第11回の内容

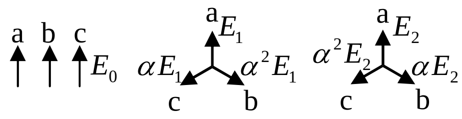
- 三相交流発電機の基本式
- 無負荷三相交流発電機の故障計算

キーワード: 一線地絡故障

中性点接地インピーダンス, 健全相電圧

対称成分

$$\dot{E}_0 = \tfrac{1}{3}\left(\dot{E}_a + \dot{E}_b + \dot{E}_c\right)$$
$$\dot{E}_1 = \tfrac{1}{3}\left(\dot{E}_a + \alpha\dot{E}_b + \alpha^2\dot{E}_c\right)$$
$$\dot{E}_2 = \tfrac{1}{3}\left(\dot{E}_a + \alpha^2\dot{E}_b + \alpha\dot{E}_c\right)$$



零相　　正相　　逆相

$$\alpha = \mathrm{e}^{\mathrm{j}\frac{2}{3}\pi} = \mathrm{e}^{\mathrm{-j}\frac{4}{3}\pi} = -\frac{1}{2} + j\frac{\sqrt{3}}{2},\ \alpha^2 = \mathrm{e}^{\mathrm{j}\frac{4}{3}\pi} = \mathrm{e}^{\mathrm{-j}\frac{2}{3}\pi} = -\frac{1}{2} - j\frac{\sqrt{3}}{2},\ 1+\alpha+\alpha^2 = 0,\ \alpha^3 = 1$$

4.2.1 対称分インピーダンス

(a) 同期機

$\dot{Z}_2 < \dot{Z}_1$, $\dot{Z}_0$ は $\dot{Z}_1$ の 10%以下

(b) 変圧器

$\dot{Z}_2 = \dot{Z}_1$, $\dot{Z}_0 = \dot{Z}_1$ 又は接地方法でかわる

(c) 送電線

$\dot{Z}_2 = \dot{Z}_1$, $\dot{Z}_0$ は対地容量, インダクタンス

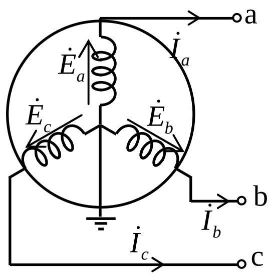
(d) 三相対称負荷

三相対称構造の静止機器は $\dot{Z}_2 = \dot{Z}_1$

$\dot{Z}_0 = \dot{Z}_1$ 又は接地方法でかわる

4.2.2 三相交流発電機の基本式

$$\dot{V}_0 = -\dot{Z}_0\dot{I}_0$$
$$\dot{V}_1 = \dot{E}_a - \dot{Z}_1\dot{I}_1$$
$$\dot{V}_2 = -\dot{Z}_2\dot{I}_2$$



導出:

発電機の端子電圧

$$\dot{V}_a = \dot{E}_a - \dot{v}_a,\ \dot{V}_b = \dot{E}_b - \dot{v}_b,\ \dot{V}_c = \dot{E}_c - \dot{v}_c$$

ここで, $\dot{V}_a, \dot{V}_b, \dot{V}_c$: 端子電圧,

$\dot{E}_a, \dot{E}_b, \dot{E}_c$: 起電力,

$\dot{v}_a, \dot{v}_b, \dot{v}_c$: 発電機内部での電圧降下

また, $\dot{E}_a = \dot{E}_a$, $\dot{E}_b = \alpha^2\dot{E}_a$, $\dot{E}_c = \alpha\dot{E}_a$

端子電圧の対称分

$$\dot{V}_0 = \tfrac{1}{3}\left\{\left(\dot{E}_a - \dot{v}_a\right) + \left(\dot{E}_b - \dot{v}_b\right) + \left(\dot{E}_c - \dot{v}_c\right)\right\}$$
$$\dot{V}_1 = \tfