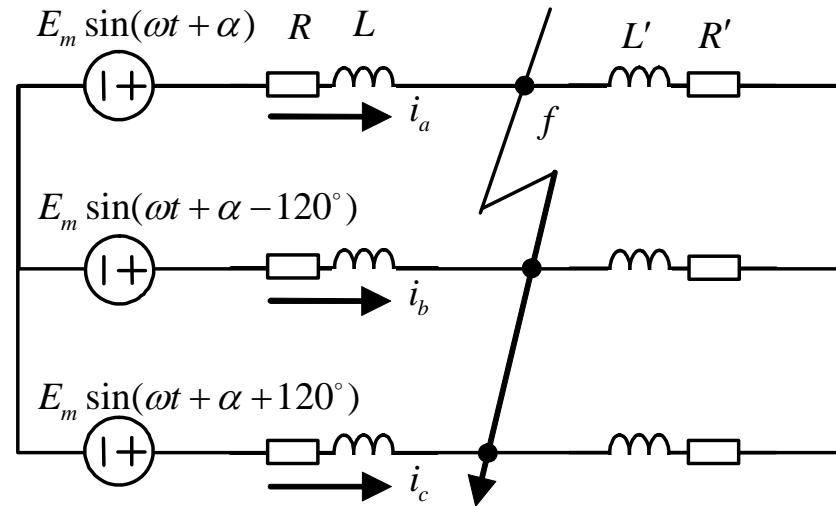
三相对称，以a相为例

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

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

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

$$\lambda = -\frac{R}{L}; \quad T_a = \frac{L}{R}$$



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

短路前: $i = I_m \sin(\omega t + \alpha - \varphi')$

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

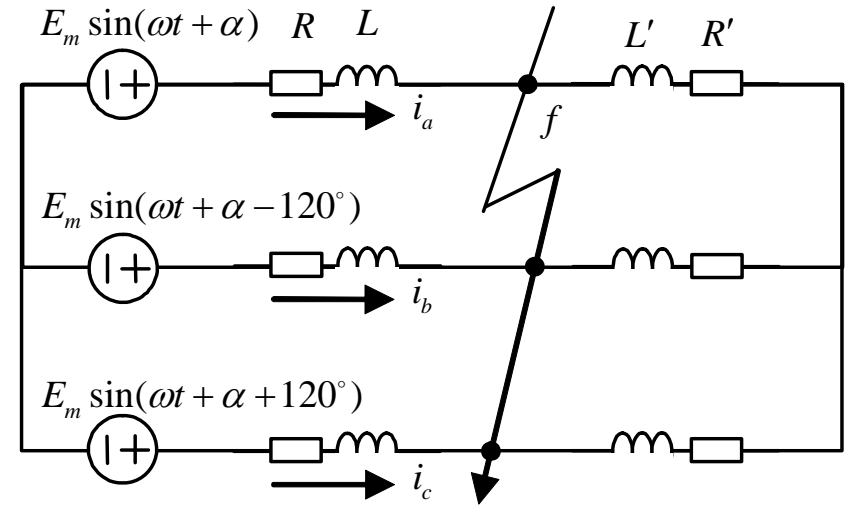
α : 合闸角

短路瞬间: $t=0$

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

$C = i_{ap0}$

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



5-2 恒定电势源电路的三相短路

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

主要结论:

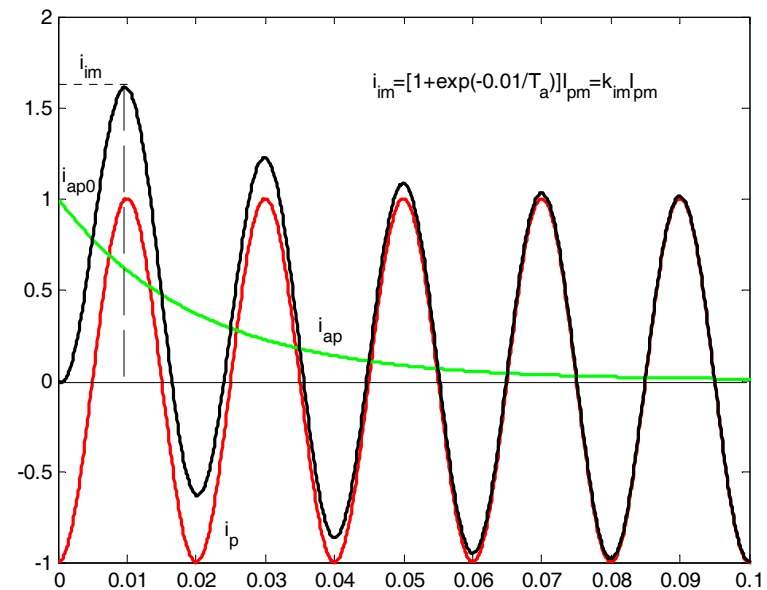
(1) 定义短路发生时刻系统A相电

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;

5-2 恒定电势源电路的三相短路

2. 短路冲击电流

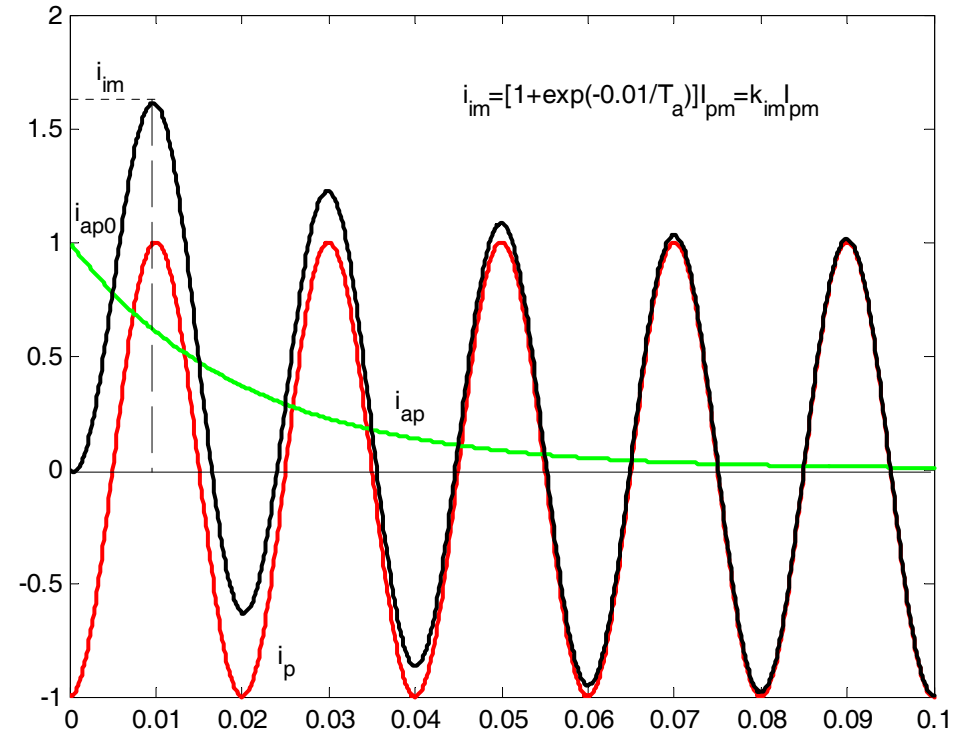
短路电流最大可能瞬时值：

空载；

纯感性电路；

合闸角 0° ；

短路后半周波时刻；



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

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

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

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

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 k_{im}

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

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

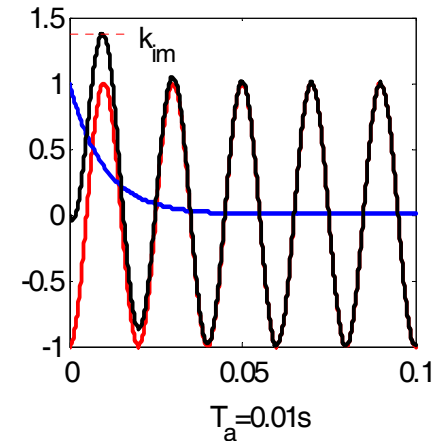
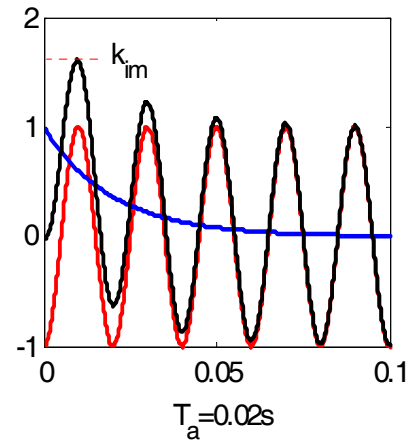
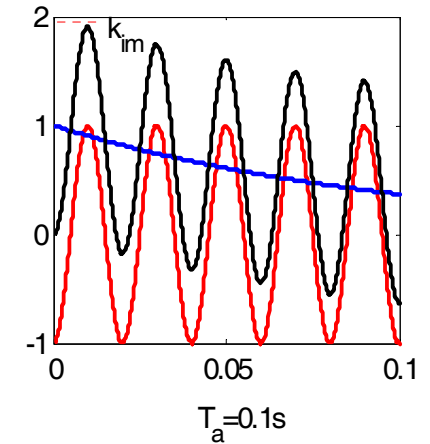
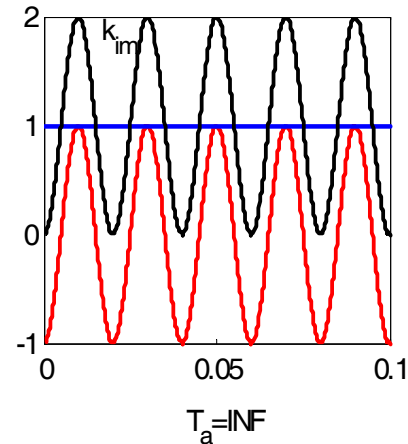
$$T_a = L/R$$

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

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: $k_{im} = 1.8$



5-2 恒定电势源电路的三相短路

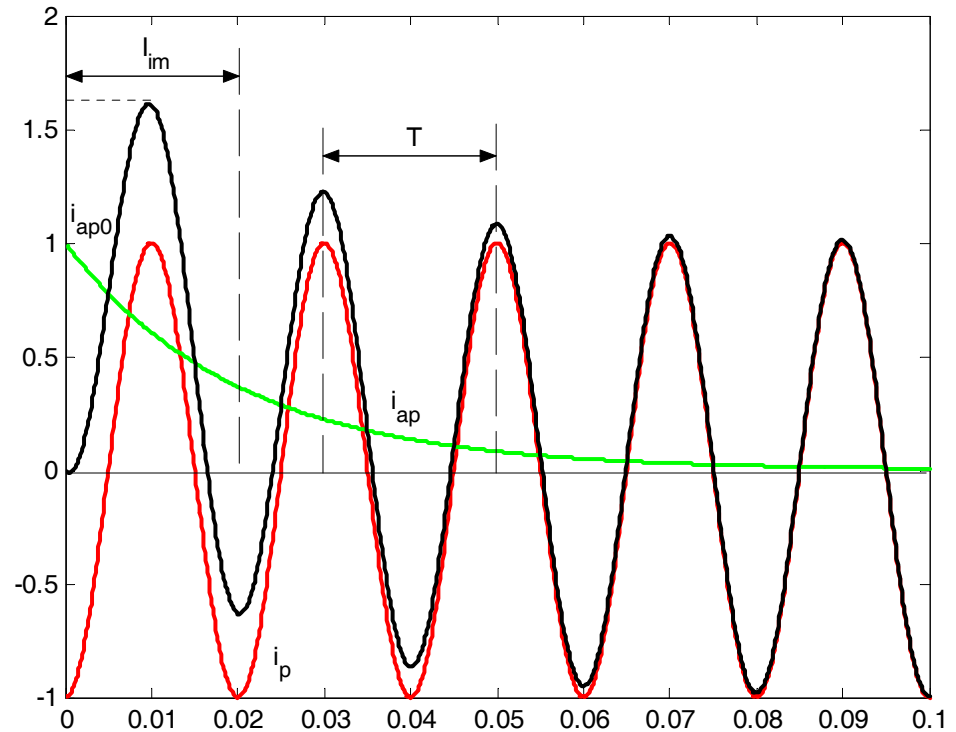
3. 短路电流有效值—定义、近似计算、最大值

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



工程简化

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



短路电流的最大有效值

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

5-2 恒定电势源电路的三相短路

4. 短路容量—定义、标么值

短路电流有效值与短路处
正常工作电压的乘积



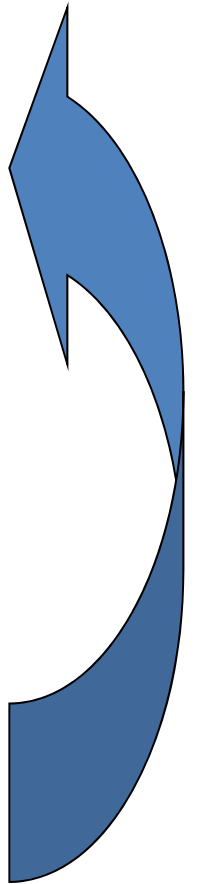
$$S_t = \sqrt{3}V_{av}I_t$$

标么值



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

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



5-2 恒定电势源电路的三相短路

短路电流 与 短路电流周期分量

- (1) 冲击电流
- (2) 短路电流非周期分量
- (3) 短路电流有效值
- (4) 短路功率

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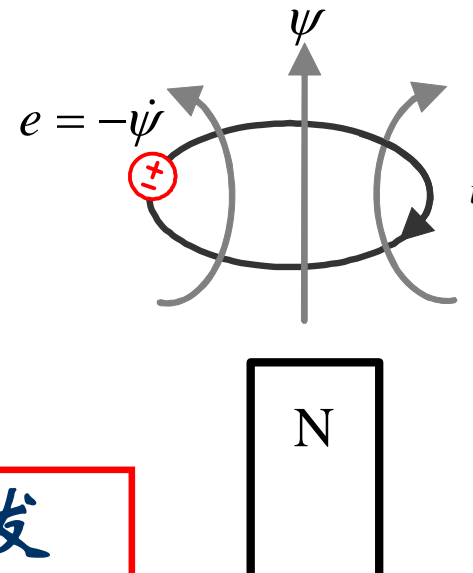
5-3 同步电机突然三相短路的物理分析

1. 超导体闭合回路磁链守恒原则

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

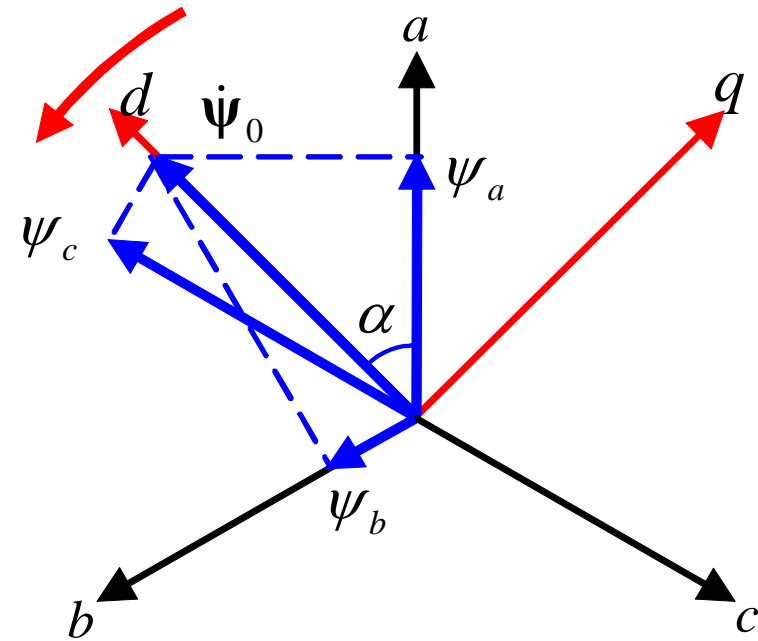
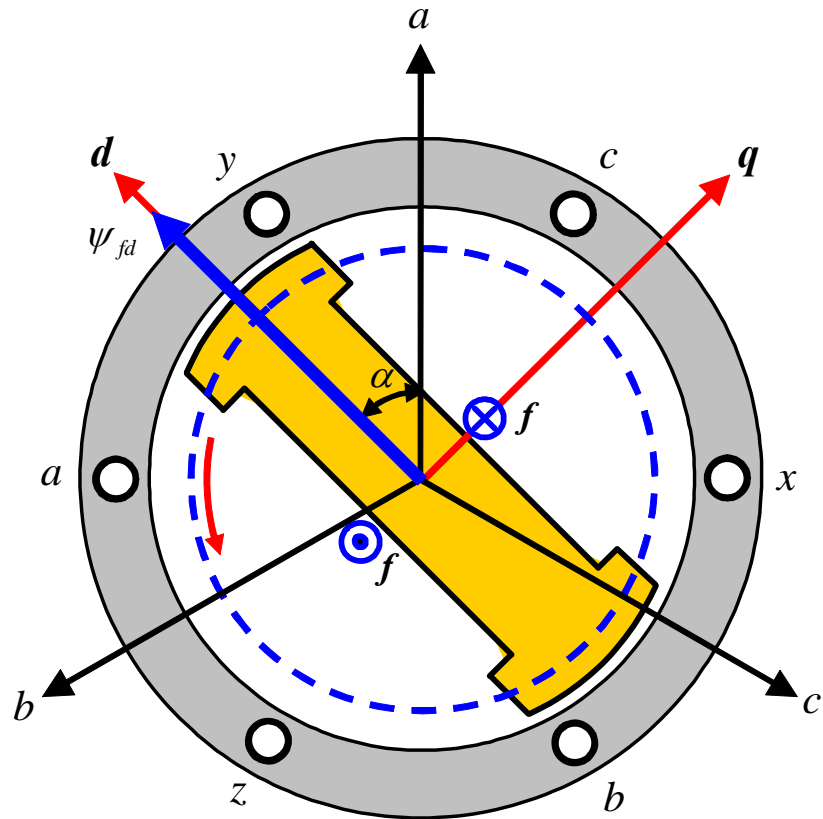
$$Li + \psi = \psi_0$$

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。



2. 无阻尼绕组同步电机突然三相短路的物理分析

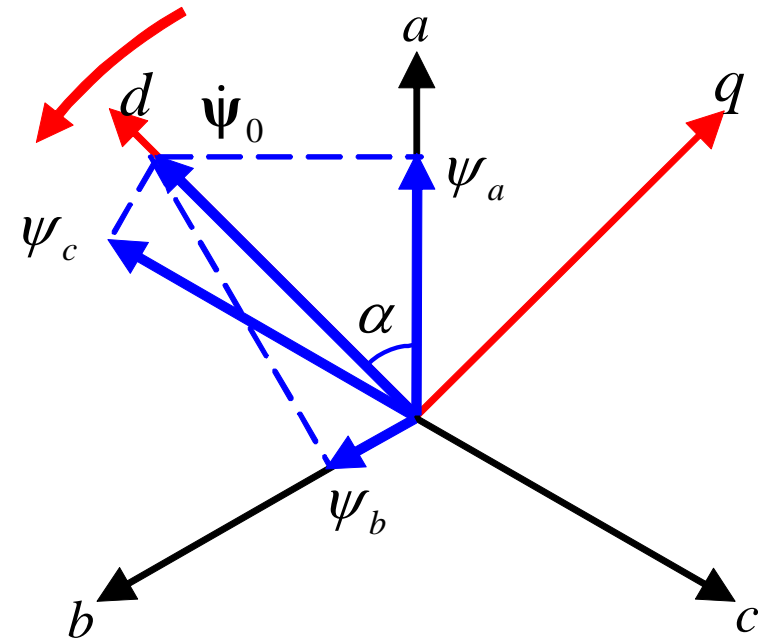
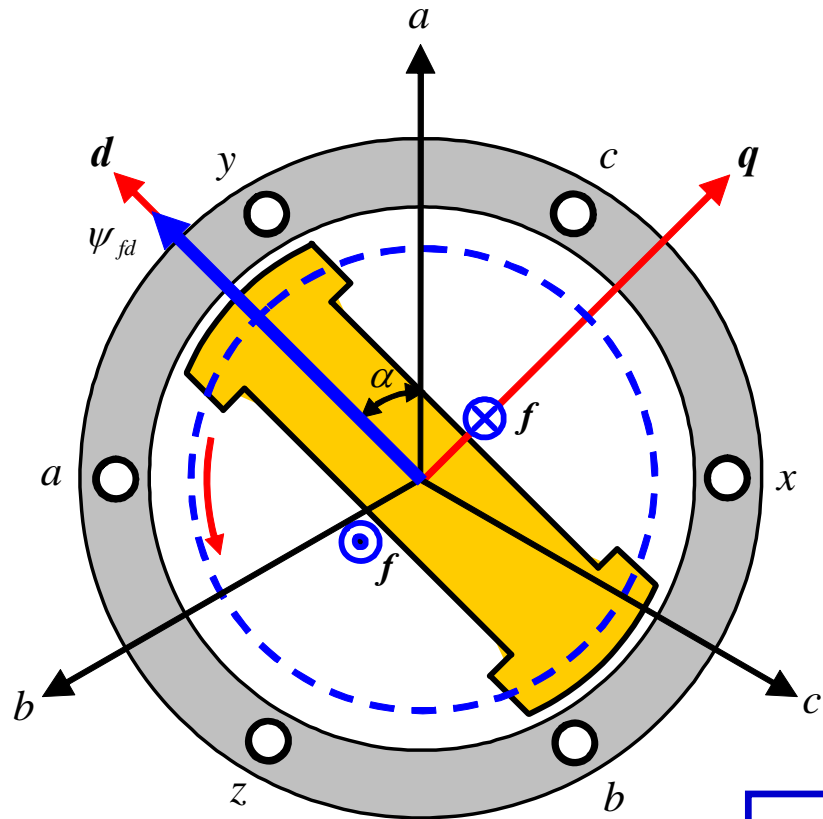
(1) 短路前定子各相绕组磁链——仅有励磁电流作用



$$\psi_a = \psi_0 \cos(\omega t + \alpha_0), \quad \psi_b = \psi_0 \cos(\omega t + \alpha_0 - 120^\circ), \quad \psi_c = \psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

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 (0-时刻) 定子各相绕组磁链: 励磁电流

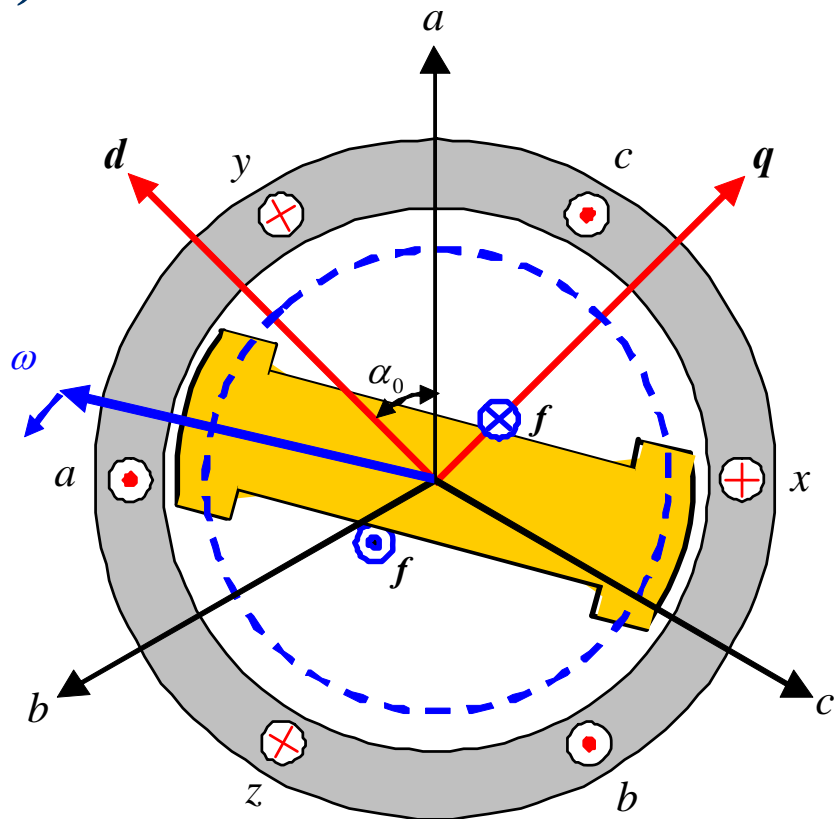


$t = 0$

$$\psi_{a0} = \psi_0 \cos \alpha_0, \quad \psi_{b0} = \psi_0 \cos(\alpha_0 - 120^\circ), \quad \psi_{c0} = \psi_0 \cos(\alpha_0 + 120^\circ)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(3) 短路之后 ($0+$ 时刻及以后) : 定子电流 + 励磁电流



定子电流产生的磁链

$$\Delta\psi_a, \Delta\psi_b, \Delta\psi_c$$

励磁电流产生的磁链

$$\text{a相: } \psi_0 \cos(\omega t + \alpha_0)$$

$$\text{b相: } \psi_0 \cos(\omega t + \alpha_0 - 120^\circ)$$

$$\text{c相: } \psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

t 时刻定子各相绕组磁链

$$\psi_{at} = \Delta\psi_a + \psi_0 \cos(\omega t + \alpha_0)$$

$$\psi_{bt} = \Delta\psi_b + \psi_0 \cos(\omega t + \alpha_0 - 120^\circ)$$

$$\psi_{ct} = \Delta\psi_c + \psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(4) 短路前后定子各相绕组磁链守恒

短路瞬间:

$$\psi_{a0} = \Psi_0 \cos \alpha_0$$

$$\psi_{b0} = \Psi_0 \cos(\alpha_0 - 120^\circ)$$

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

短路后 t 时刻

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

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

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

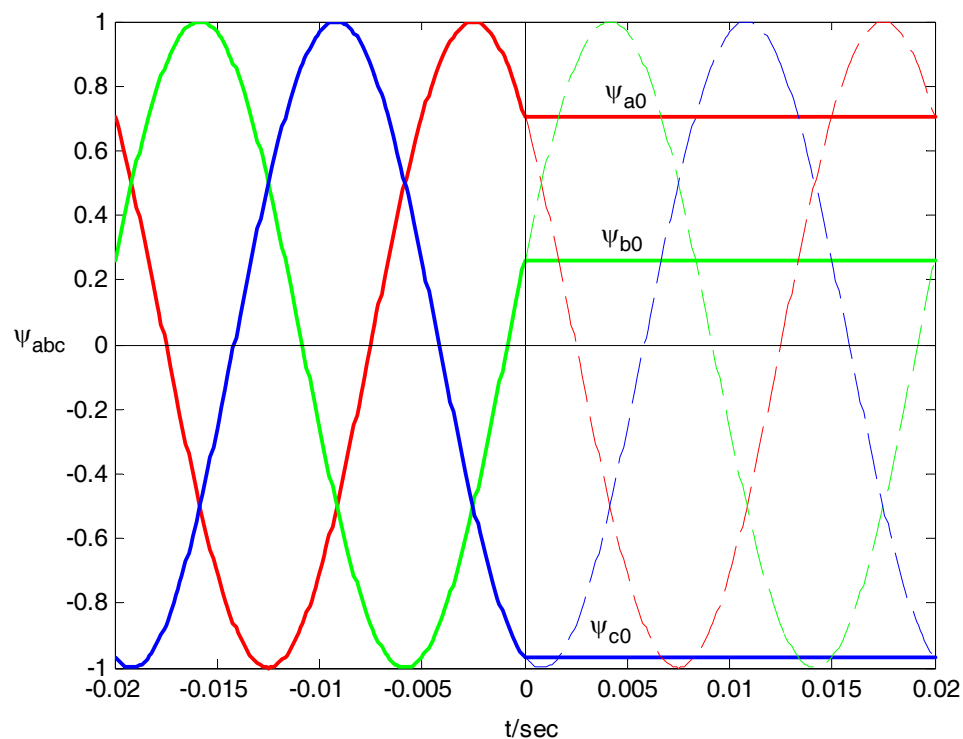
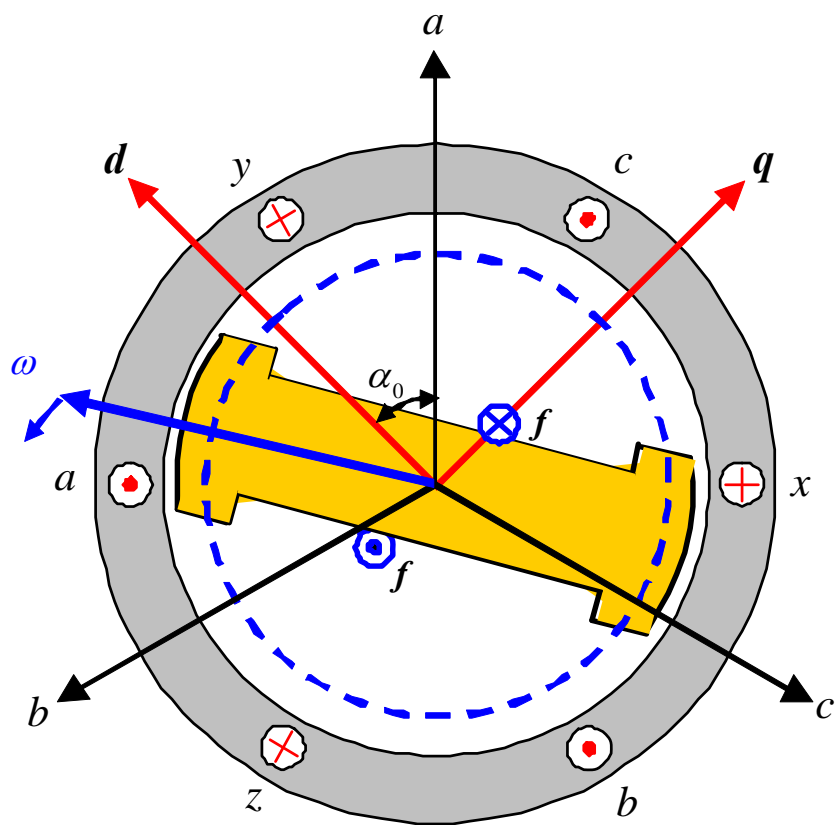
$$\psi_{a0} = \Delta\psi_a + \Psi_0 \cos(\omega t + \alpha_0)$$

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

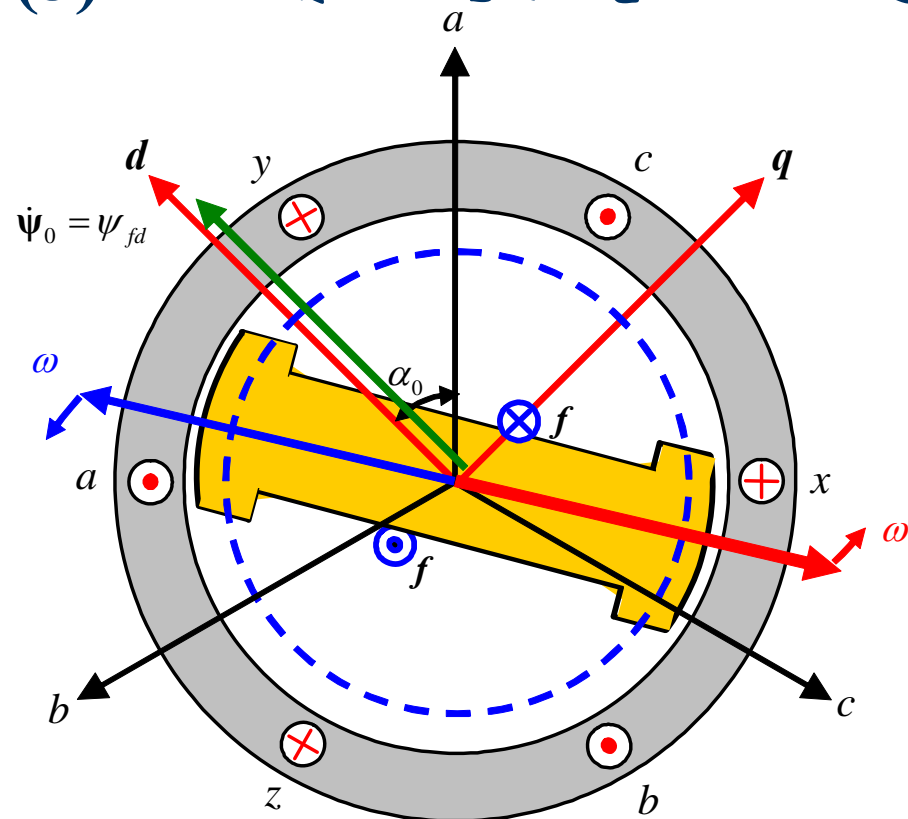
$$\psi_{c0} = \Delta\psi_c + \Psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

2. 无阻尼绕组同步电机突然三相短路的物理分析

(4) 短路前后定子各相绕组磁链守恒



(5) 短路前后定子绕组磁链守恒——定子电流+励磁电流



$$\psi_{a0} = \Delta\psi_a + \psi_0 \cos(\omega t + \alpha_0)$$

$$\psi_{b0} = \Delta\psi_b + \psi_0 \cos(\omega t + \alpha_0 - 120^\circ)$$

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

$$\Delta\psi_a = \psi_{a0} - \psi_0 \cos(\omega t + \alpha_0)$$

$$\Delta\psi_b = \psi_{b0} - \psi_0 \cos(\omega t + \alpha_0 - 120^\circ)$$

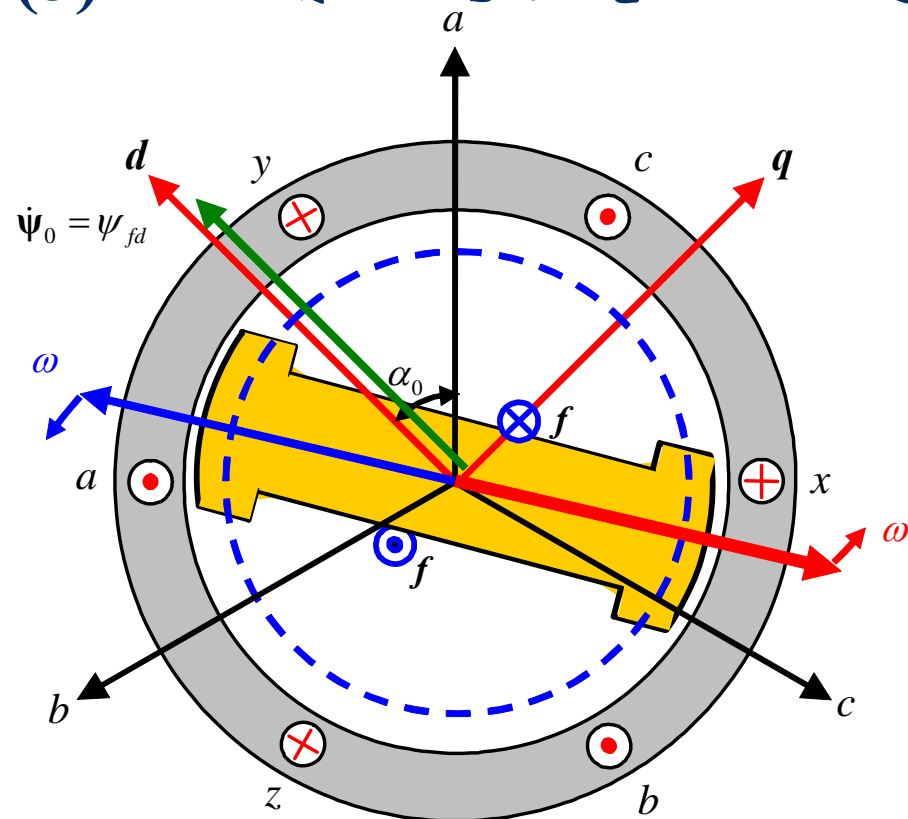
$$\Delta\psi_c = \psi_{c0} - \psi_0 \cos(\omega t + \alpha_0 + 120^\circ)$$

定子电流包含两大部分，共同作用产生 $\Delta \Psi_{abc}$:

(1) 工频 $i_{abc}(\omega) \rightarrow -\Psi_0$ (ω 旋转)，抵消励磁电流产生的磁链；

(2) 另外的电流 $i \rightarrow \Psi_{abc0}$ (静止)，维持初始磁链。

(5) 短路前后定子绕组磁链守恒——定子电流+励磁电流



另外的电流 $i \rightarrow$ 静止 Ψ_{abc0} ,

是直流吗?

$i \rightarrow (\omega) F \rightarrow (\lambda) \Phi \rightarrow (\omega) \Psi$

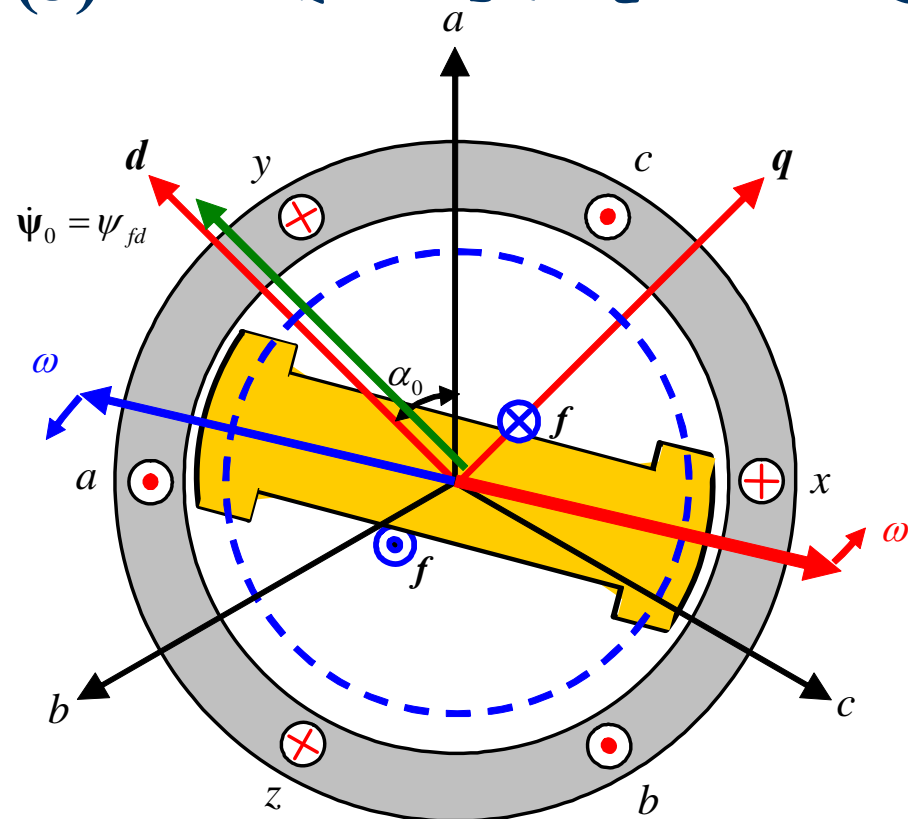
λ : 回路磁导率, 2ω 为周期变化

定子电流包含两大部分

(1) 工频 $i_{abc}(\omega) \rightarrow -\Psi_0$ (ω 旋转)

(2) 另外的电流 $i \rightarrow \Psi_{abc0}$ (静止)

(5) 短路前后定子绕组磁链守恒——定子电流+励磁电流



另外的电流 $i \rightarrow$ 静止 Ψ_{abc0} ,

不是直流!

$i \rightarrow (\omega) F \rightarrow (\lambda) \Phi \rightarrow (\omega) \Psi$

λ : 回路磁导率, 2ω 为周期变化

定子电流包含两大部分

(1) 工频 $i_{abc}(\omega) \rightarrow -\Psi_0$ (ω 旋转)

(2) 另外的电流 $i \rightarrow \Psi_{abc0}$ (静止)

另外的电流 i 中, 有两个分量:

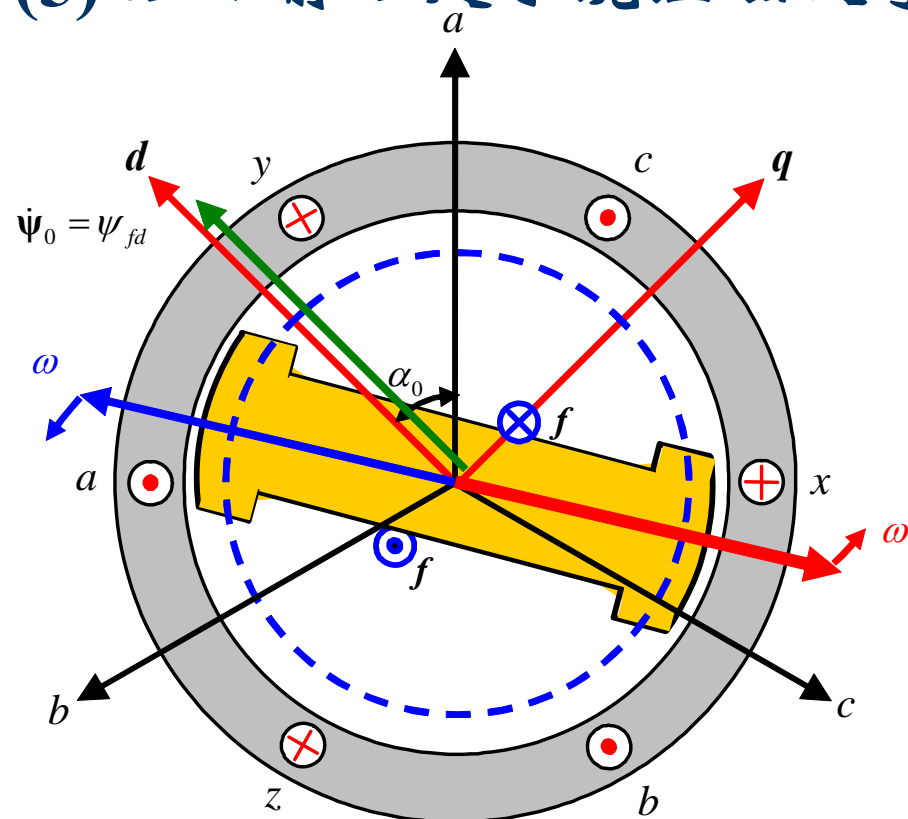
(1) 直流 $i_{ap} \rightarrow \Psi_{abc0}^*$

(产生静止 Ψ + 2倍频 Ψ)

(2) 2倍频 $i_{2\omega} \rightarrow \Psi_{2\omega}$ (抵消磁路磁

导率变化产生的2倍频 Ψ)

(5) 短路前后定子绕组磁链守恒—定子电流+励磁电流



定子电流中：有3种分量

(1) 直流 $i_{ap} \rightarrow \Psi_{abc0^*}$
(静止 Ψ + 2倍频 Ψ)

(2) 2倍频 $i_{2\omega} \rightarrow \Psi_{2\omega}$, 抵消
磁导率变化产生的2倍频 Ψ

(1+2) 产生空间静止的磁链

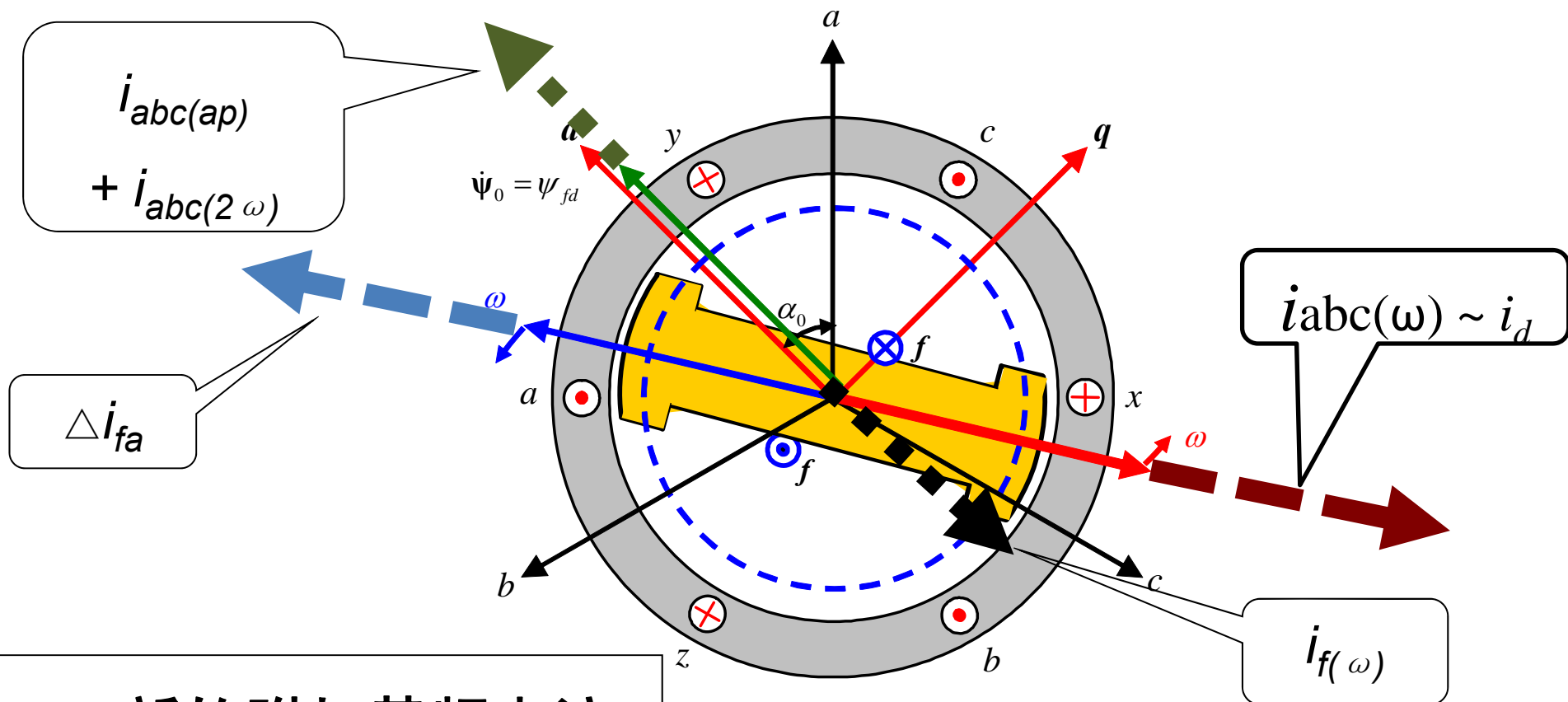
(3) 工频 $i_{abc}(\omega) \rightarrow -\Psi_0$ (空间旋转磁链), 抵消励磁电流产生的磁链

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

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

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

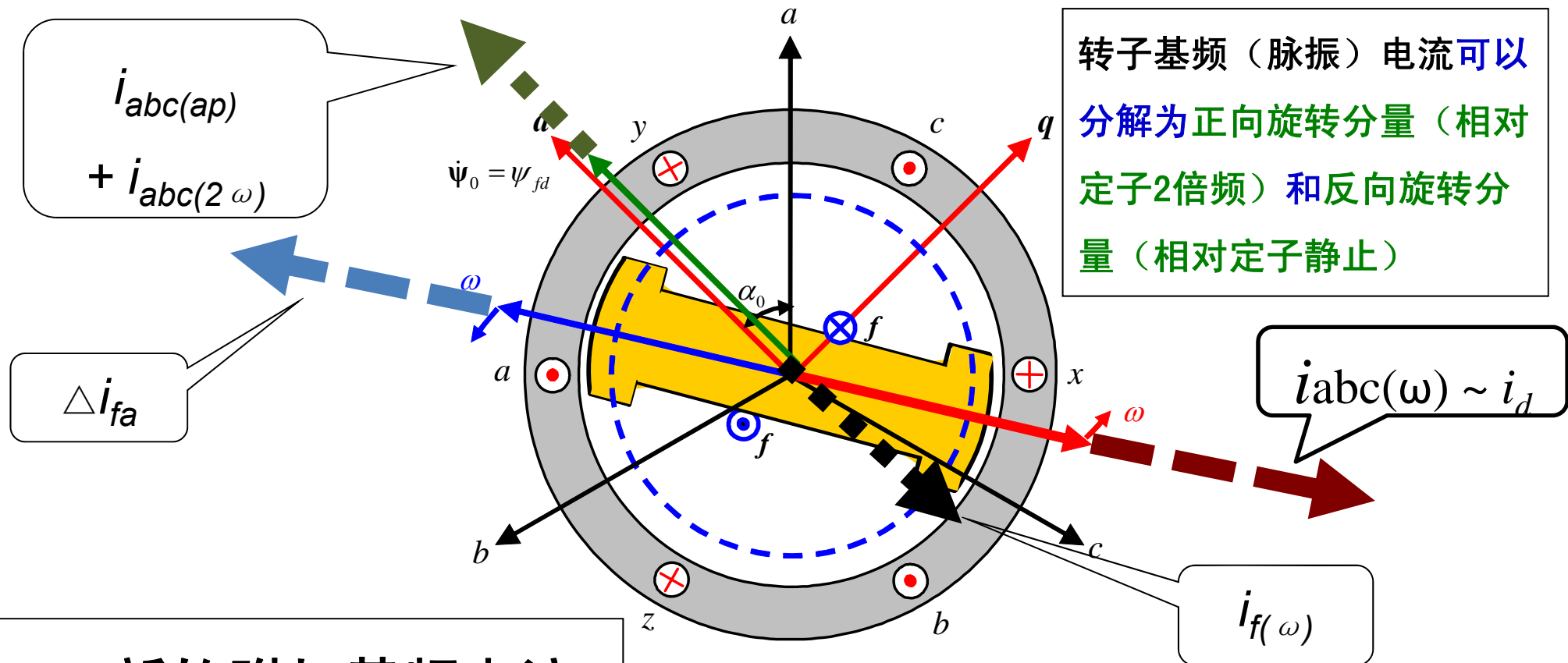
(3) 短路瞬间转子绕组磁链守恒——励磁电流+定子电流



转子新的附加基频电流分量，抵消定子直流和倍频电流产生的静止 Ψ_0 （转子上看是 ω 速旋转的）

这反过来又激发定子产生更大的直流和倍频电流以维持定子磁链守恒。

(3) 短路瞬间转子绕组磁链守恒——励磁电流+定子电流

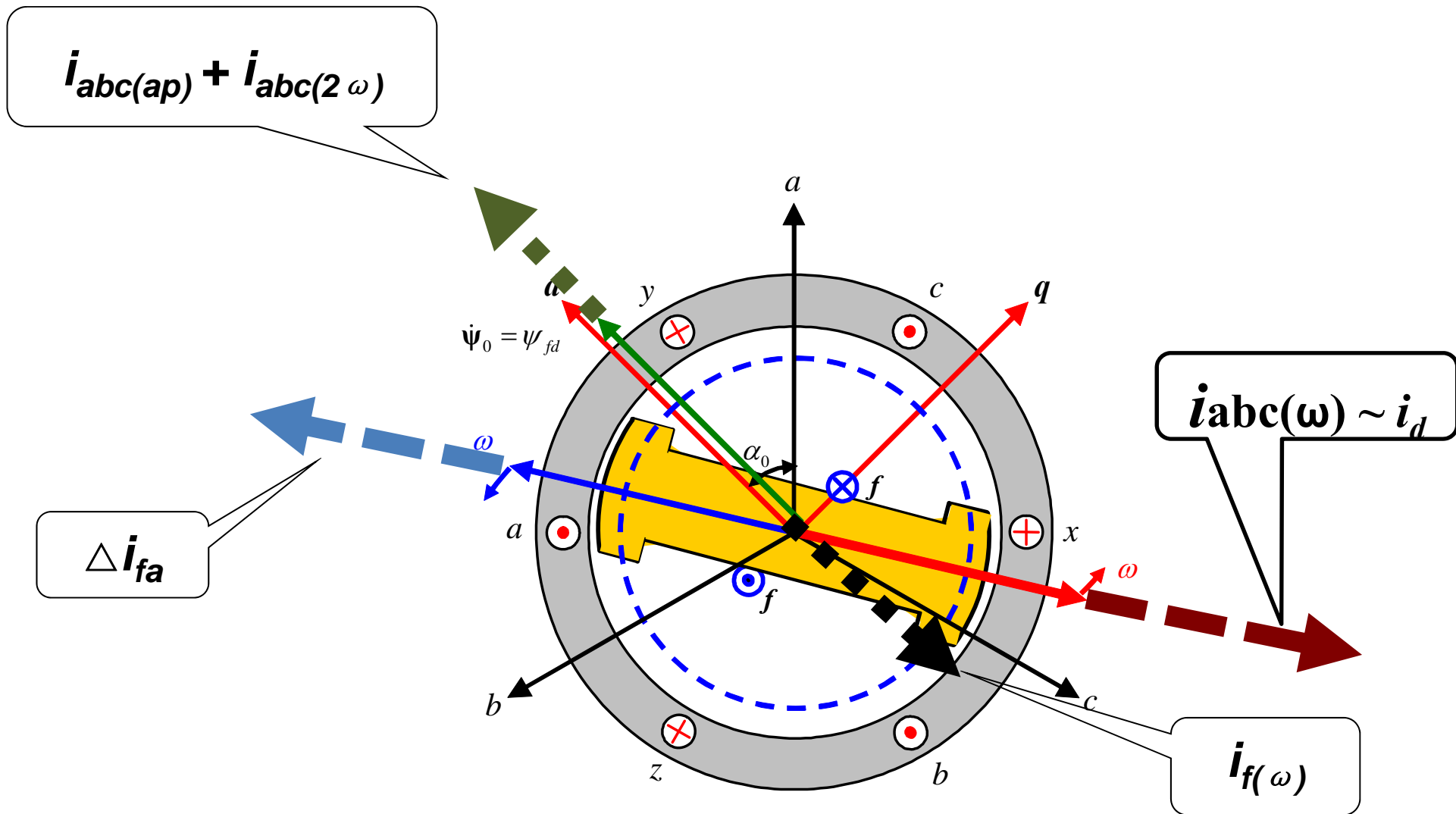


转子基频（脉振）电流可以分解为正向旋转分量（相对定子2倍频）和反向旋转分量（相对定子静止）

转子新的附加基频电流分量，抵消定子直流和倍频电流产生的静止 Ψ_0 （转子上看是 ω 速旋转的）

这反过来又激发定子产生更大的直流和倍频电流以维持定子磁链守恒。

(3) 定转子绕组各种电流分量



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

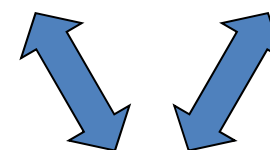
倍频电流

$$i_{abc(\infty)}$$

$$\Delta i_{abc(\omega)} = i_{abc(\omega)} - i_{abc(\infty)}$$

$$i_{abc(ap)}$$

$$i_{abc(2\omega)}$$



$$i_{f[0]}$$

$$\Delta i_{fa}$$

$$\Delta i_{f\omega}$$

转子绕组

稳态励磁电流

自由直流

基频电流

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

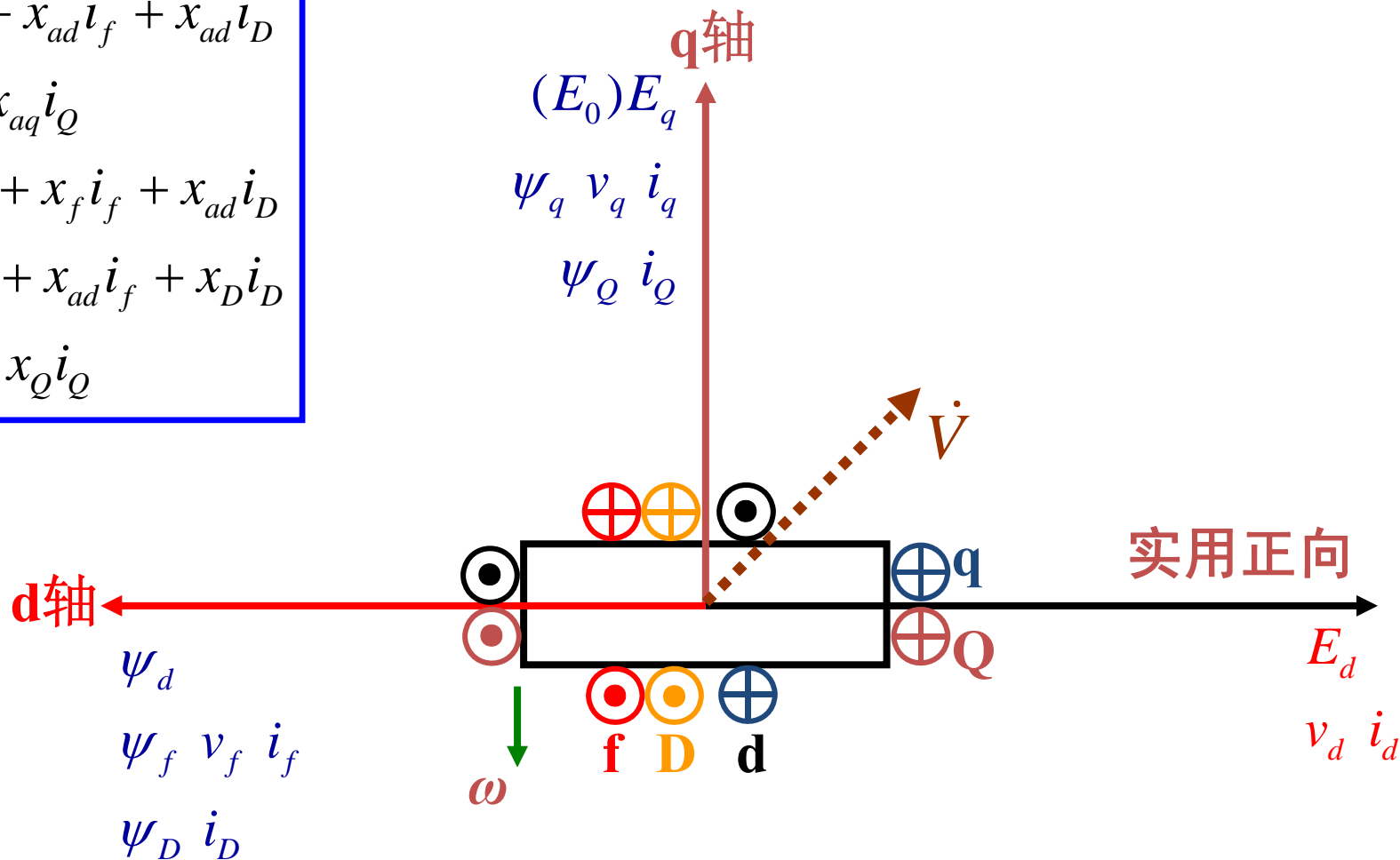
5-5 有阻尼绕组同步电机的突然三相短路

5-6 强行励磁对短路暂态过程的影响

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

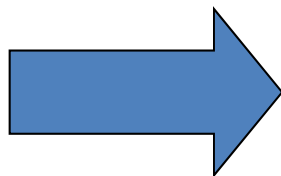
$$\begin{cases} \psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\ \psi_q = x_q i_q + x_{aq} i_Q \\ \psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\ \psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \\ \psi_Q = x_{aq} i_q + x_Q i_Q \end{cases}$$



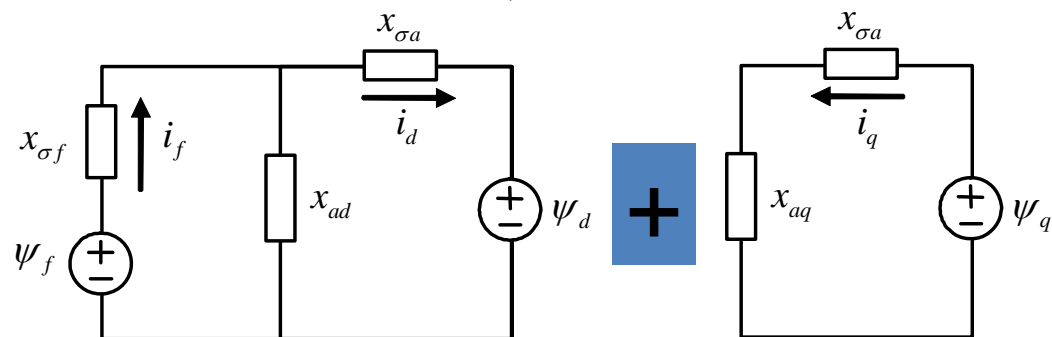
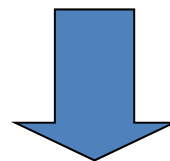
5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——磁链平衡等值电路

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

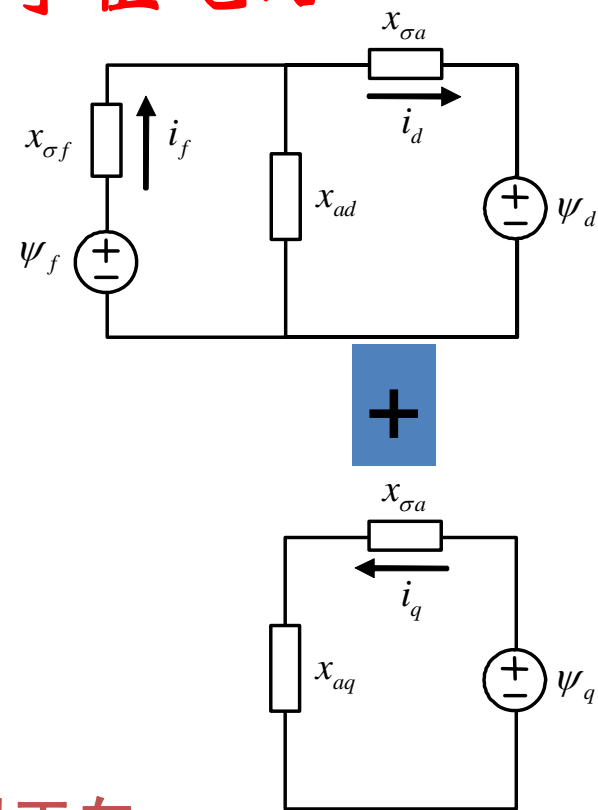
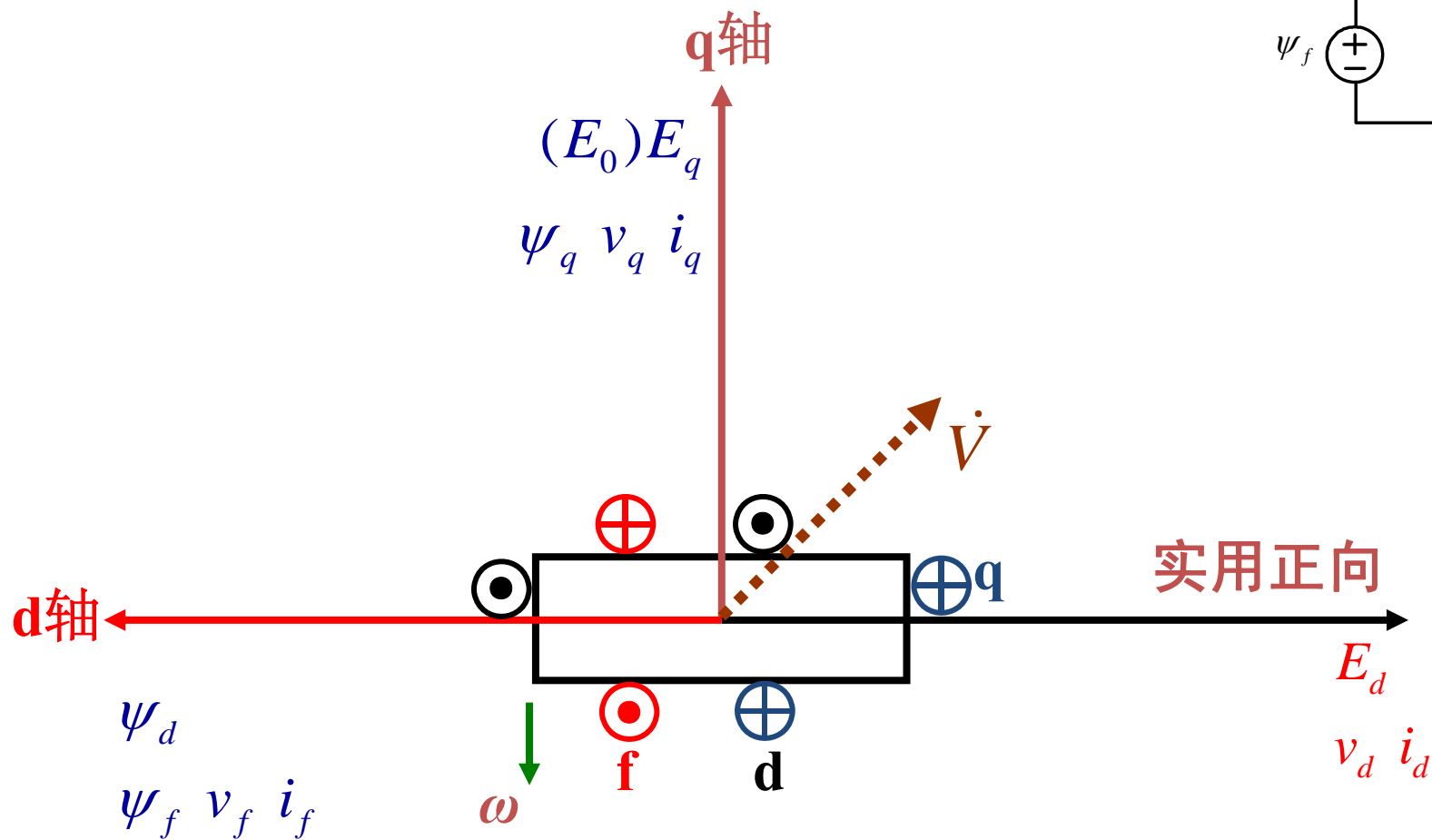


$$\begin{aligned}\psi_d &= -x_{\sigma a} i_d + x_{ad} (i_f - i_d) \\ \psi_q &= x_q i_q \\ \psi_f &= x_{ad} (i_f - i_d) + x_{\sigma f} i_f\end{aligned}$$



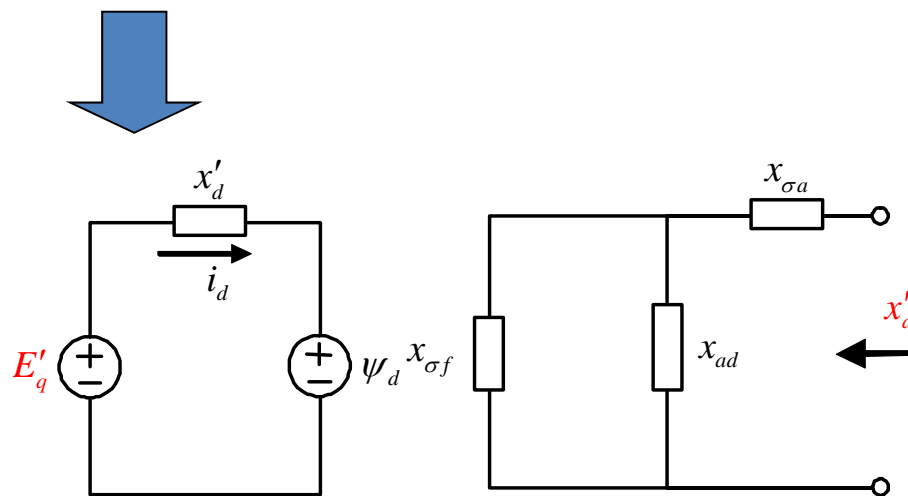
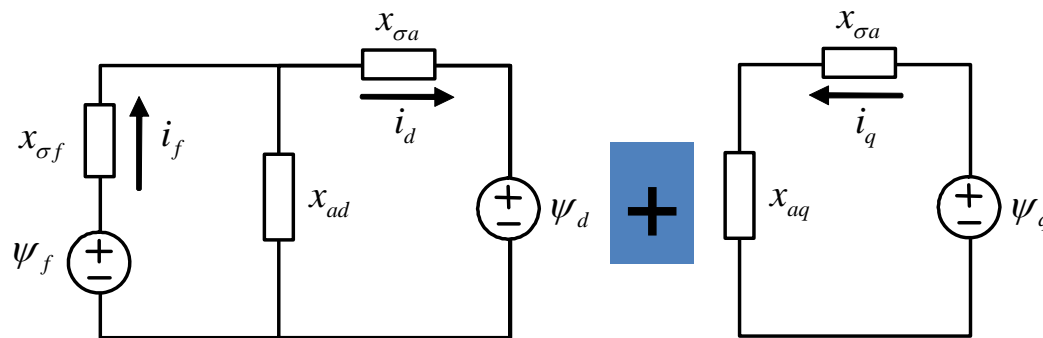
5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——磁链平衡等值电路



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



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

$$E'_{q0} = E'_{q[0]}$$

短路瞬间暂态电势保持不变

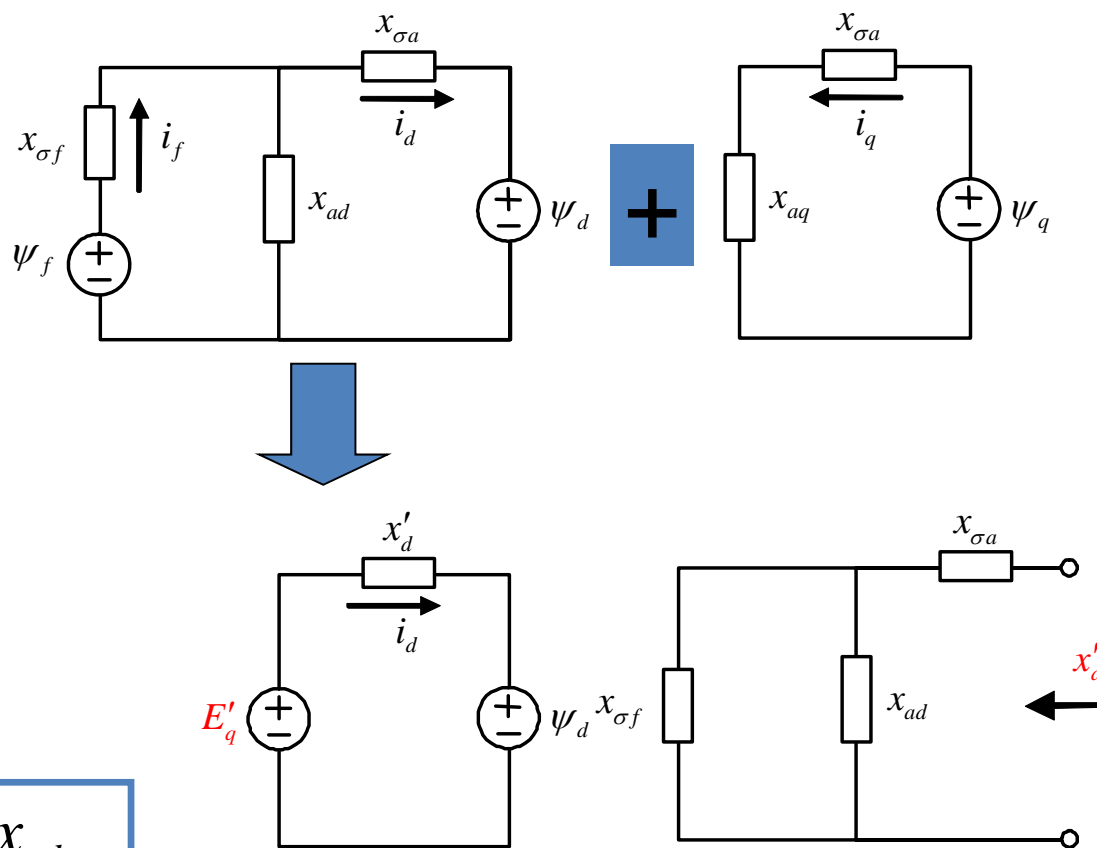
5-4 无阻尼绕组同步电机三相短路电流计算

1. 短路电流各分量计算——暂态电抗和暂态电势

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

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

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



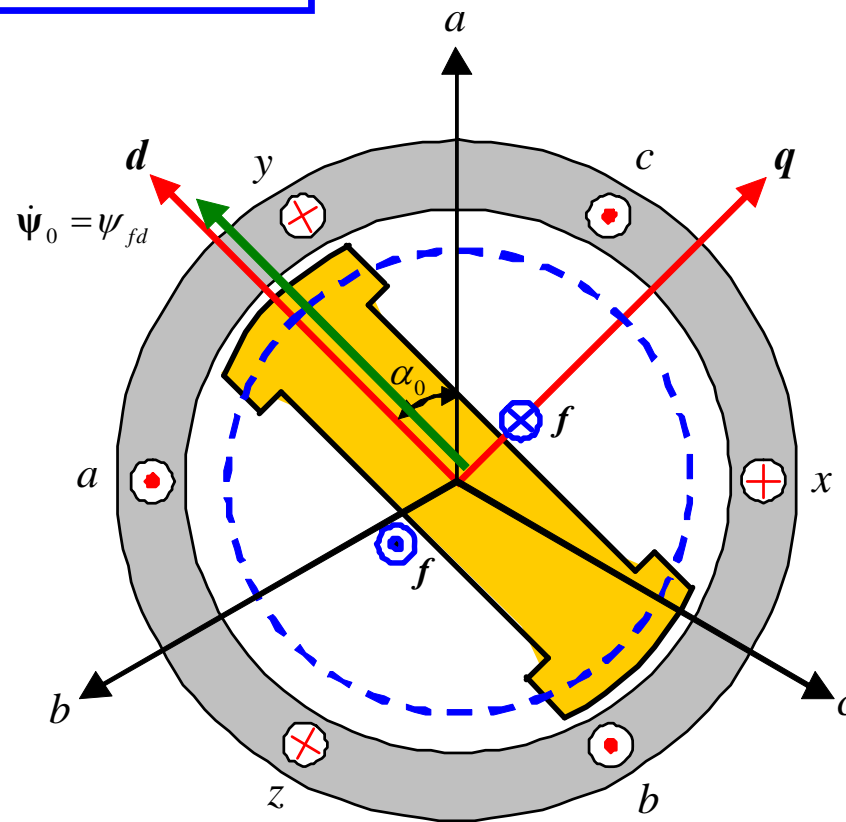
短路瞬间暂态电势保持不变

1. 短路电流各分量计算——短路状态磁链平衡关系

短路瞬间定子绕组磁链： Ψ_{abc0}

$$\begin{aligned} \psi_{a0} &= \psi_0 \cos \alpha_0 \\ \psi_{b0} &= \psi_0 \cos(\alpha_0 - 120^\circ) \\ \psi_{c0} &= \psi_0 \cos(\alpha_0 + 120^\circ) \end{aligned}$$

从转子上看：

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


短路瞬间转子绕组磁链： $\Psi_{f[0]}$ （源于 i_{f0} ）

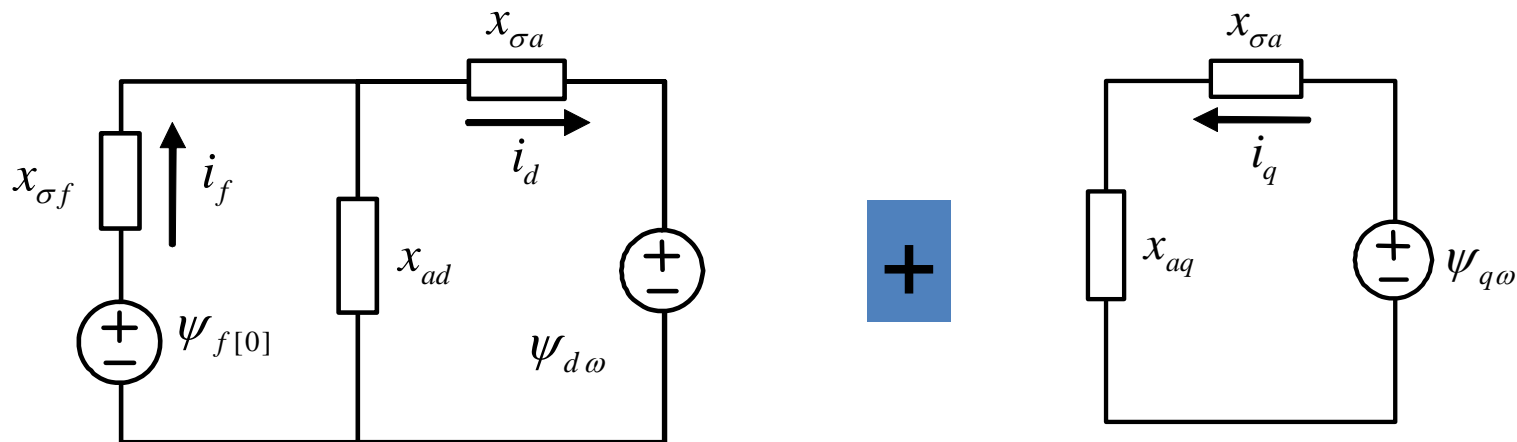
1. 短路电流各分量计算——短路状态磁链平衡关系

短路瞬间定子绕组磁链： Ψ_{abc0}

$$\begin{aligned} \Psi_{a0} &= \Psi_0 \cos \alpha_0 \\ \Psi_{b0} &= \Psi_0 \cos(\alpha_0 - 120^\circ) \\ \Psi_{c0} &= \Psi_0 \cos(\alpha_0 + 120^\circ) \end{aligned}$$

$$\begin{cases} \Psi_{d\omega} = \Psi_0 \cos \omega t \\ \Psi_{q\omega} = \Psi_0 \sin \omega t \end{cases}$$

短路瞬间转子绕组磁链： $\Psi_f[0]$ （源于 i_f0 ）

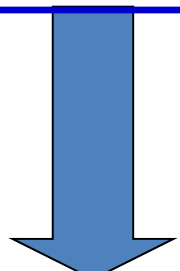


1. 短路电流各分量计算——短路状态磁链平衡关系

$$\begin{aligned} i_{abc(\omega)} &\Leftrightarrow i'_d, i'_q \\ i_{abc(a\varphi)} &\left. \vphantom{i_{abc(a\varphi)}} \right\} i_{d\omega}, i_{q\omega} \\ i_{abc(2\omega)} &\left. \vphantom{i_{abc(2\omega)}} \right\} \end{aligned}$$

$$\begin{aligned} i_{f[0]} \\ \Delta i_{fa} \\ \Delta i_{f\omega} \end{aligned}$$

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



$$\begin{aligned} \psi_{d\omega} &= -x_d (i'_d + i_{d\omega}) + x_{ad} (i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}) \\ \psi_{q\omega} &= x_q (i'_q + i_{q\omega}) \\ \psi_{f[0]} &= -x_{ad} (i'_d + i_{d\omega}) + x_f (i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}) \end{aligned}$$

1. 短路电流各分量计算——短路状态磁链平衡关系

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

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

$$i_{f[0]}$$

$$\Delta i_{fa}$$

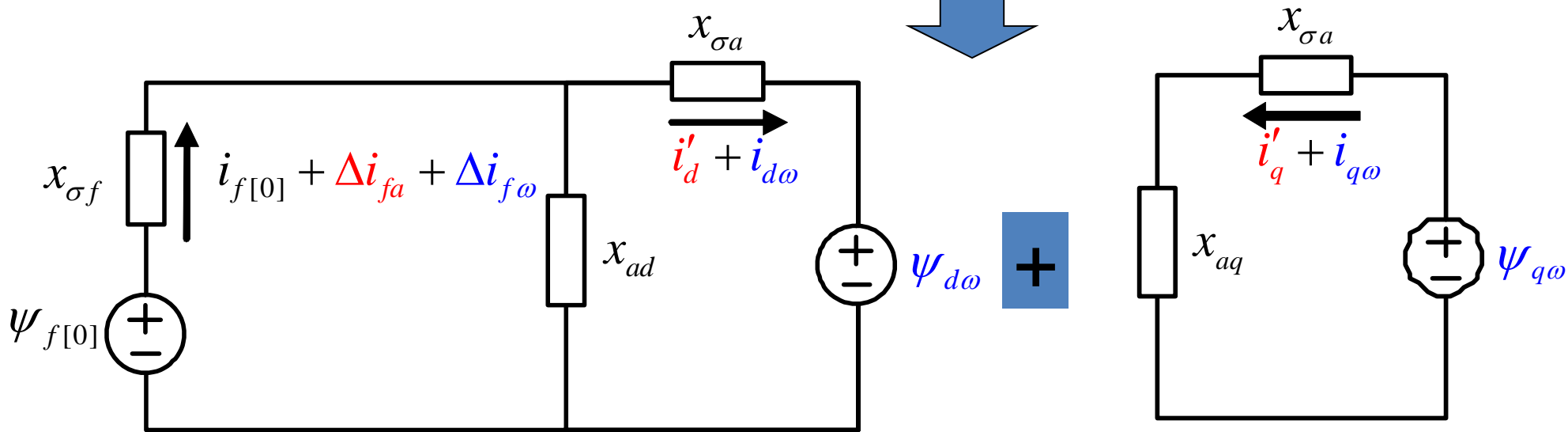
$$\Delta i_{f\omega}$$

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

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

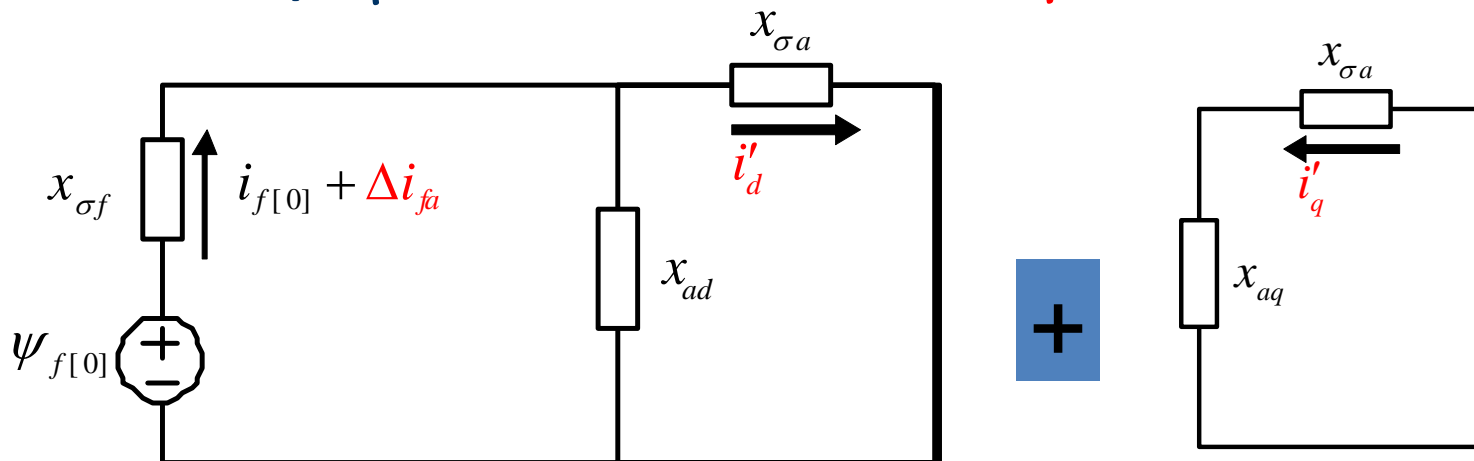
$$\psi_{f[0]} = -x_{ad} (i'_d + i_{d\omega}) + x_f (i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega})$$

按dq轴分解

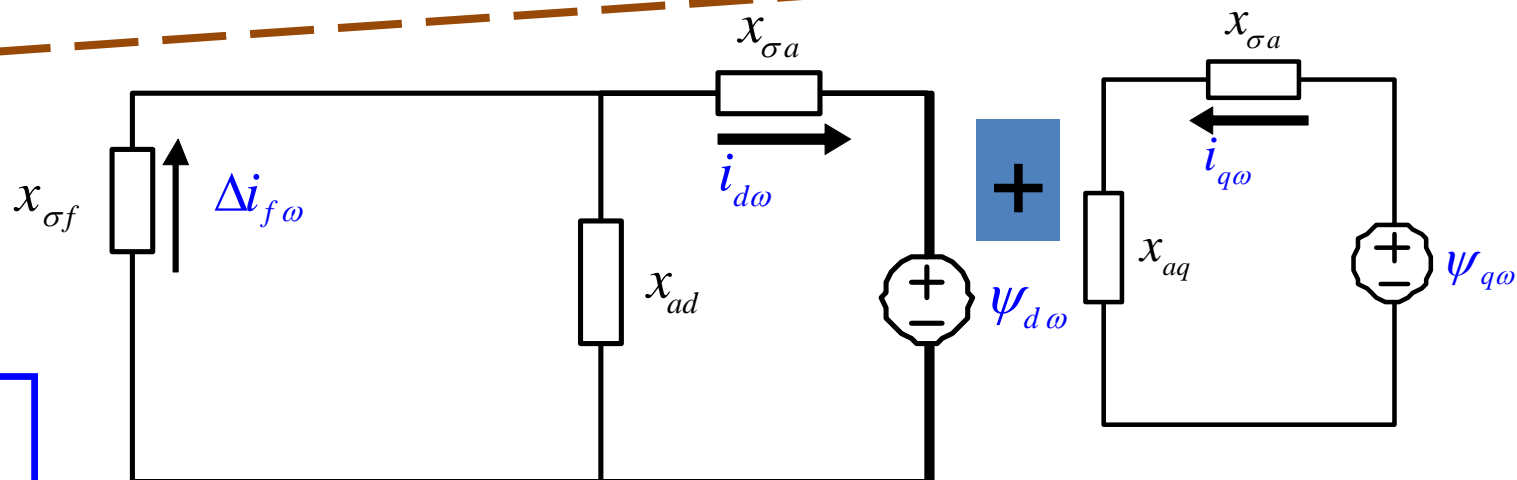


1. 短路电流各分量计算——短路状态磁链平衡关系

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



按定、转子分解

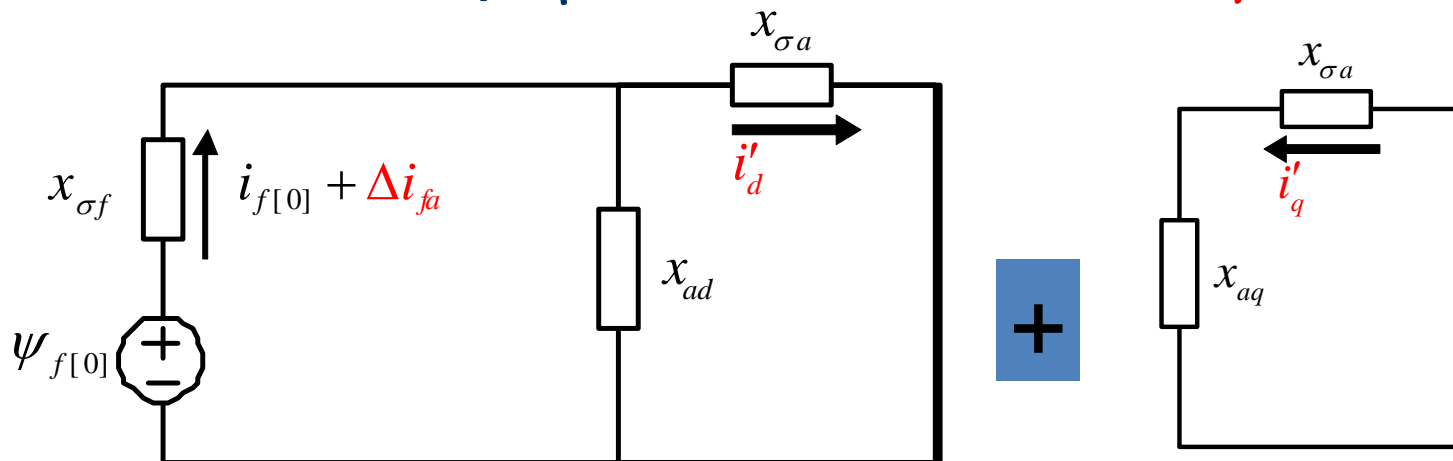


$$\left. \begin{aligned} i_{abc(a\omega)} \\ i_{abc(2\omega)} \\ \Delta i_{f\omega} \end{aligned} \right\} \Leftrightarrow \begin{cases} i_{d\omega} \\ i_{q\omega} \\ \Delta i_{f\omega} \end{cases}$$

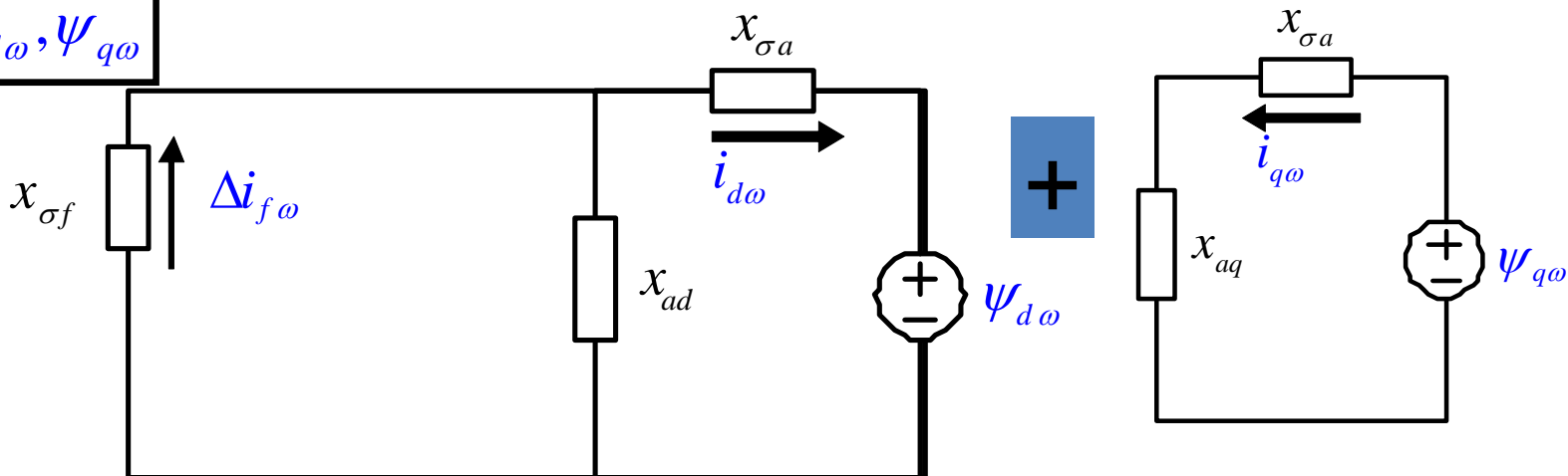
$$\begin{cases} \psi_{abc} = \psi_{abc[0]} \\ \psi_f = 0 \end{cases}$$

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

1. 短路电流各分量计算——短路状态磁链平衡关系



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



定子电流：4部分组成： i'_d, i'_q （无源）， $i_{d\omega}, i_{q\omega}$

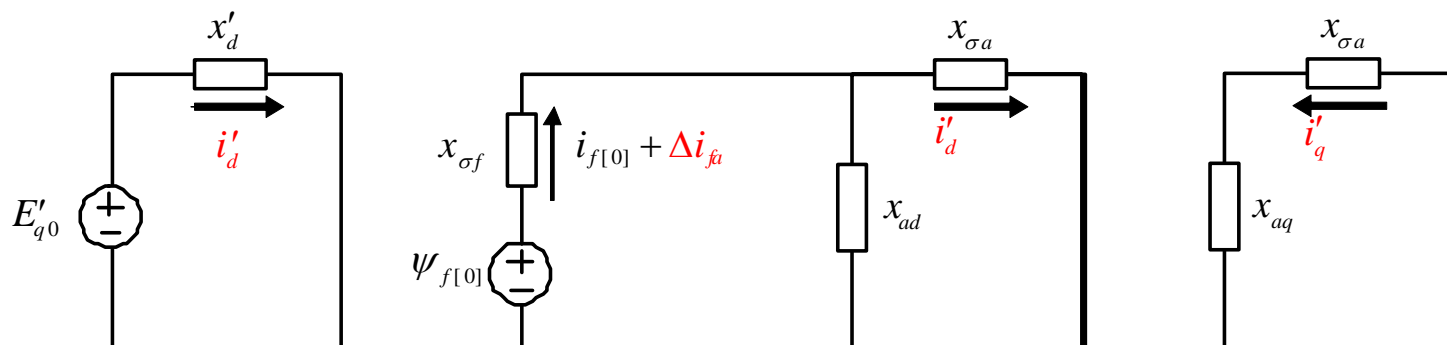
转子电流：3部分组成： $i_{f[0]}, \Delta i_{fa}, \Delta i_{f\omega}$

1. 短路电流各分量计算—定子起始暂态电流

4部分组成: i'_d, i'_q (无源), $i_{d\omega}, i_{q\omega}$

$$i'_d = \frac{E'_{q0}}{x'_d}$$

$$i'_q = 0$$

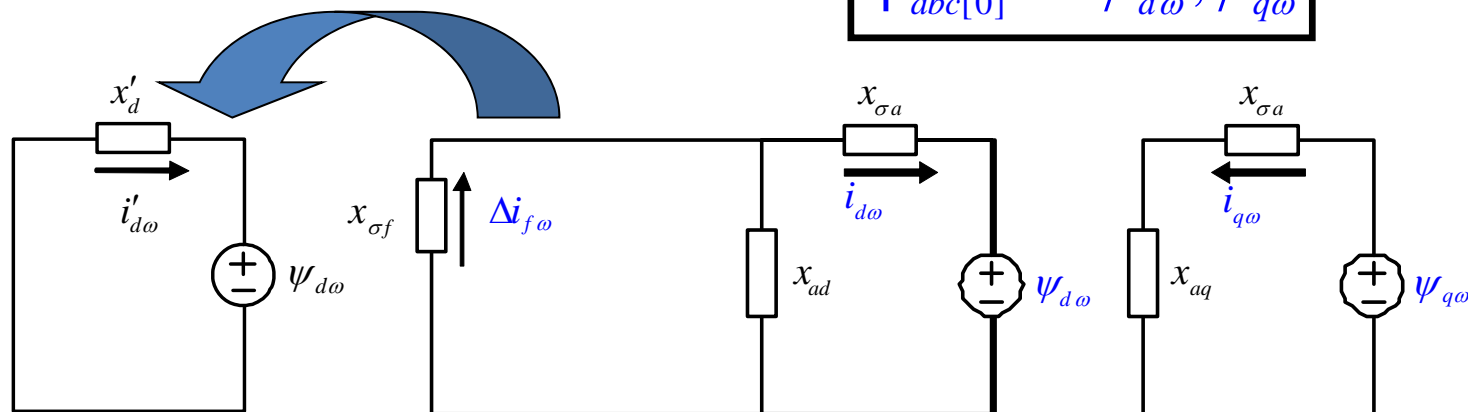


$$E'_{q0} = \frac{x_{ad}}{x_f} \psi_{f[0]}$$

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

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

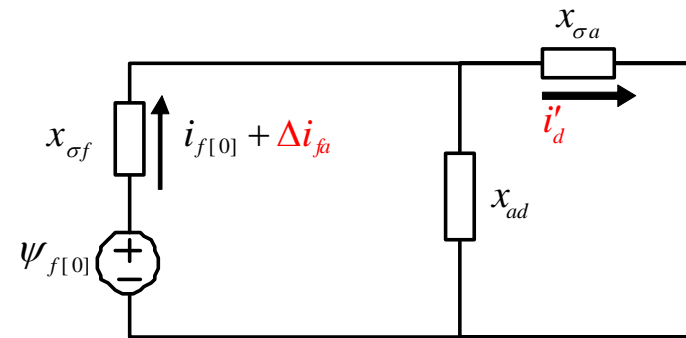
$$i_{q\omega} = \frac{\Psi_{q\omega}}{x_q}$$



1. 短路电流各分量计算—转子电流

3部分组成: $i_{f[0]}$, Δi_{fa} , $\Delta i_{f\omega}$

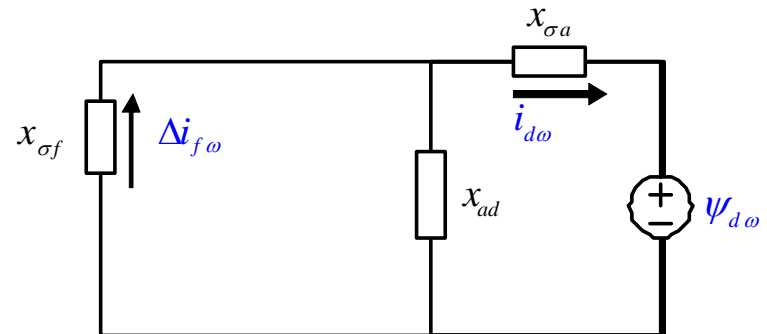
$$\Delta i_{fa} = \frac{x_d i'_d - x_{ad} i_{f[0]}}{x_{ad}} = \frac{x_d}{x_{ad}} \left(\frac{E'_{q[0]}}{x'_d} - \frac{E_{q[0]}}{x_d} \right)$$



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

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

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



1. 短路电流各分量计算——稳态短路电流

所有自由分量均衰减完：只剩 $i_{d\infty}$

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

$$E_{q0} \neq E_{q[0]}$$

$$E_{q0} \text{ 来自于 } (i_{f[0]} + \Delta i_{fa})$$

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

$$i_d = i'_d + i_{d\omega} = i_{d\infty} + (i'_d - i_{d\infty}) + i_{d\omega}$$

$$i_q = i'_q + i_{q\omega} = i_{q\omega}$$

$$i_f = i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}$$

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

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

根据短路前稳态确定

$$E'_{q0}, E_{q[0]}, \Psi_{d\omega}, \Psi_{q\omega}$$

1. 短路电流各分量计算——短路状态磁链平衡关系

短路瞬间定子绕组磁链： Ψ_{abc0}

$$\Psi_{a0} = \Psi_0 \cos \alpha_0$$

$$\Psi_{b0} = \Psi_0 \cos(\alpha_0 - 120^\circ)$$

$$\Psi_{c0} = \Psi_0 \cos(\alpha_0 + 120^\circ)$$

$$\left\{ \begin{array}{l} \Psi_{d\omega} = \Psi_0 \cos \omega t = \frac{x_{ad}}{x_f} \Psi_{f[0]} \cos \omega t = E'_{q0} \cos \omega t \\ \Psi_{q\omega} = \Psi_0 \sin \omega t = \frac{x_{ad}}{x_f} \Psi_{f[0]} \sin \omega t = E'_{q0} \sin \omega t \end{array} \right.$$

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

$$i_d = i_{d\infty} + (i'_d - i_{d\infty}) + i_{d\omega}$$

$$i_q = i'_q + i_{q\omega} = i_{q\omega}$$

$$i_f = i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}$$

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

$$i_{d\omega} = -\frac{E'_{q0} \cos \omega t}{x'_d}, \quad i_{q\omega} = \frac{E'_{q0} \sin \omega t}{x_q}, \quad \Delta i_{f\omega} = -\frac{x_{ad}}{x_f} \times \frac{E'_{q0} \cos \omega t}{x'_d}$$

只需确定

$E'_{q0}, E_{q[0]}$

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——相量方程式和相量图

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

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

忽略变压器电势及电阻

$$u_d = \psi_q$$

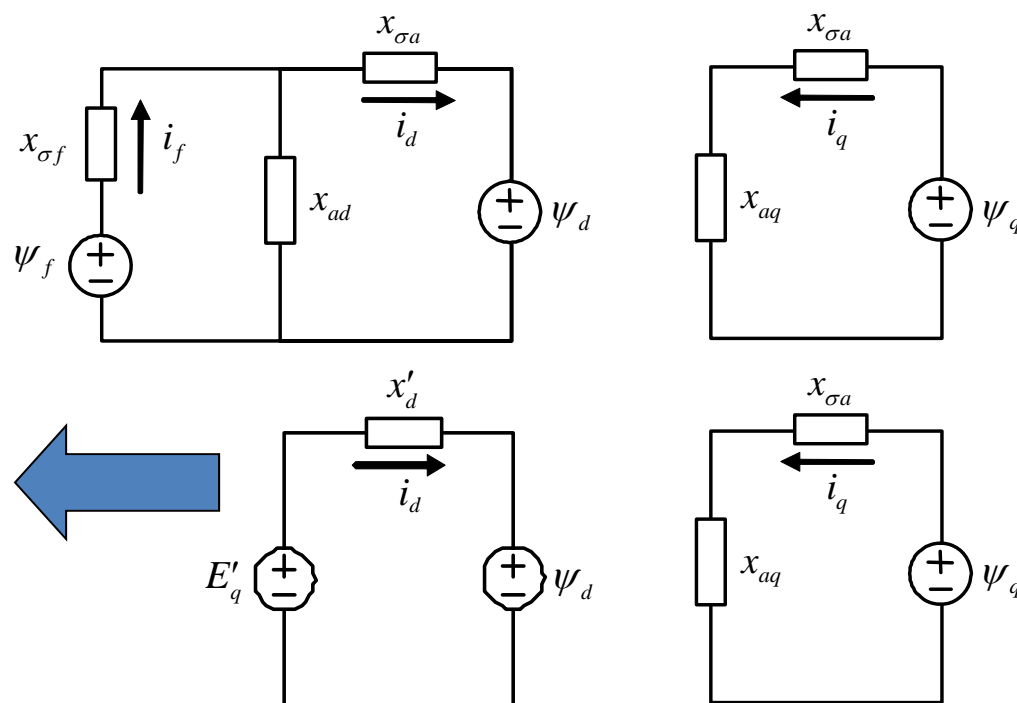
$$u_q = \psi_d$$

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

$$\psi_q = x_q i_q$$

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

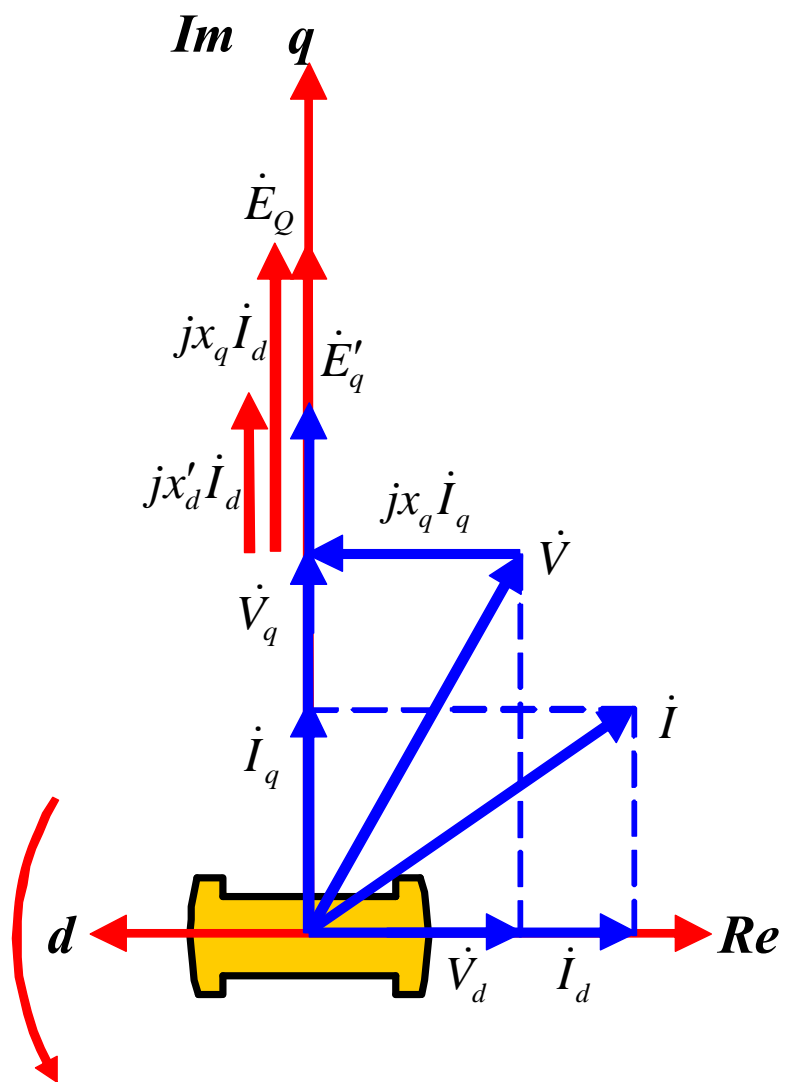
$$u_d = x_q i_q$$



反映了定子方面电势、电压和电流的基频分量之间的关系，可以写成交流相量的形式

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



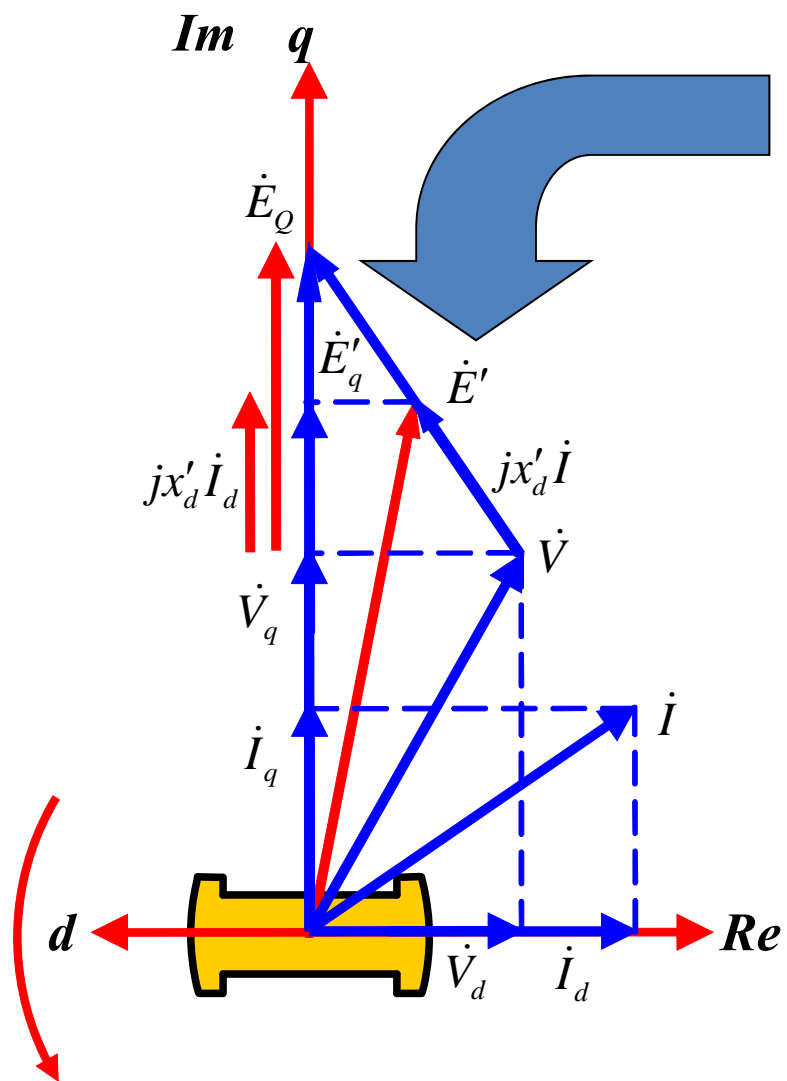
$$\begin{cases} u_d = x_q i_q \\ u_q = E'_q - x'_d i_d \end{cases}$$

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

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

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



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

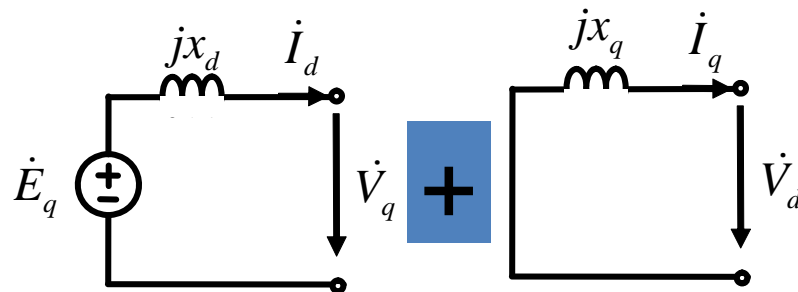
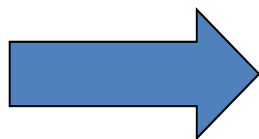
$$\dot{V} = \dot{E}' - jx'_d \dot{I}$$

暂态电抗后的电势—计算电势

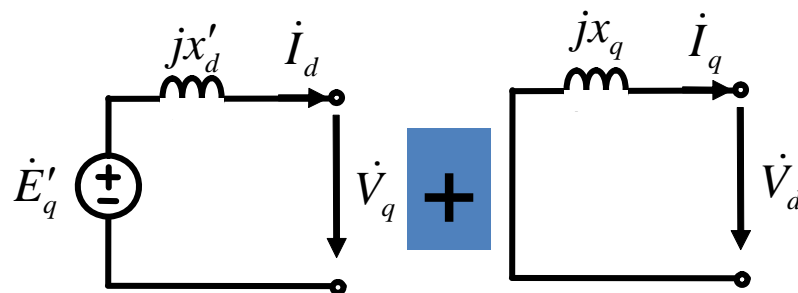
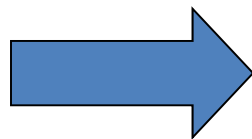
5-4 无阻尼绕组同步电机三相短路电流计算

2. 同步电机暂态模型—等值电路

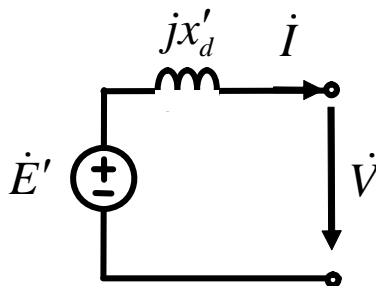
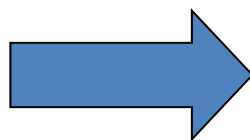
$$\begin{cases} \dot{V}_d = -jx_q \dot{I}_q \\ \dot{V}_q = \dot{E}_q - jx_d \dot{I}_d \end{cases}$$



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



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



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

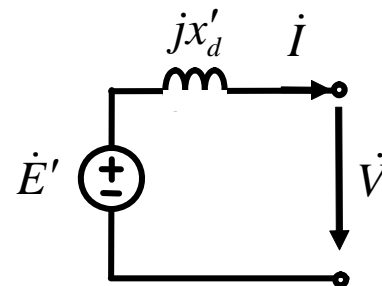
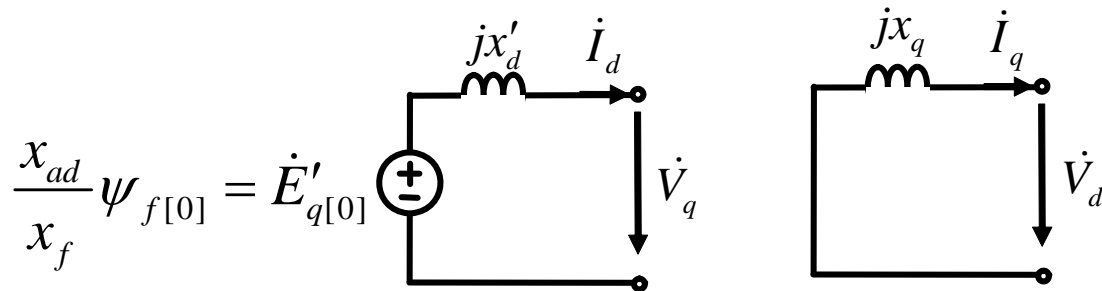
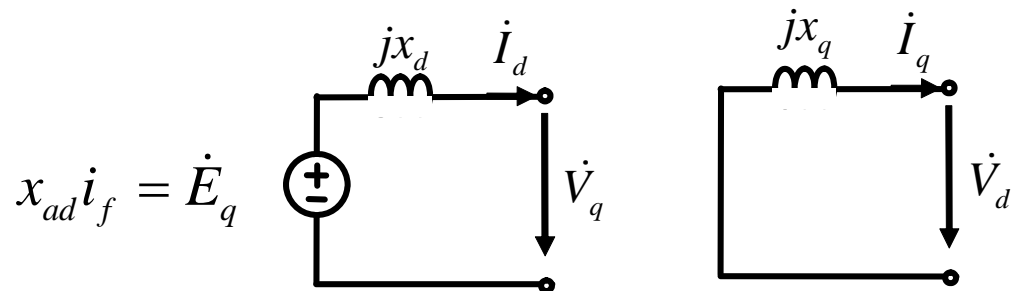
同步电机运行参数:

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

根据运行状态计算

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

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

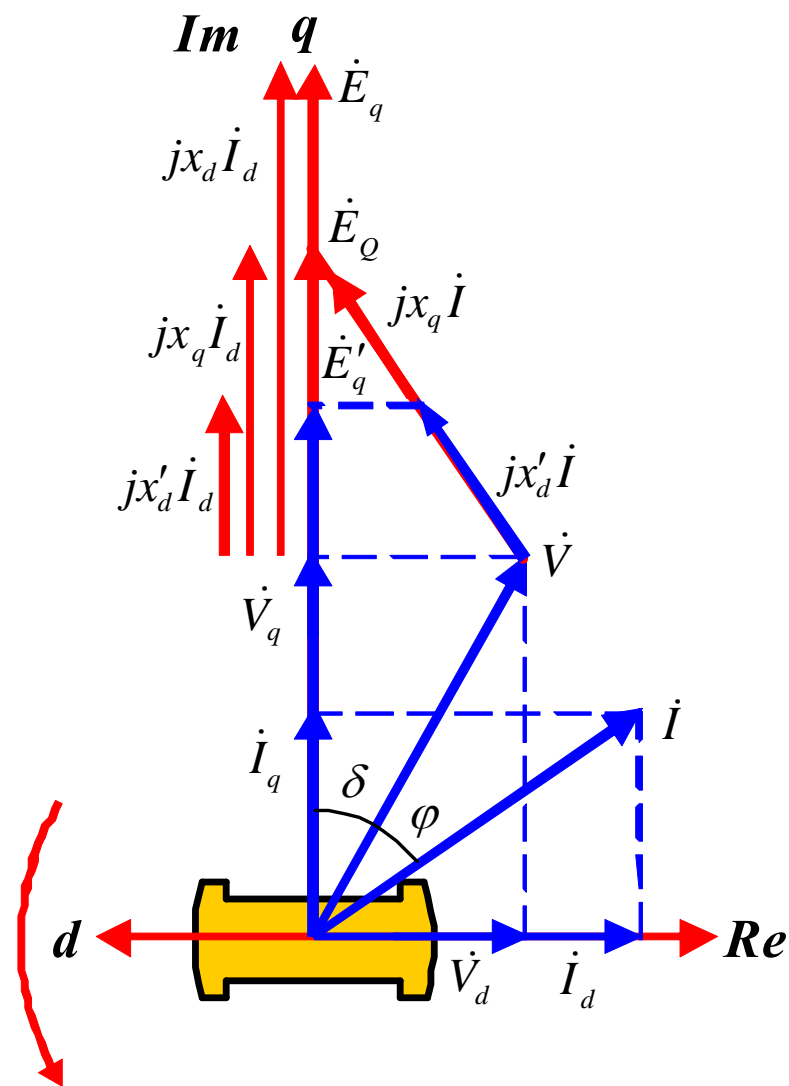


5-4 无阻尼绕组同步电机三相短路电流计算

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

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



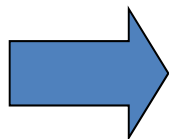
5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——全电流计算式（不计衰减）

$$i_d = i_{d\infty} + (i'_d - i_{d\infty}) + i_{d\omega}$$

$$i_q = i'_q + i_{q\omega} = i_{q\omega}$$

$$i_f = i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega}$$



$$i_a = -i_d \cos \alpha + i_q \sin \alpha$$

$$i_b = -i_d \cos(\alpha - 120^\circ) + i_q \sin(\alpha - 120^\circ)$$

$$i_c = -i_d \cos(\alpha + 120^\circ) + i_q \sin(\alpha + 120^\circ)$$

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

$$i_{d\omega} = -\frac{E'_{q0} \cos \omega t}{x'_d}, \quad i_{q\omega} = \frac{E'_{q0} \sin \omega t}{x_q}, \quad \Delta i_{f\omega} = -\frac{x_{ad}}{x_f} \times \frac{E'_{q0} \cos \omega t}{x'_d}$$

只需确定

$$E'_{q0}, E_{q[0]}$$

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——全电流计算式（不计衰减）

$$\begin{aligned}i_a &= -i_d \cos(\omega t + \alpha_0) + i_q \sin(\omega t + \alpha_0) \\&= -\frac{E_{q[0]}}{x_d} \cos(\omega t + \alpha_0) - \left(\frac{E'_{q0}}{x'_d} - \frac{E_{q[0]}}{x_d} \right) \cos(\omega t + \alpha_0) \\&\quad + \frac{E'_{q0}}{x'_d} \cos \omega t \cos(\omega t + \alpha_0) + \frac{E'_{q0}}{x_q} \sin \omega t \sin(\omega t + \alpha_0) \\&= -\frac{E_{q[0]}}{x_d} \cos(\omega t + \alpha_0) - \left(\frac{E'_{q0}}{x'_d} - \frac{E_{q[0]}}{x_d} \right) \cos(\omega t + \alpha_0) \\&\quad + \frac{E'_{q0}}{2} \left(\frac{1}{x'_d} + \frac{1}{x_q} \right) \cos \alpha_0 + \frac{E'_{q0}}{2} \left(\frac{1}{x'_d} - \frac{1}{x_q} \right) \cos(2\omega t + \alpha_0)\end{aligned}$$

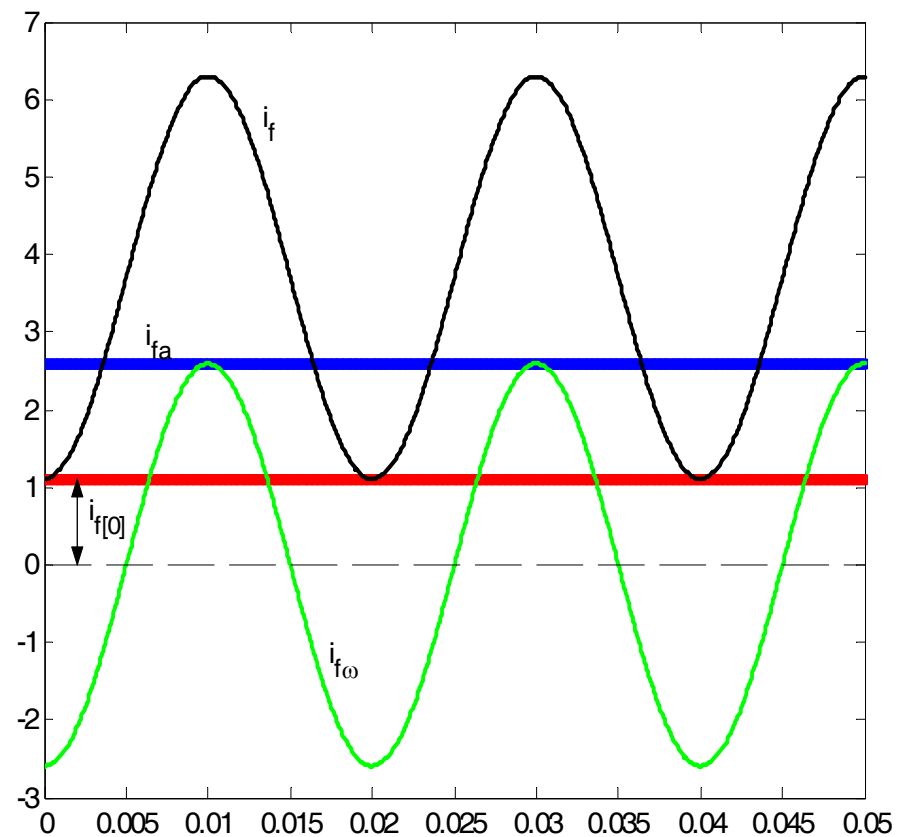
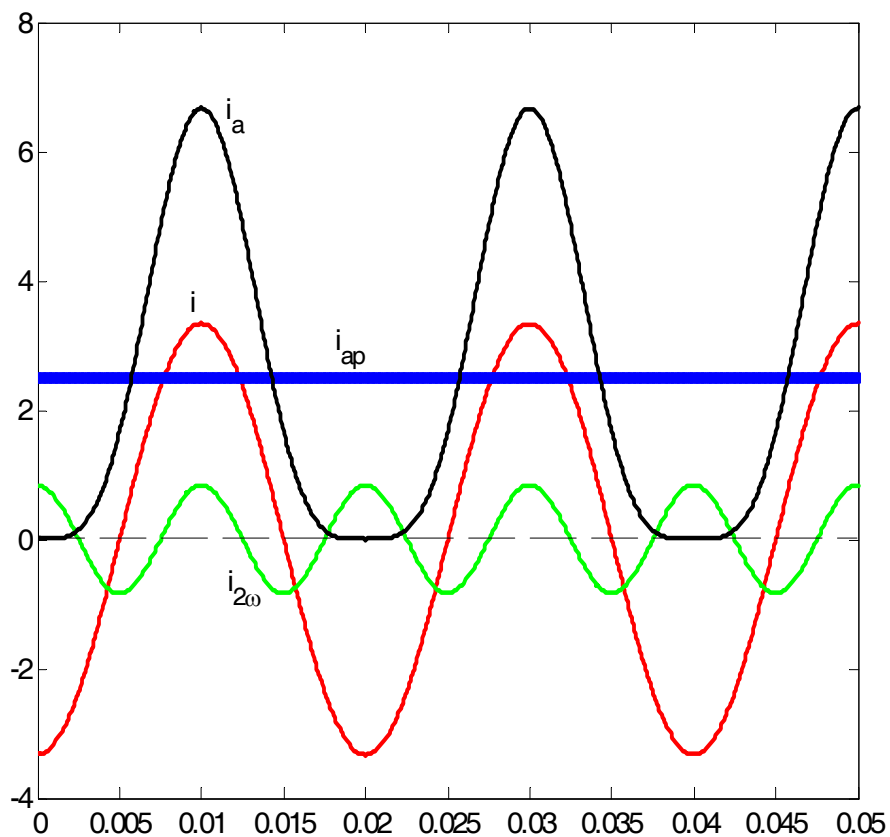
5-4 无阻尼绕组同步电机三相短路电流计算

3. 短路电流计算——全电流计算式（不计衰减）

$$\begin{aligned} i_f &= i_{f[0]} + \Delta i_{fa} + \Delta i_{f\omega} \\ &= i_{f[0]} + \frac{(x_d - x'_d) E'_{q0}}{x_{ad} x'_d} - \frac{(x_d - x'_d) E'_{q0}}{x_{ad} x'_d} \cos \omega t \end{aligned}$$

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

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

$i_{abc(ap)} \Rightarrow \psi_0$, 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,

$$\text{即有 } \rightarrow T_a = \frac{2x'_d x_q}{\omega(x'_d + x_q)} / r$$

$$\omega = 2\pi f (\text{rad/s}), x'_d, x_q (\text{p.u.})$$

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

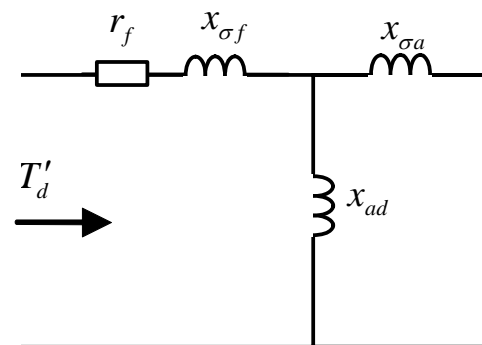
$i_{abc(ap)} \Rightarrow \psi_0$, 相对定子绕组静止, 因此 $i_{abc(ap)}$, $i_{abc(2\omega)}$, $\Delta i_{f\omega}$ 依定子绕组时间常数衰减,

$$\text{即有 } \rightarrow T_a = \frac{2x'_d x_q}{\omega(x'_d + x_q)} / r$$

$$\omega = 2\pi f (\text{rad/s}), x'_d, x_q (\text{p.u.})$$

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

$$\text{即 } T'_d = T'_{d0} \frac{x'_d}{x_d}, T'_{d0} = \frac{x_f}{\omega r_f}$$



5-4 无阻尼绕组同步电机三相短路电流计算

5. 短路电流计算—全电流计算式（计及衰减）

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

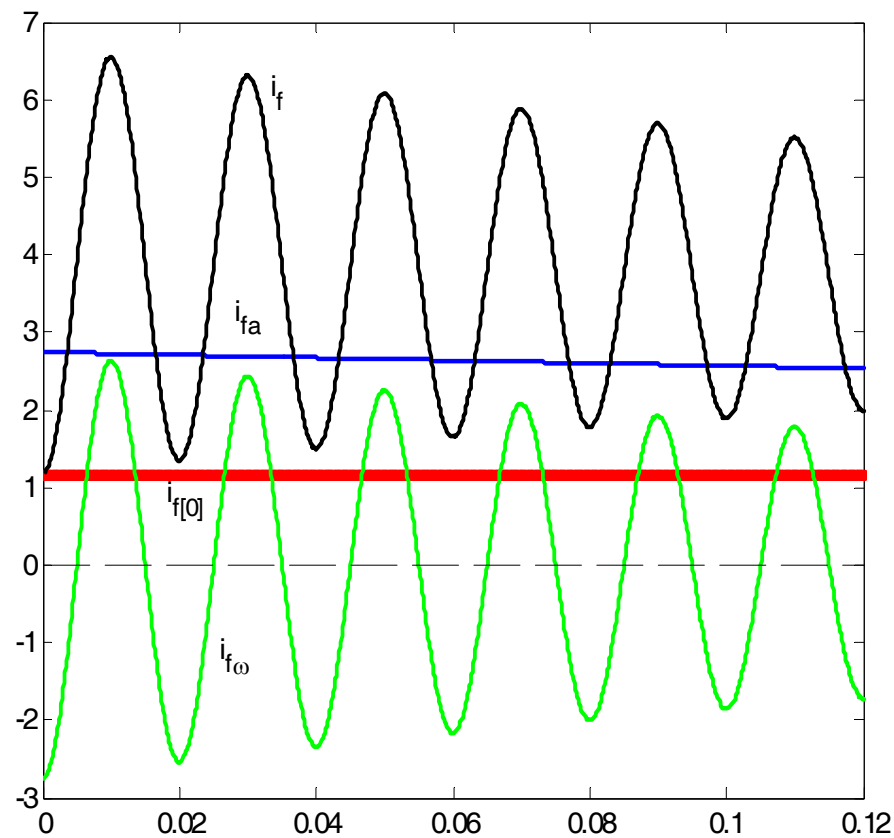
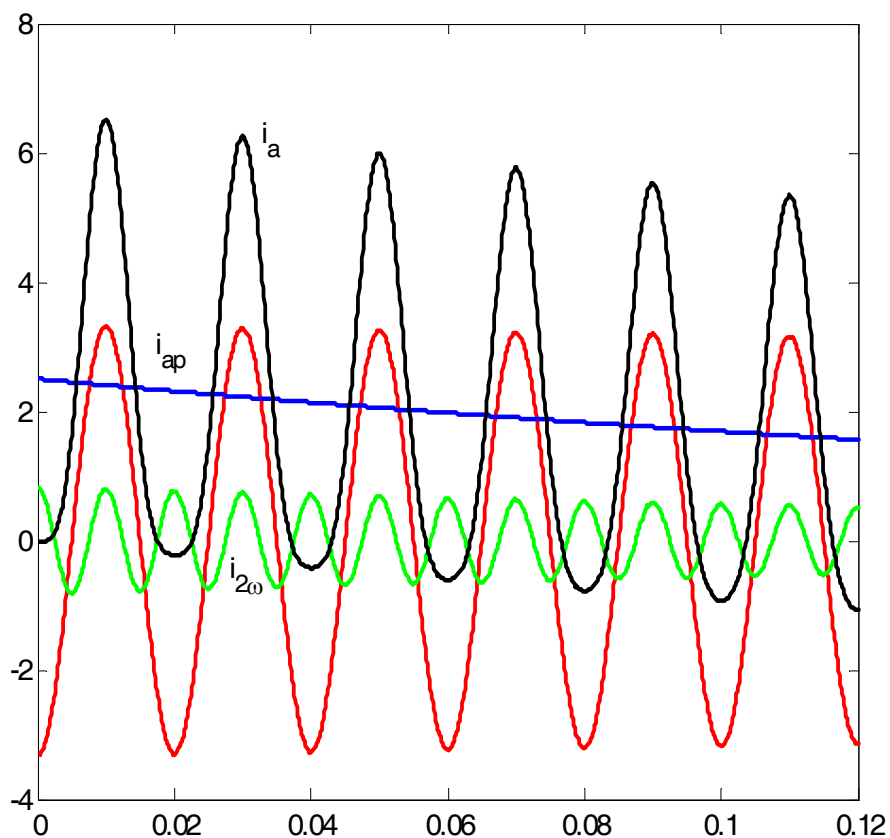
5-4 无阻尼绕组同步电机三相短路电流计算

5. 自由电流的衰减——全电流算式

$$i_f = i_{f[0]} + \frac{(x_d - x'_d) E'_{q0}}{x_{ad} x'_d} \exp\left(-\frac{t}{T'_d}\right) - \frac{(x_d - x'_d) E'_{q0}}{x_{ad} x'_d} \exp\left(-\frac{t}{T_a}\right) \cos \omega t$$

5-4 无阻尼绕组同步电机三相短路电流计算

5. 自由电流的衰减——全电流波形



5-4 无阻尼绕组同步电机三相短路电流计算

6. 其他短路情况——短路前带负载

- 1、原理相同：磁链守恒，但需考虑电枢反应
- 2、 E'_{q0} 的计算需计及负载
- 3、短路前，转子磁链 $\Psi_{f0} = x_f i_{f[0]} - x_{ad} i_{d[0]}$
- 4、短路前，定子磁链 $\Psi_0 = V$

5-4 无阻尼绕组同步电机三相短路电流计算

6. 其他短路情况—外接电抗短路

外接电抗 x_e 短路,则

$$x_d + x_e \rightarrow x_d,$$

$$x_q + x_e \rightarrow x_q,$$

$$x'_d + x_e \rightarrow x'_d$$

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

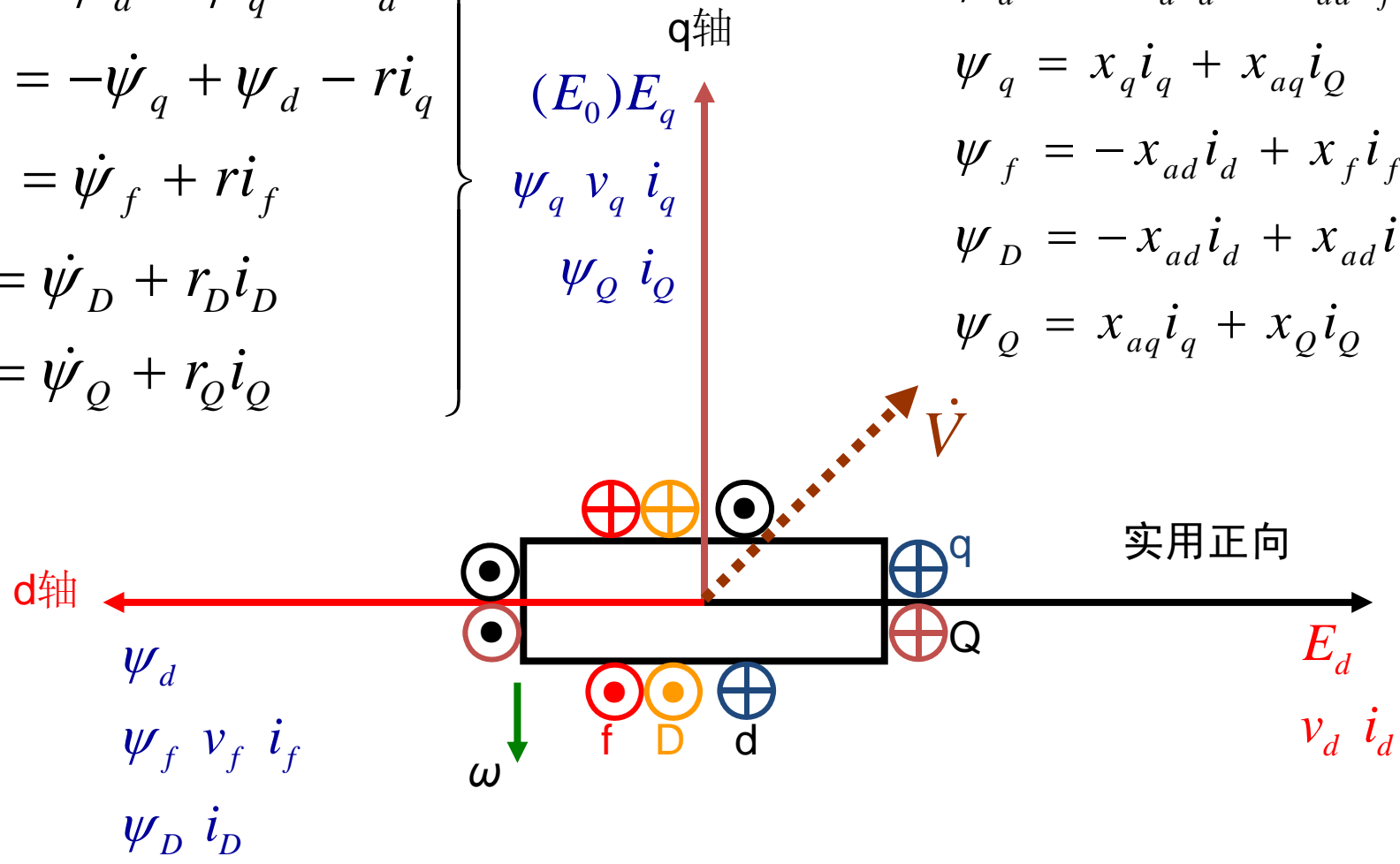
5-6 强行励磁对短路暂态过程的影响

3-6 同步电机的对称稳态运行

实用方程

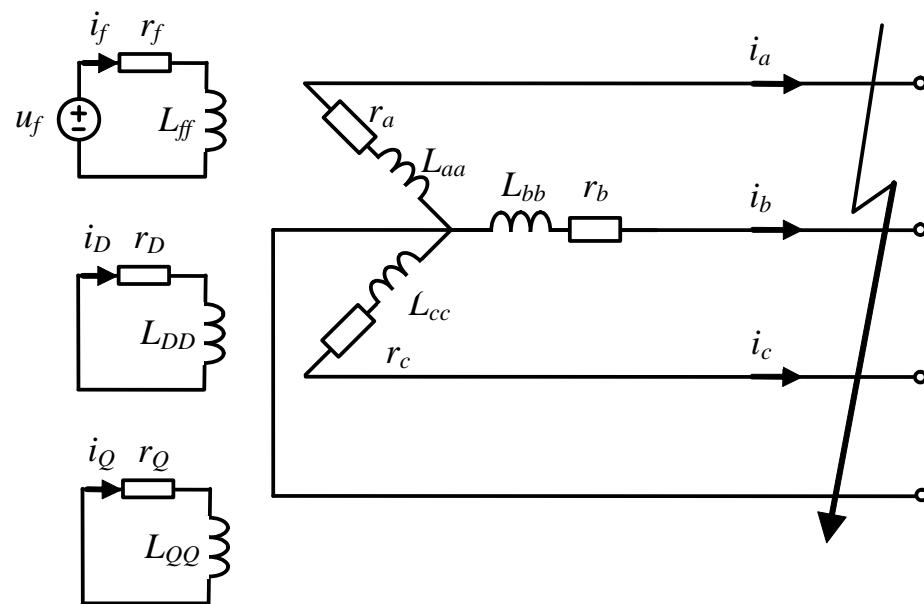
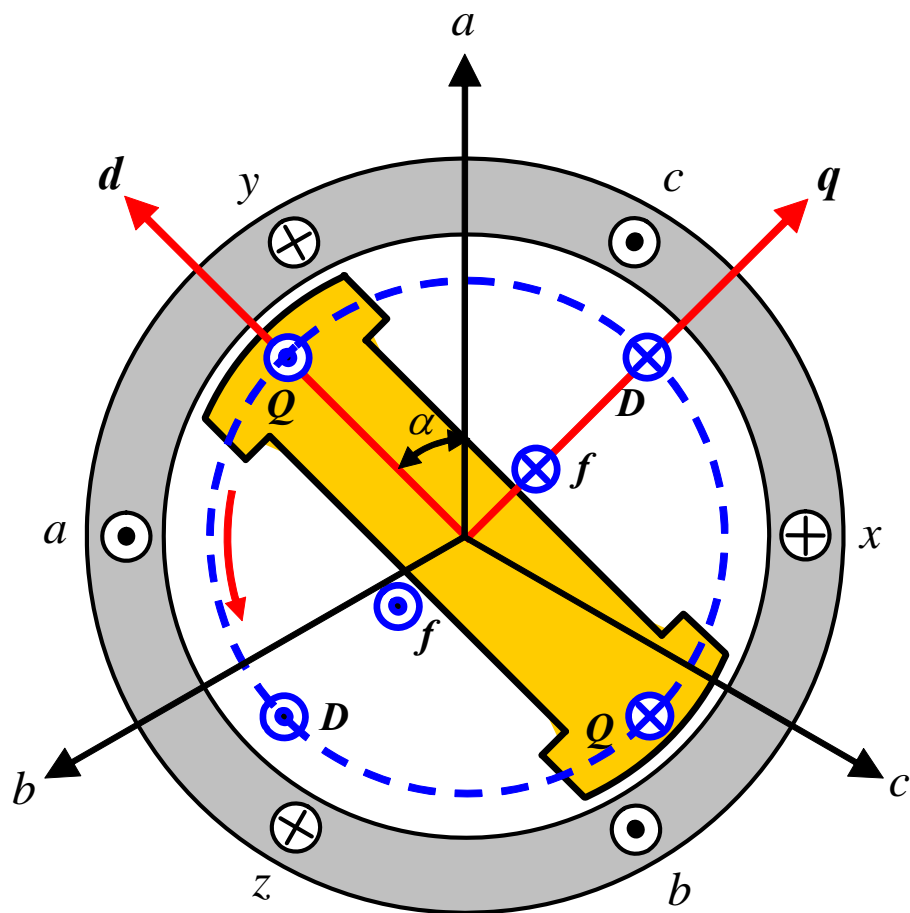
$$\left. \begin{aligned} v_d &= \dot{\psi}_d + \psi_q - r i_d \\ v_q &= -\dot{\psi}_q + \psi_d - r i_q \\ v_f &= \dot{\psi}_f + r i_f \\ 0 &= \dot{\psi}_D + r_D i_D \\ 0 &= \dot{\psi}_Q + r_Q i_Q \end{aligned} \right\}$$

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



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

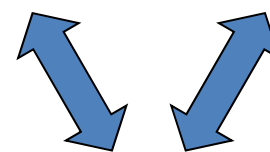
倍频电流

$$i_{abc(\infty)}$$

$$\Delta i_{abc(\omega)} = i_{abc(\omega)} - i_{abc(\infty)}$$

$$i_{abc(ap)}$$

$$i_{abc(2\omega)}$$



$$i_{f[0]}$$

$$\Delta i_{fa}$$

$$\Delta i_{Da}$$

$$\Delta i_{Qa}$$

$$\Delta i_{f\omega}$$

$$\Delta i_{D\omega}$$

$$\Delta i_{Q\omega}$$

转子绕组

稳态励磁电流

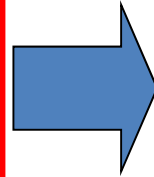
自由直流

基频电流

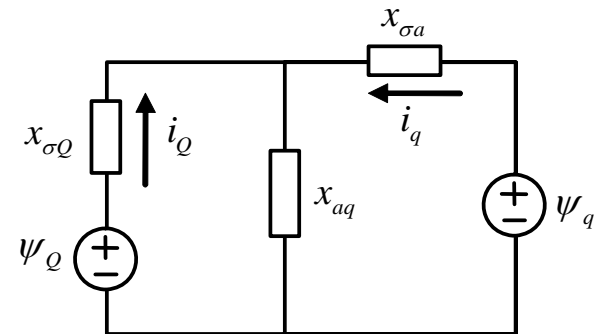
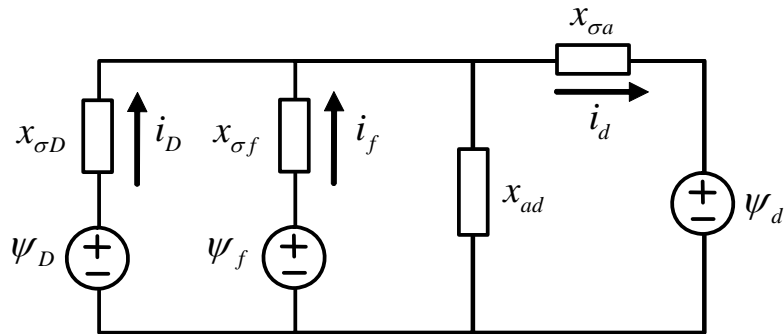
2. 次暂态电抗和次暂态电势

(1) 磁链平衡等值电路

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



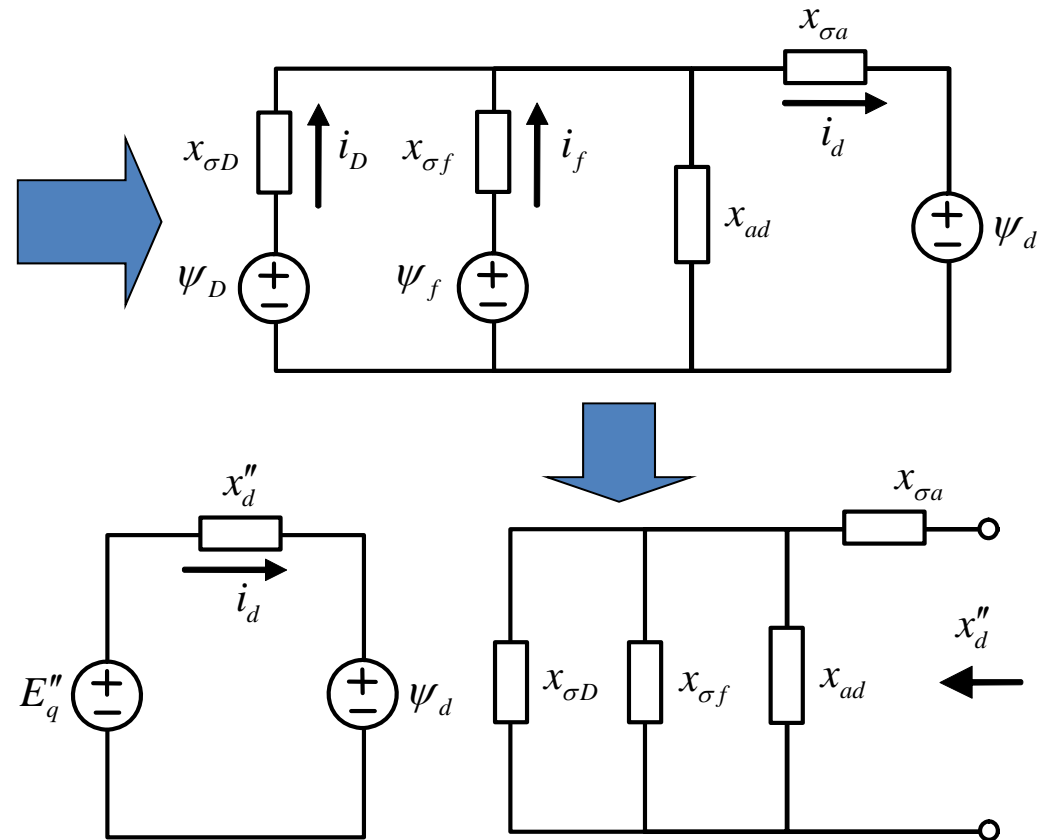
$$\begin{cases} \psi_d = x_{ad} (i_f + i_D - i_d) - x_{\sigma a} i_d \\ \psi_f = x_{ad} (i_f + i_D - i_d) + x_{\sigma f} i_f \\ \psi_D = x_{ad} (i_f + i_D - i_d) + x_{\sigma D} i_D \\ \psi_q = x_{\sigma a} i_q + x_{aq} (i_q + i_Q) \\ \psi_Q = x_{\sigma Q} i_Q + x_{aq} (i_q + i_Q) \end{cases}$$



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

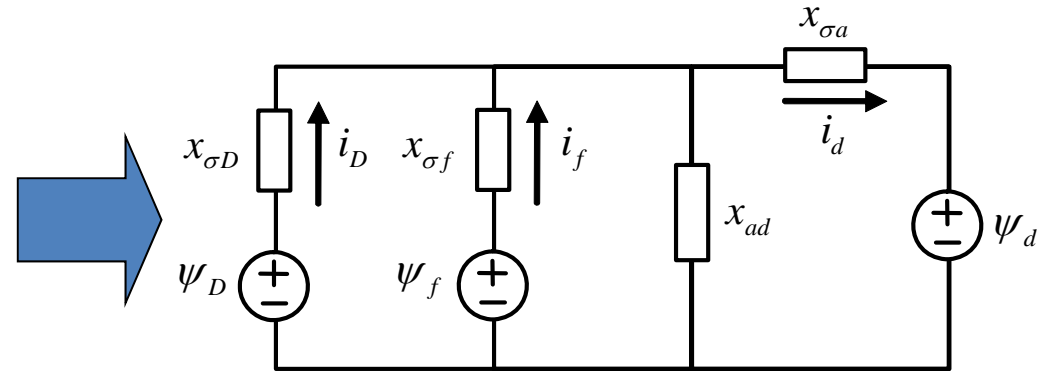
$$\begin{cases} \psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\ \psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\ \psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \end{cases}$$



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

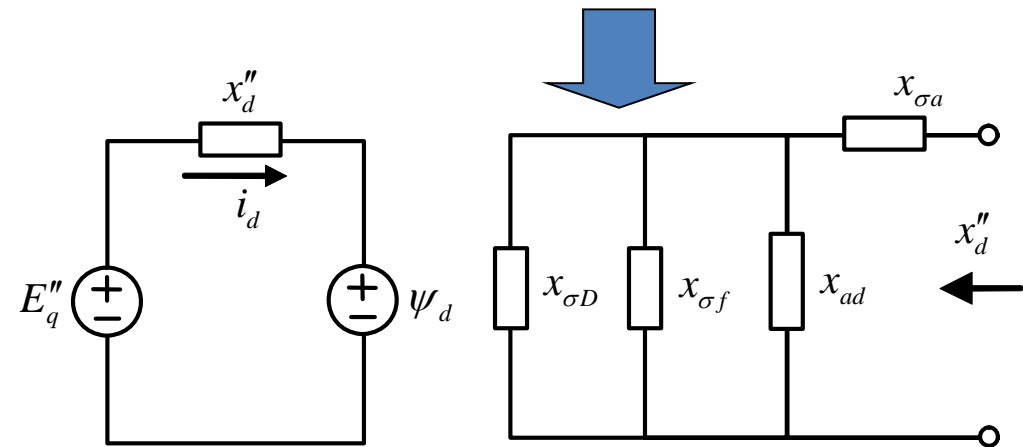
$$\begin{cases} \psi_d = -x_d i_d + x_{ad} i_f + x_{ad} i_D \\ \psi_f = -x_{ad} i_d + x_f i_f + x_{ad} i_D \\ \psi_D = -x_{ad} i_d + x_{ad} i_f + x_D i_D \end{cases}$$



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

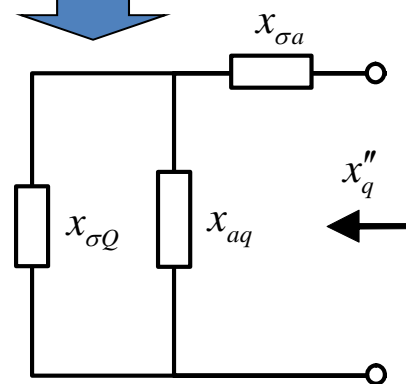
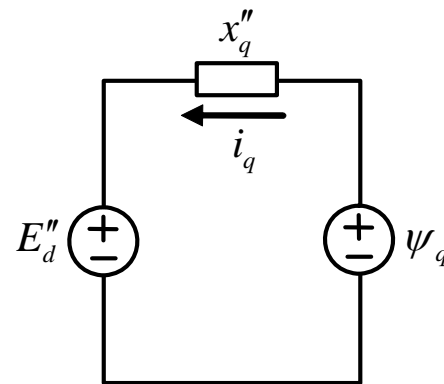
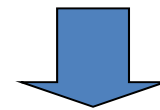
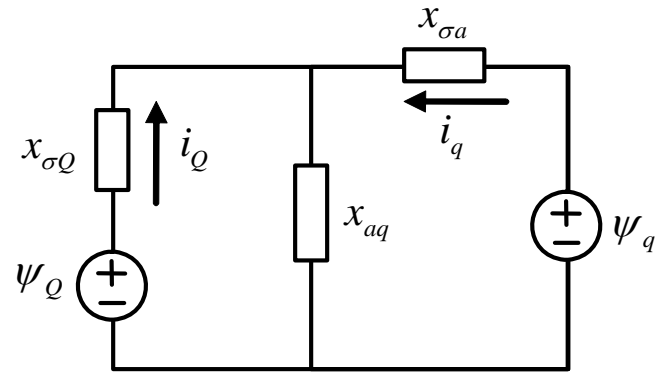
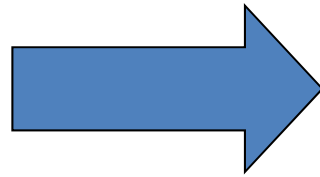


纵轴次暂态电抗 $x_d'' = x_{\sigma a} + x_{ad} // x_{\sigma f} // x_{\sigma D}$

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

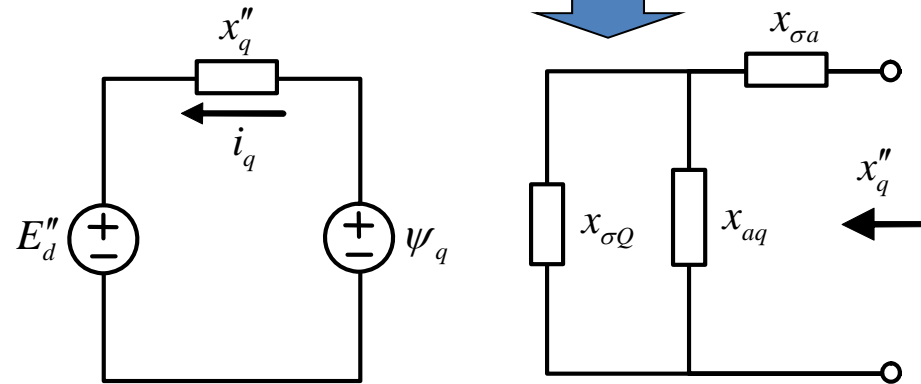
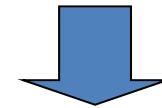
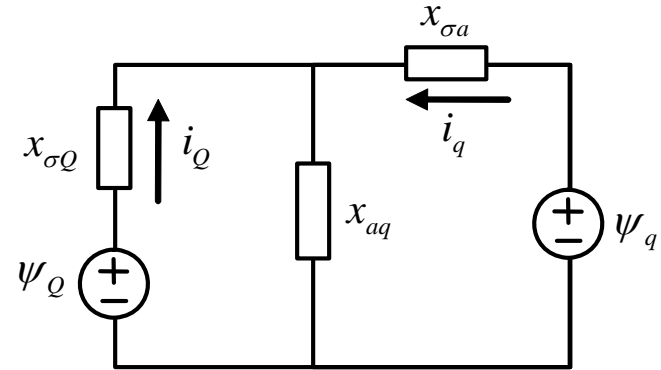
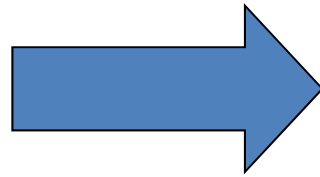
$$\begin{cases} \psi_q = x_q i_q + x_{aq} i_Q \\ \psi_Q = x_{aq} i_q + x_Q i_Q \end{cases}$$



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

$$\begin{array}{l} i_{abc(\omega)} \Leftrightarrow i''_d, i''_q \\ i_{abc(p)} \\ i_{abc(2\omega)} \end{array} \left. \vphantom{\begin{array}{l} i_{abc(\omega)} \\ i_{abc(p)} \\ i_{abc(2\omega)} \end{array}} \right\} i_{d\omega}, i_{q\omega}$$

$$\begin{array}{l} i_{f[0]} \\ \Delta i_{fa} \\ \Delta i_{f\omega} \end{array} \quad \begin{array}{l} \Delta i_{Da} \\ \Delta i_{D\omega} \\ \Delta i_{Qa} \\ \Delta i_{Q\omega} \end{array}$$

3. 有阻尼绕组电机的短路电流

(1) 短路状态磁链平衡关系

$$\begin{array}{l} i_{abc(\omega)} \Leftrightarrow i''_d, i''_q \\ i_{abc(p\omega)} \\ i_{abc(2\omega)} \end{array} \left. \vphantom{\begin{array}{l} i_{abc(\omega)} \\ i_{abc(p\omega)} \\ i_{abc(2\omega)} \end{array}} \right\} i_{d\omega}, i_{q\omega}$$

$$\begin{array}{l} i_{f[0]} \\ \Delta i_{fa} \\ \Delta i_{f\omega} \end{array}$$

$$\begin{array}{l} \Delta i_{Da} \\ \Delta i_{D\omega} \\ \Delta i_{Qa} \\ \Delta i_{Q\omega} \end{array}$$

$$\begin{array}{l} \psi_{a0} = \psi_0 \cos(\alpha_0 - \delta_0) \\ \psi_{b0} = \psi_0 \cos(\alpha_0 - \delta_0 - 120^\circ) \\ \psi_{c0} = \psi_0 \cos(\alpha_0 - \delta_0 + 120^\circ) \end{array}$$

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

3. 有阻尼绕组电机的短路电流

(1) 短路状态磁链平衡关系

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

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

$$i_{f[0]}$$

$$\Delta i_{fa}$$

$$\Delta i_{f\omega}$$

$$\Delta i_{Da}$$

$$\Delta i_{D\omega}$$

$$\Delta i_{Qa}$$

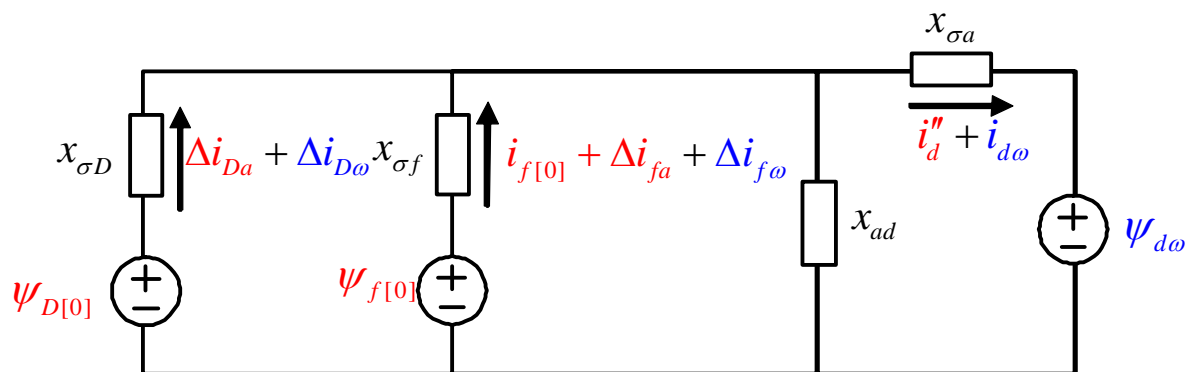
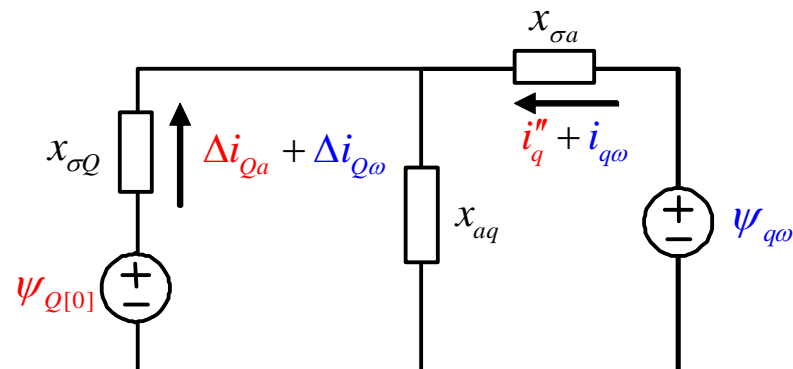
$$\Delta i_{Q\omega}$$

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

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

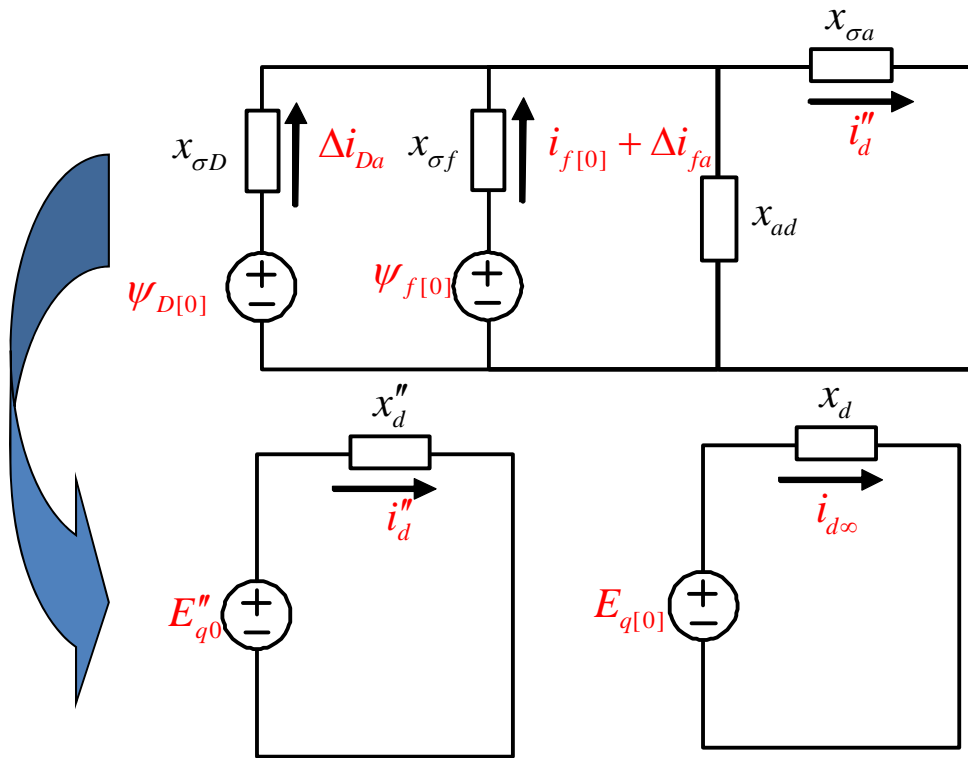
$$\psi_{c0} = \psi_0 \cos(\alpha_0 - \delta_0 + 120^\circ)$$

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



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

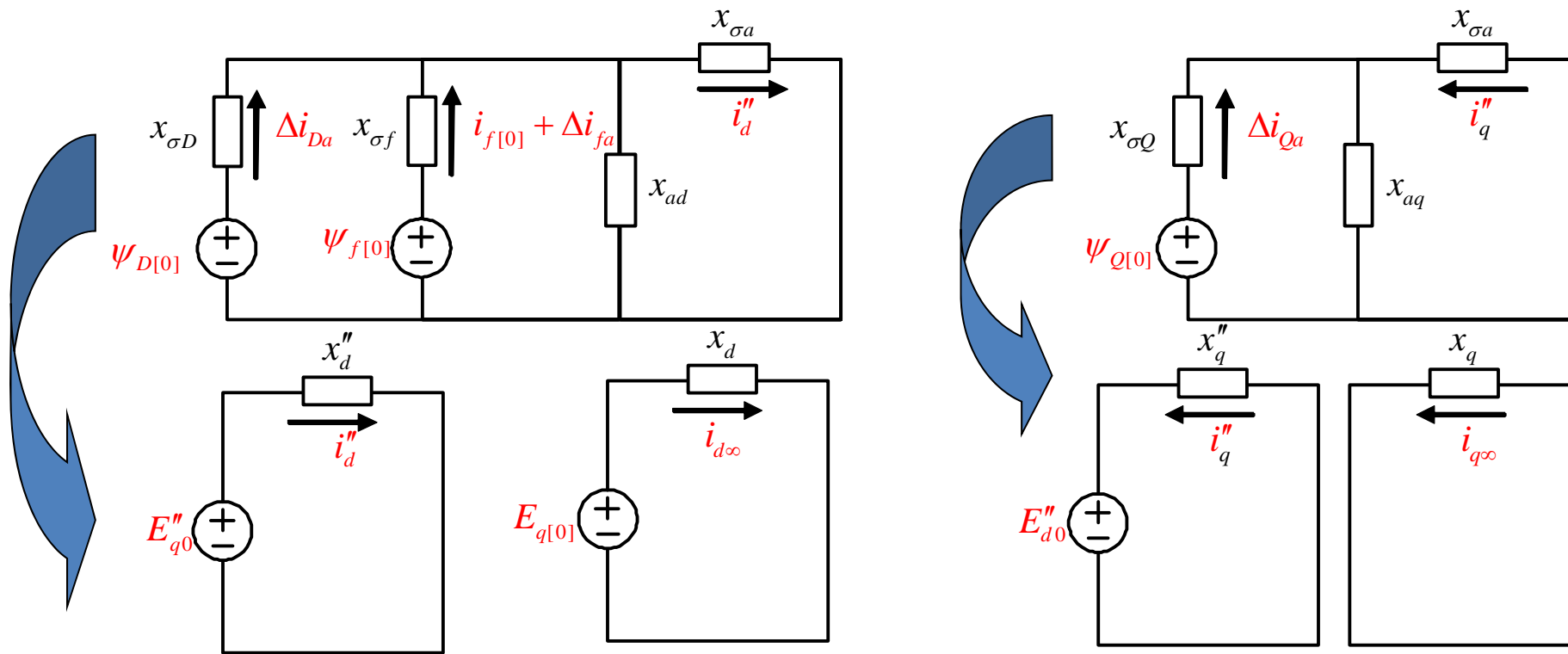


$$i_d'' = E_{q0}'' / x_d'', \quad i_{d\infty} = E_{q[0]} / x_d$$

$$E_{q0}'' = V_{[0]} \cos \delta_0 + x_d'' i_{d[0]}$$

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



$$i_d'' = E_{q0}'' / x_d'', \quad i_{d\infty} = E_{q[0]} / x_d$$

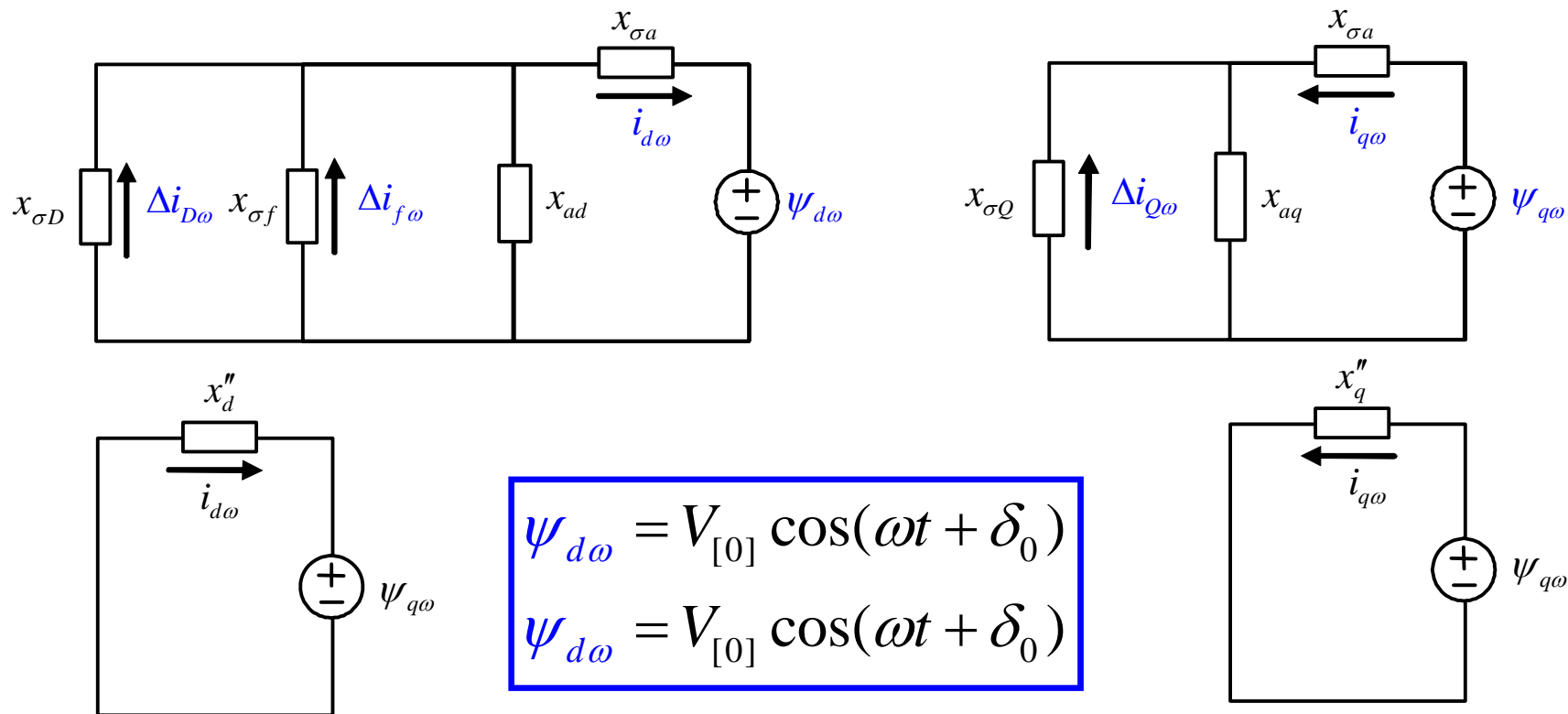
$$E_{q0}'' = V_{[0]} \cos \delta_0 + x_d'' i_{d[0]}$$

$$i_q'' = -E_{d0}'' / x_q'', \quad i_{q\infty} = 0$$

$$E_{d0}'' = u_{d[0]} - i_{q[0]} x_q'' = (x_q - x_q'') / x_q V_{[0]} \sin \delta_0$$

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



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

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

3. 有阻尼绕组电机的短路电流

(4) 各种电流分量计算式—Summary

$$\begin{aligned}i_d'' &= E_{q0}''/x_d'', \quad i_{d\infty} = E_{q[0]}/x_d, \quad i_d' = E_{q[0]}'/x_d' \\i_q'' &= -E_{d0}''/x_q'', \quad i_{q\infty} = 0\end{aligned}$$

$$\begin{aligned}i_{d\omega} &= -V_{[0]} \cos(\omega t + \delta_0)/x_d'' \\i_{q\omega} &= V_{[0]} \sin(\omega t + \delta_0)/x_q''\end{aligned}$$

$$\begin{aligned}\Delta i_{fa} &= \frac{x_{ad} x_{\sigma D}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]} \cos \delta_0}{x_d''} \\ \Delta i_{Da} &= \frac{x_{ad} x_{\sigma f}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]} \cos \delta_0}{x_d''} \\ \Delta i_{Qa} &= -\frac{x_q - x_q''}{x_{aq} x_q''} \times V_{[0]} \sin \delta_0\end{aligned}$$

$$\begin{aligned}\Delta i_{f\omega} &= -\frac{x_{ad} x_{\sigma D}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]} \cos(\omega t + \delta_0)}{x_d''} \\ \Delta i_{D\omega} &= -\frac{x_{ad} x_{\sigma f}}{x_f x_D - x_{ad}^2} \times \frac{V_{[0]} \cos(\omega t + \delta_0)}{x_d''} \\ \Delta i_{Q\omega} &= -\frac{x_q - x_q''}{x_{aq} x_q''} \times \frac{V_{[0]} \cos(\omega t + \delta_0)}{x_d''}\end{aligned}$$

4. 同步电机 次暂态模型

(1) 次暂态参数表示的电势方程

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

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

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

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

$$\begin{aligned} u_d &= \dot{\psi}_d + \omega \psi_q - r i_d \\ u_q &= -\dot{\psi}_q + \omega \psi_d - r i_q \end{aligned}$$

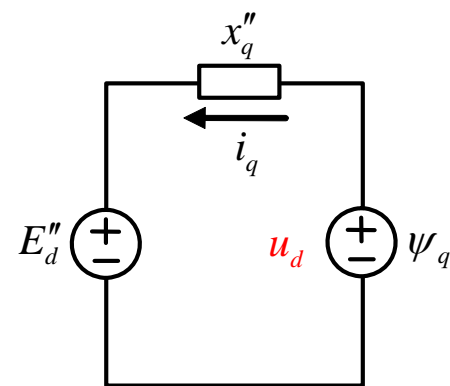
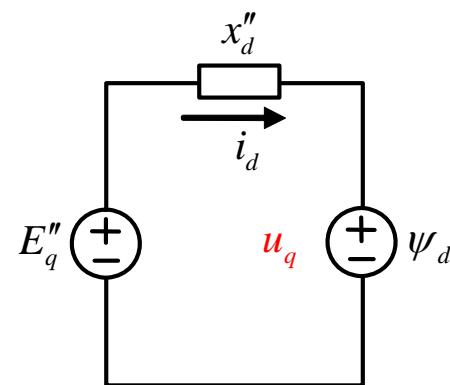
不考虑 $\dot{\psi}_d$ 和 $\dot{\psi}_q$
 $\omega = 1.0$, 忽略 r

$$\begin{aligned} u_d &= \psi_q \\ u_q &= \psi_d \end{aligned}$$

$$\begin{aligned} u_q &= E_q'' - x_d'' i_d \\ u_d &= E_d'' + x_q'' i_q \end{aligned}$$

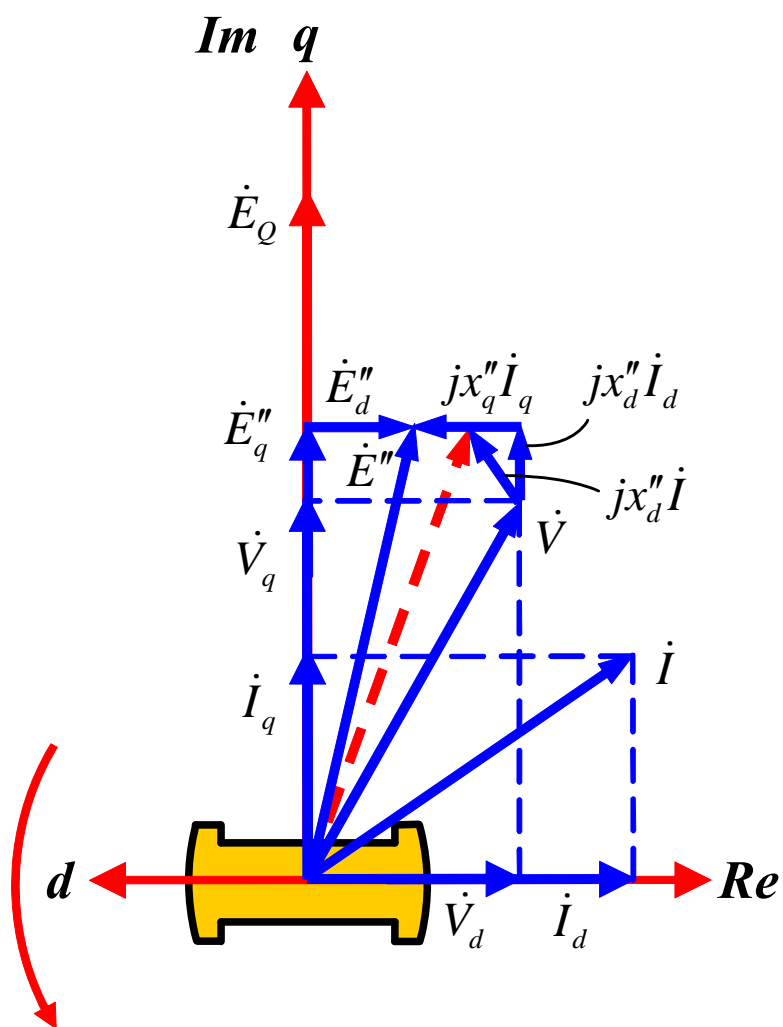
电势方程

$$\begin{aligned} \psi_d &= E_q'' - x_d'' i_d \\ \psi_q &= E_d'' - x_q'' i_q \end{aligned}$$



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



$$\begin{aligned} u_q &= E_q'' - x_d'' i_d \\ u_d &= E_d'' + x_q'' i_q \end{aligned}$$

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

$$\begin{aligned} \dot{V} &= (\dot{E}_q'' + \dot{E}_d'') - jx_d'' \dot{I}_d - jx_q'' \dot{I}_q \\ &= \dot{E}'' - jx_d'' \dot{I}_d - jx_q'' \dot{I}_q \approx \dot{E}'' - jx_d'' \dot{I} \end{aligned}$$

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

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:

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

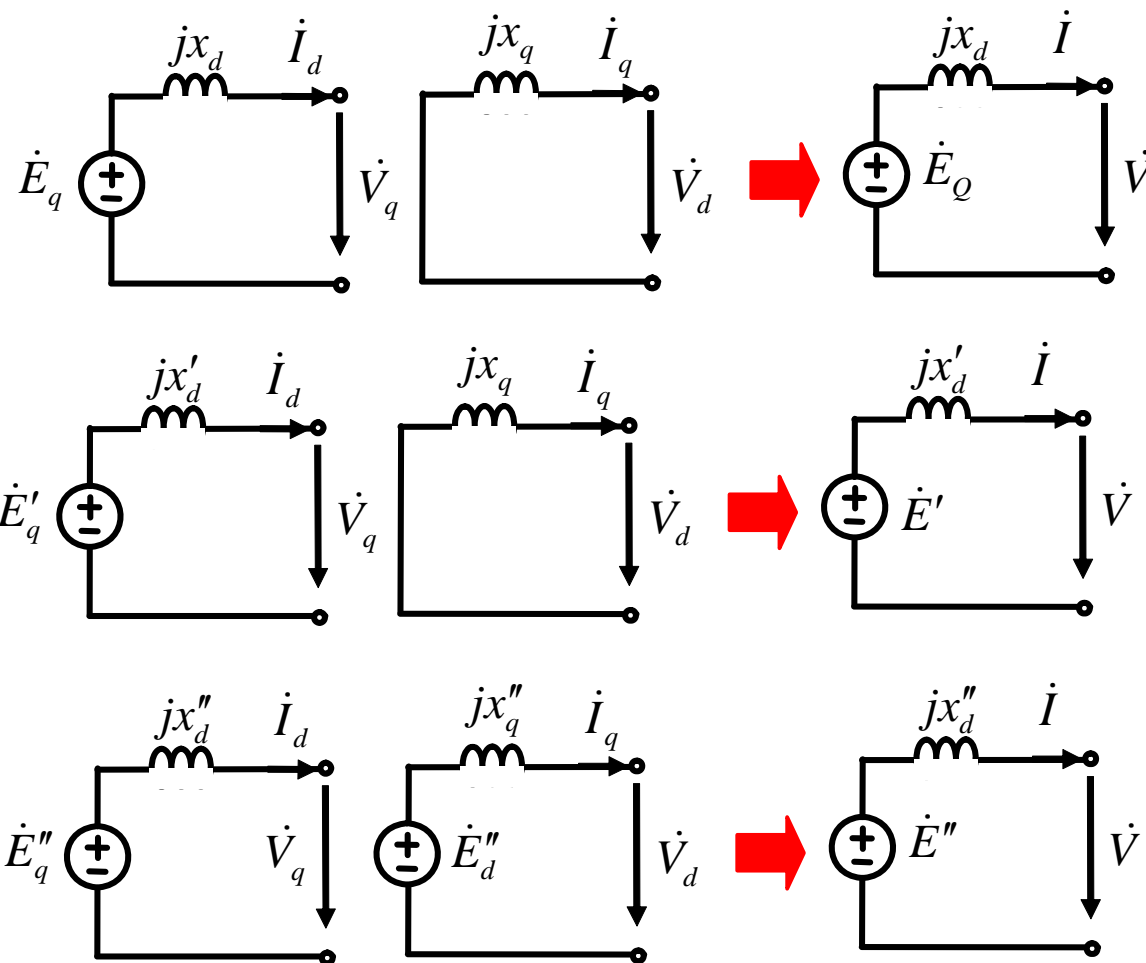
$$\dot{V}, \dot{I}, x_q \Rightarrow E_Q, \delta$$

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

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

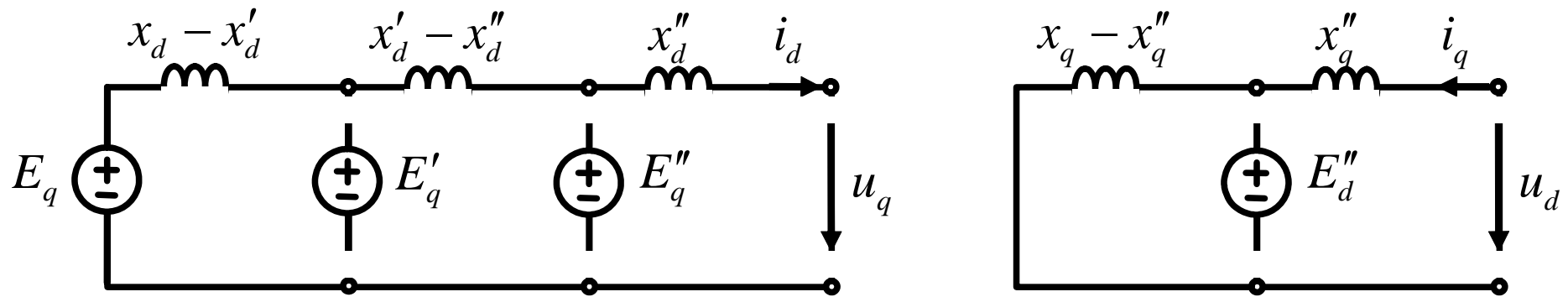
$$\Rightarrow E_q, E'_q, E''_q, E''_d$$

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



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



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

$$i_q = \frac{V \sin \delta}{x_q} = \frac{E''_d - V \sin \delta}{x''_q}$$

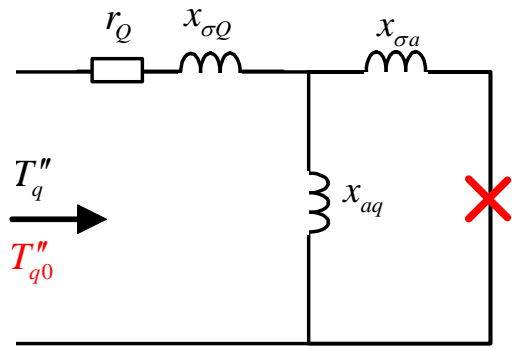
5. 自由电流的衰减

(1) 横轴次暂态电流和非周期分量

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

$$T_a = \frac{2x_d''x_q''}{\omega r(x_d'' + x_q'')}$$

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



横轴次暂态开路时间常数: $T_{q0}'' = \frac{x_Q}{\omega r_Q}$

横轴次暂态短路时间常数: $T_q'' = \frac{x_q''}{x_q} T_{q0}''$

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

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

$$i_d = i_{d\infty} + (i_d'' - i_d') + (i_d' - i_{d\infty}) + i_{d\omega}$$
$$i_f = i_{f[0]} + (\Delta i_{fa} - \Delta i_{fa}') + \Delta i_{fa}' + \Delta i_{f\omega}$$
$$i_D = \Delta i_{Da} + \Delta i_{D\omega}$$

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

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

$$\begin{aligned}
 i_d &= i_{d\infty} + \Delta i_d'' \exp\left(-\frac{t}{T_d''}\right) + \Delta i_d' \exp\left(-\frac{t}{T_d'}\right) + i_{d\omega} \exp\left(-\frac{t}{T_a}\right) \\
 i_f &= i_{f[0]} + \Delta i_{fa}'' \exp\left(-\frac{t}{T_d''}\right) + \Delta i_{fa}' \exp\left(-\frac{t}{T_d'}\right) + \Delta i_{f\omega} \exp\left(-\frac{t}{T_a}\right) \\
 i_D &= \Delta i_{Da} \exp\left(-\frac{t}{T_d''}\right) + \Delta i_{D\omega} \exp\left(-\frac{t}{T_a}\right)
 \end{aligned}$$

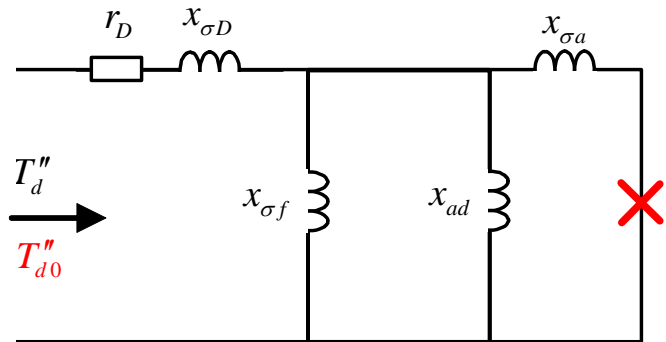
$$\begin{aligned}
 \Delta i_d'' &= \frac{E_{q0}''}{x_d''} - \frac{E_{q[0]}'}{x_d'} \\
 \Delta i_d' &= \frac{E_{q[0]}'}{x_d'} - \frac{E_{q[0]}}{x_d}
 \end{aligned}$$

$$\begin{aligned}
 i_d &= i_{d\infty} + (i_d'' - i_d') + (i_d' - i_{d\infty}) + i_{d\omega} \\
 i_f &= i_{f[0]} + (\Delta i_{fa}'' - \Delta i_{fa}') + \Delta i_{fa}' + \Delta i_{f\omega} \\
 i_D &= \Delta i_{Da} + \Delta i_{D\omega}
 \end{aligned}$$

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

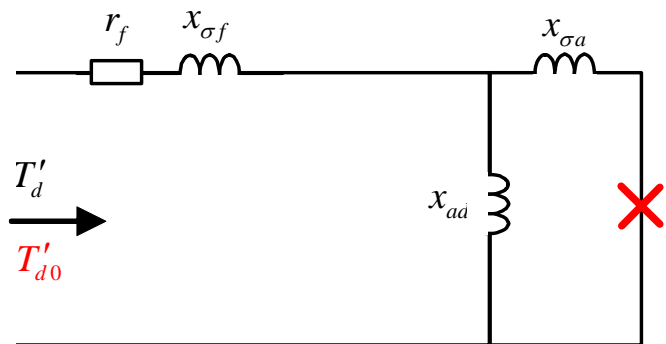
5. 自由电流的衰减

(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: $T_d'' = \frac{x_d''}{x_d'} T_{d0}''$



纵轴暂态开路时间常数: $T_{d0}' = \frac{x_f}{\omega r_f}$

纵轴暂态短路时间常数: $T_d' = \frac{x_d'}{x_d} T_{d0}'$

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

$$\begin{aligned} i_a = & -\frac{E_{q[0]}}{x_d} \cos(\omega t + \alpha_0) - \left(\frac{E''_{q0}}{x''_d} - \frac{E'_{q[0]}}{x'_d} \right) \exp\left(-\frac{t}{T''_d}\right) \cos(\omega t + \alpha_0) \\ & - \left(\frac{E'_{q[0]}}{x'_d} - \frac{E_{q[0]}}{x_d} \right) \exp\left(-\frac{t}{T'_d}\right) \cos(\omega t + \alpha_0) - \frac{E''_{d0}}{x''_q} \exp\left(-\frac{t}{T''_q}\right) \sin(\omega t + \alpha_0) \\ & + \frac{V_{[0]}}{2} \left(\frac{1}{x''_d} + \frac{1}{x''_q} \right) \exp\left(-\frac{t}{T_a}\right) \cos(\delta_0 - \alpha_0) \\ & + \frac{V_{[0]}}{2} \left(\frac{1}{x''_d} - \frac{1}{x''_q} \right) \exp\left(-\frac{t}{T_a}\right) \cos(2\omega t + \delta_0 + \alpha_0) \end{aligned}$$

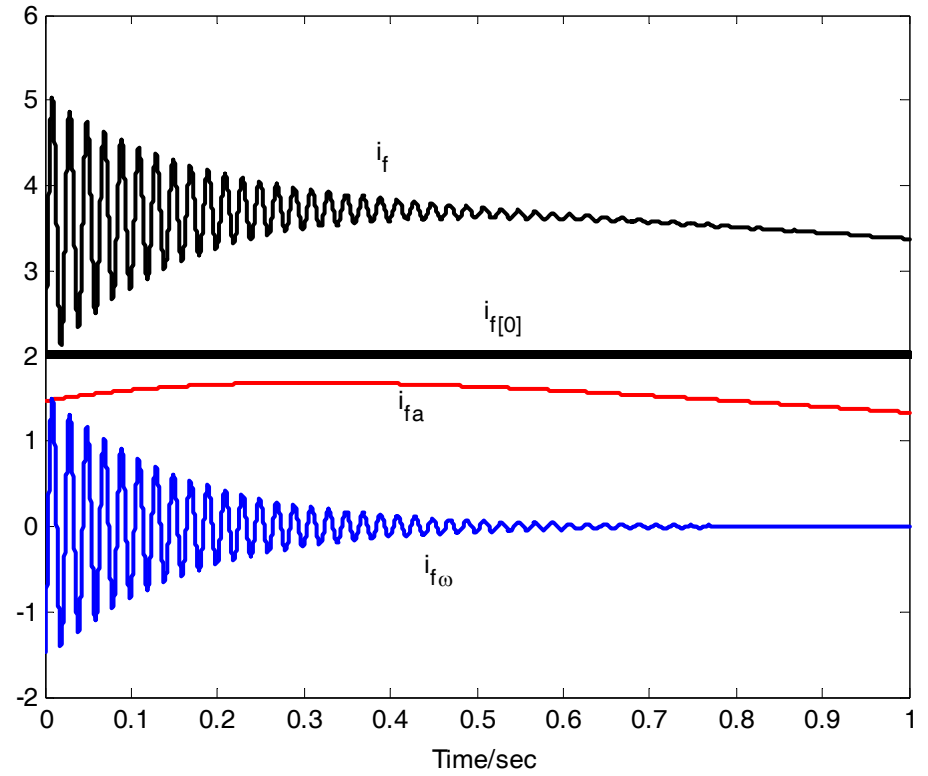
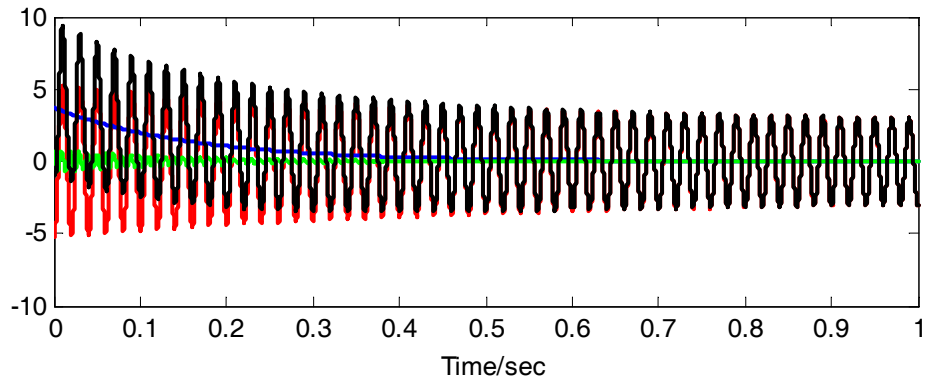
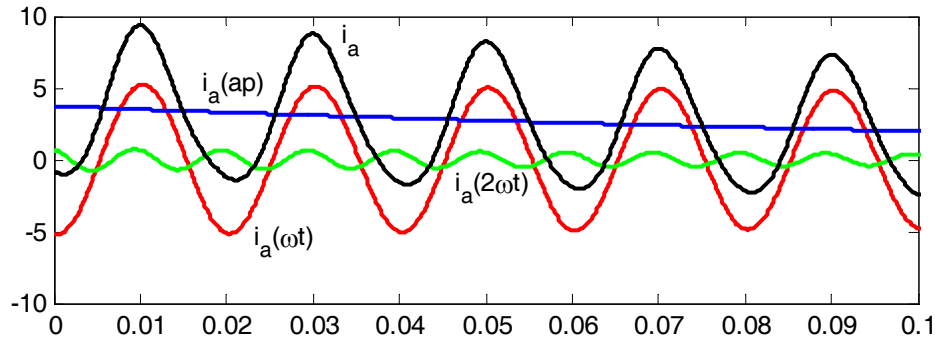
6. 短路全电流

(3) 励磁电流

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

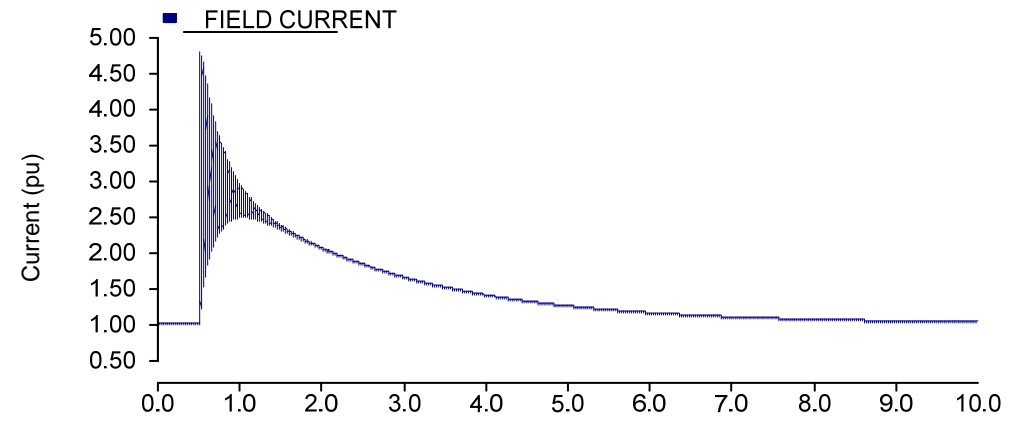
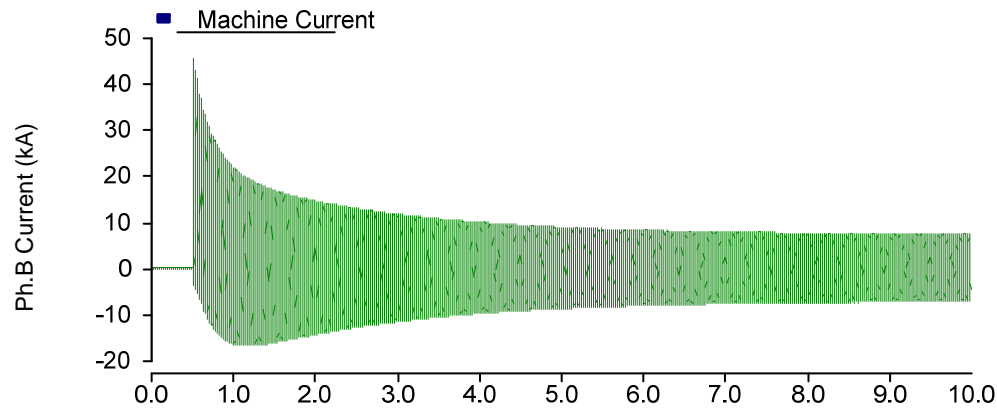
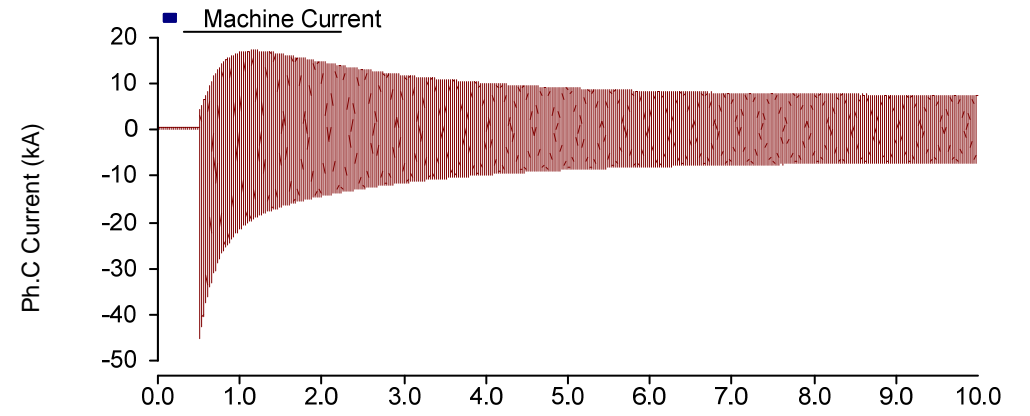
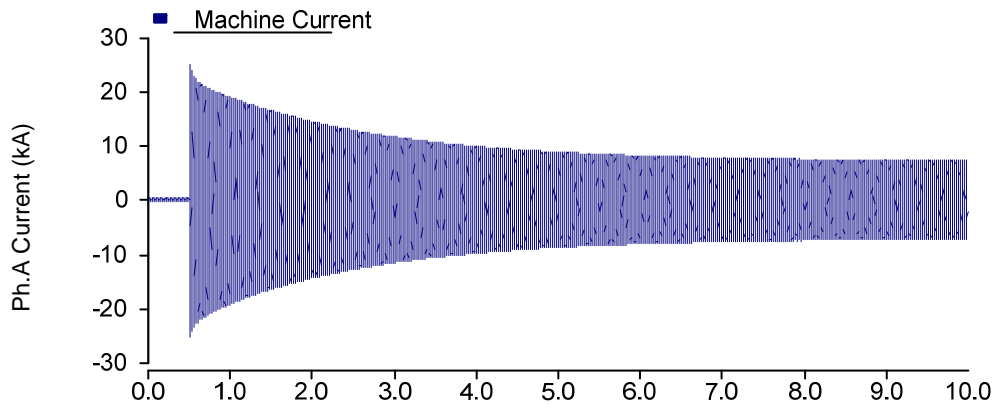
6. 短路全电流

(3) 电流波形



6. 短路全电流

(3) 电流波形

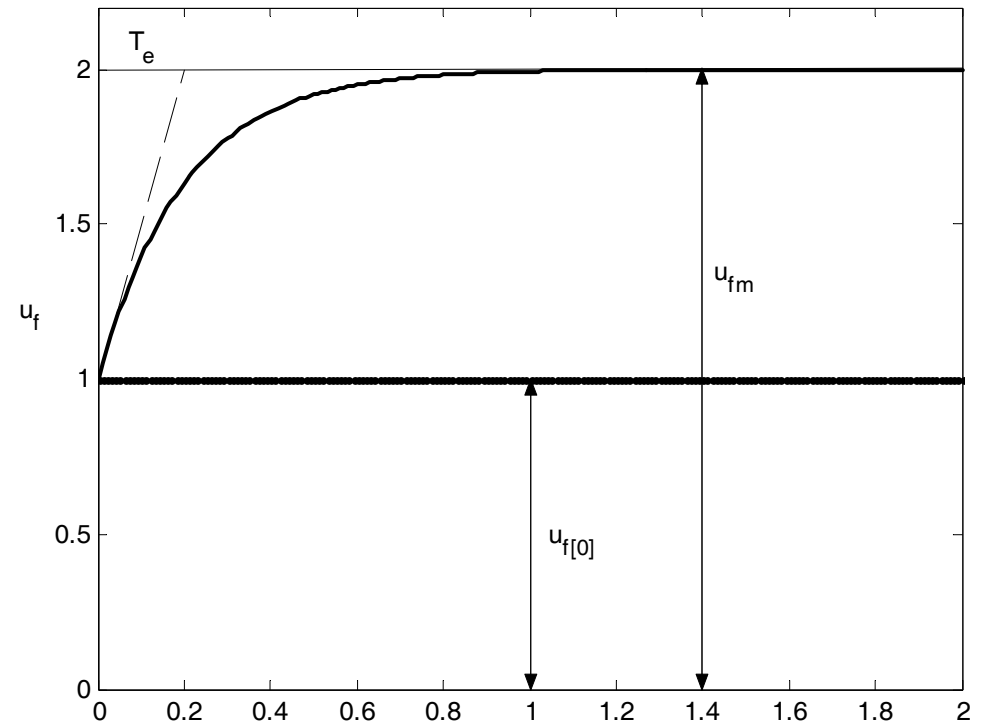
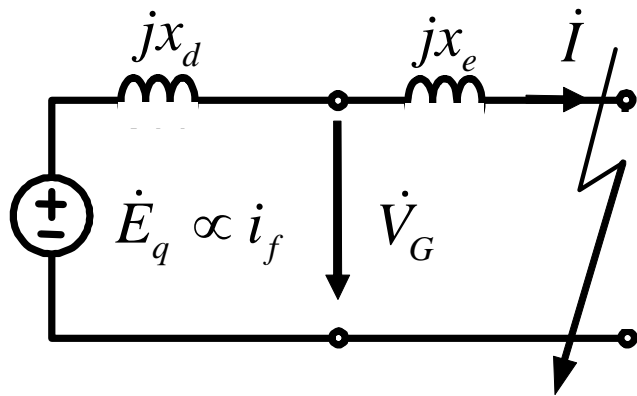


5-6 强行励磁对短路暂态过程的影响

(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

风电机组



✧单台风机容量相对较小

1.5MW - 7.5MW

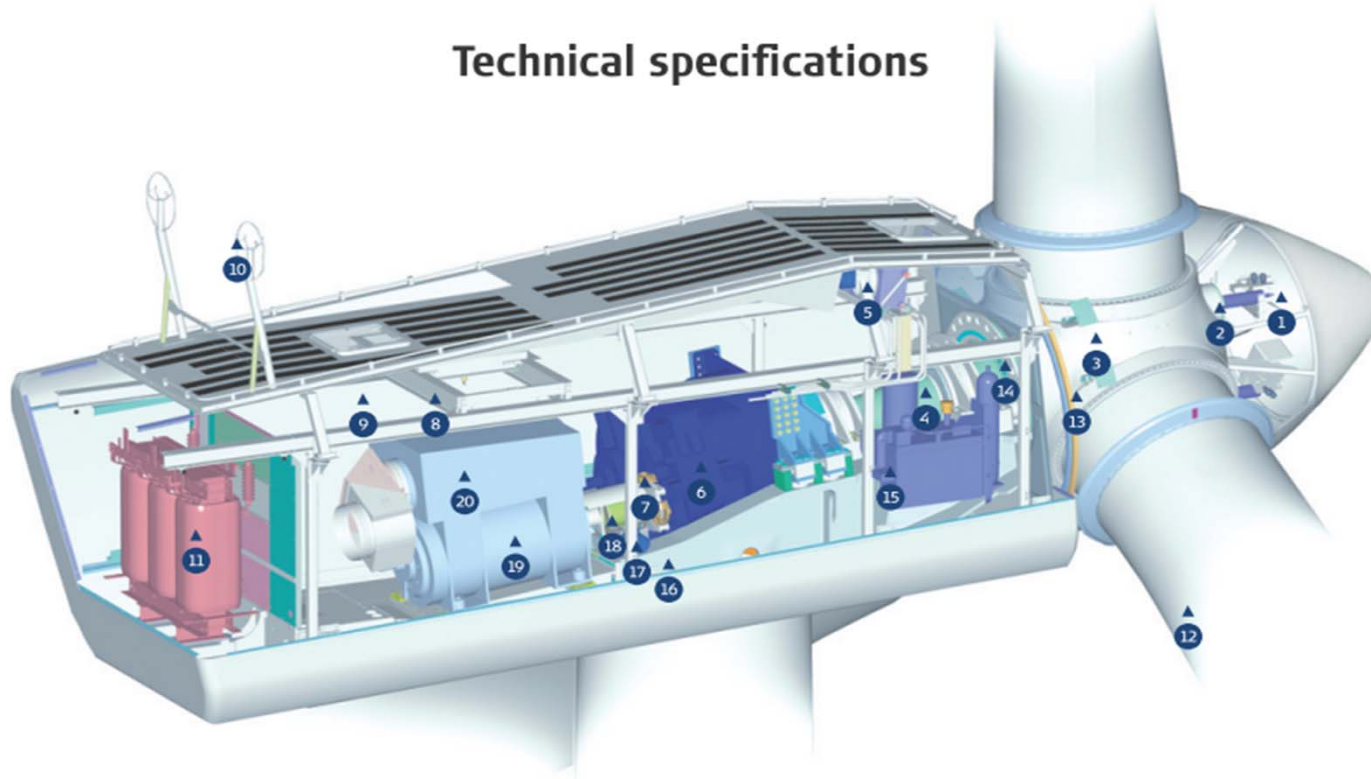
✧风场容量很大

数十MW - 千万kW



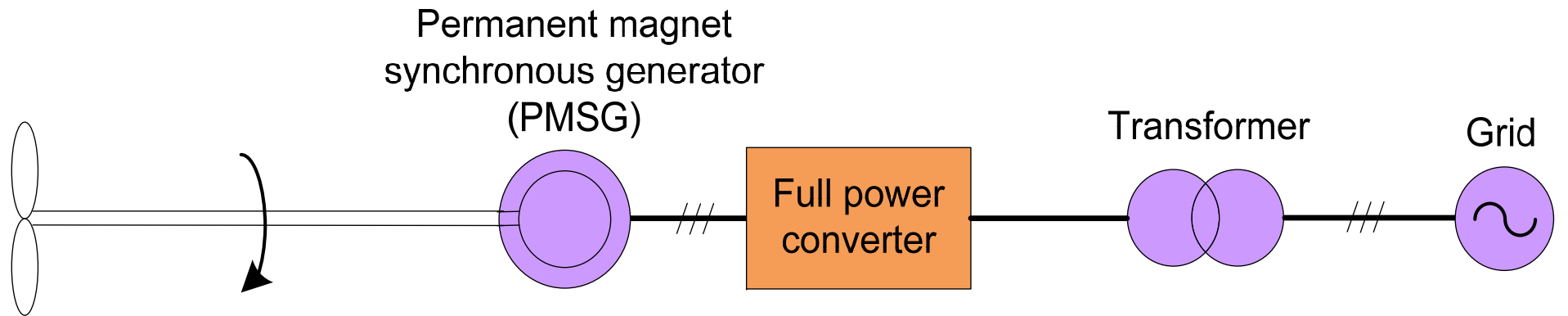
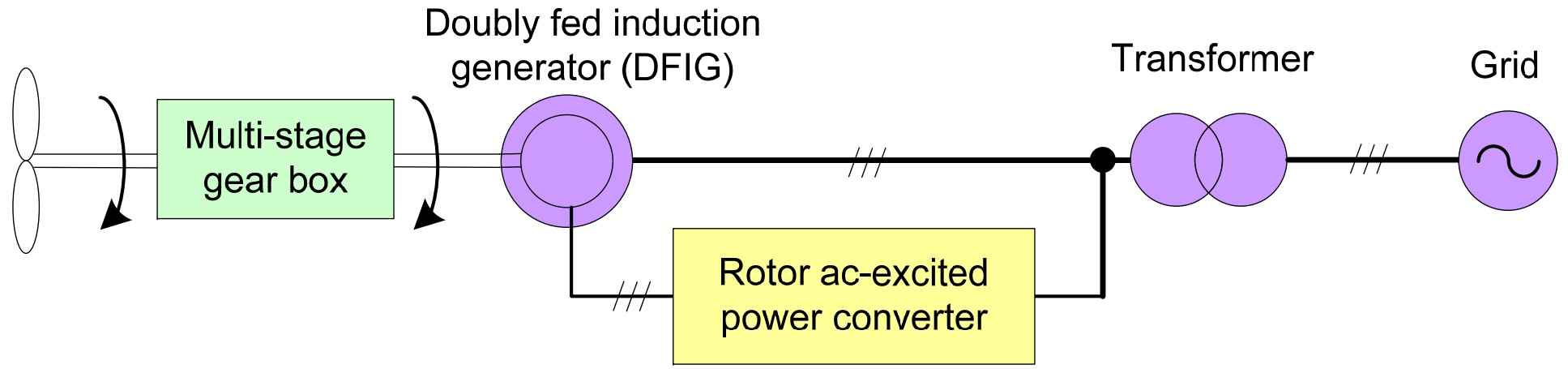
风力发电系统实物

Technical specifications



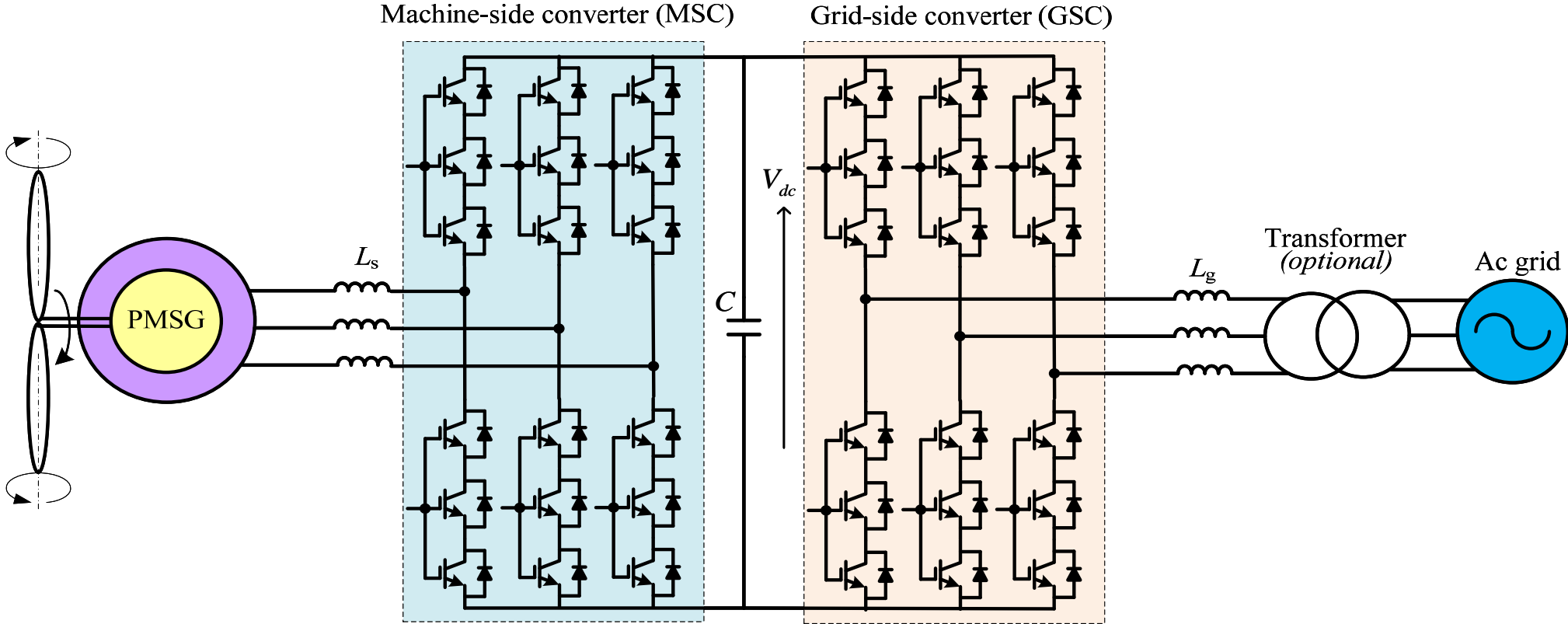
- | | | | |
|-------------------------|-------------------------------------|--------------------------------|-------------------------------|
| ① Hub controller 机舱控制 | ⑥ Gearbox 变速箱 | ⑪ High voltage transformer 变压器 | ⑬ Machine foundation 机舱外壁 |
| ② Pitch cylinders 桨距角滚筒 | ⑦ Mechanical disc brake 机械刹车片 | ⑫ Blade 叶片 | ⑭ Yaw gears 偏航系统 |
| ③ Blade hub 叶片轴 | ⑧ Service crane 内置吊车 | ⑬ Blade bearing 叶片刹车 | ⑮ Composite disc coupling 法兰盘 |
| ④ Main shaft 主轴 | ⑨ VMP-Top controller with converter | ⑭ Rotor lock system 转子刹车 | ⑯ OptiSpeed® generator 发电机 |
| ⑤ Oil cooler 油冷却器 | ⑩ Ultrasonic sensors | ⑮ Hydraulic unit 液压系统 | ⑰ Air cooler for generator 风散 |

变速风电机组-双馈异步电机

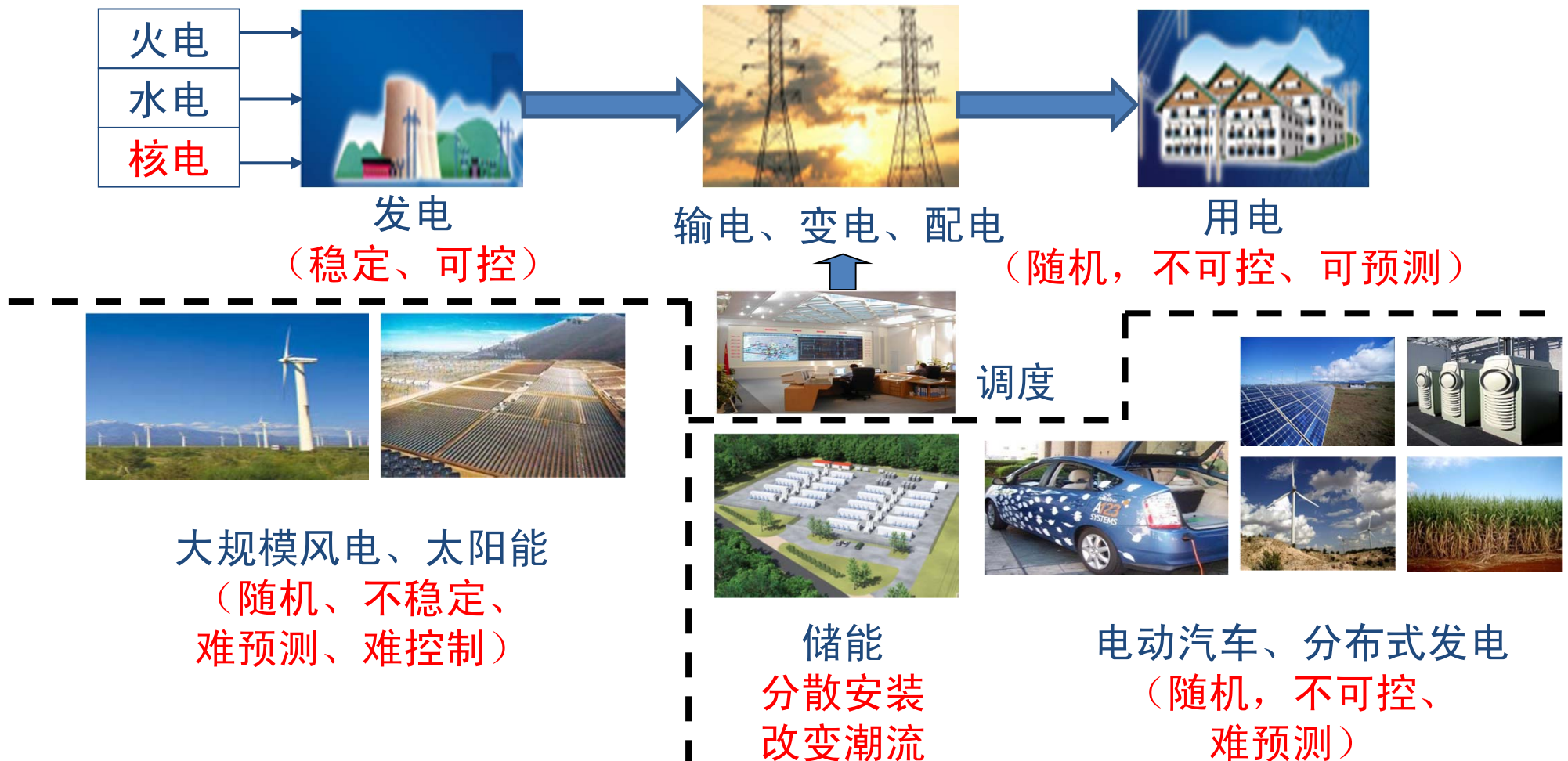


直驱风电机组-永磁同步机

High-Power PMSG based on BTB 2-level VSCs with Series-IGBTs

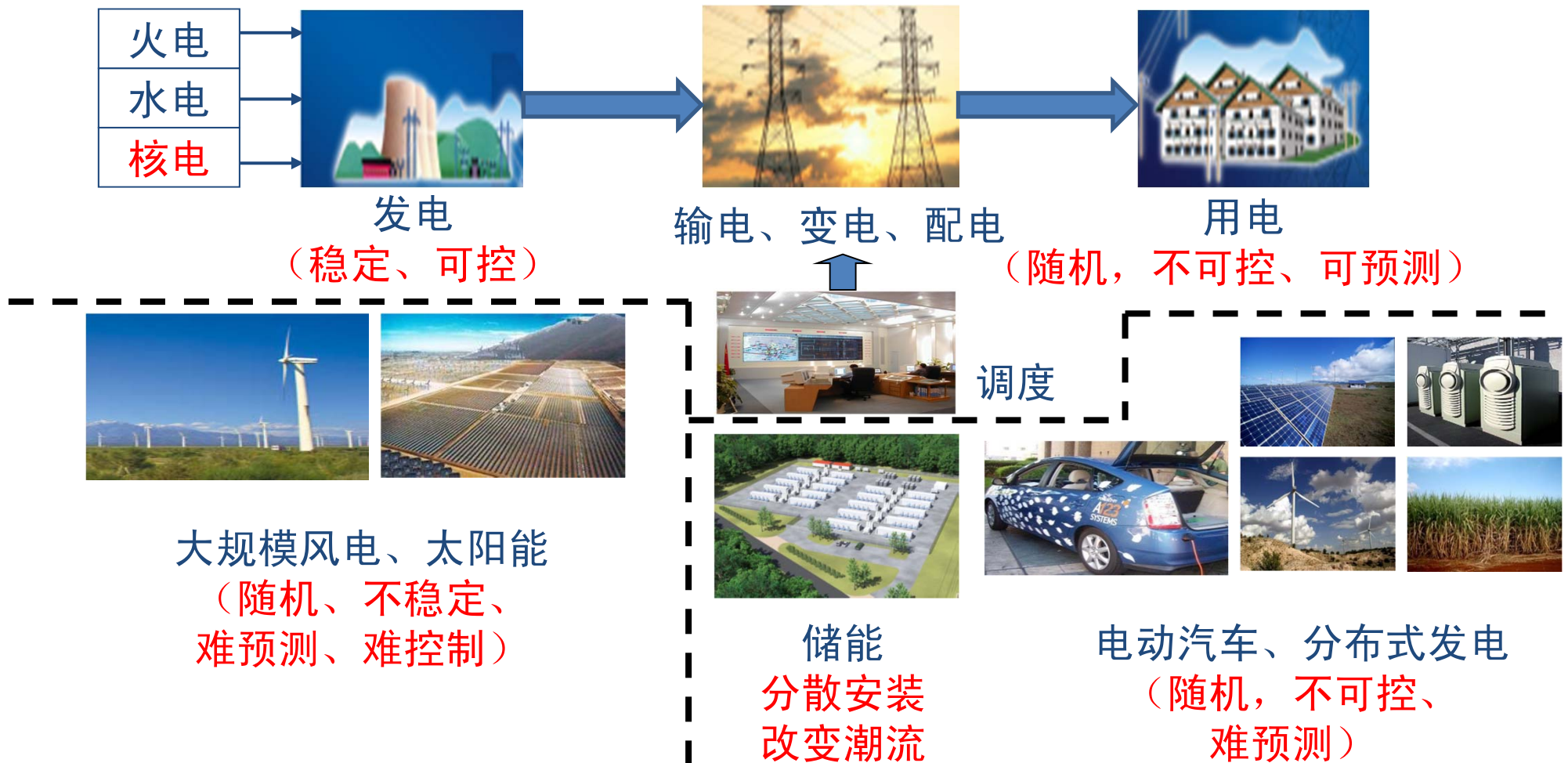


未来电力系统的特点（从数学上看）



未来电力系统：多组随机变量的平衡！

未来电力系统的特点（从物理上看）



未来电力系统：随机波动电源，电力电子！

Do you think so?

长歌行

汉乐府

青青园中葵，朝露待日晞。

阳春布德泽，万物生光辉。

常恐秋节至，焜黄华叶衰。

百川东到海，何时复西归？

少壮不努力，老大徒伤悲！

Ex: 5-3, 5-7(1)(2)

End of Chapter 5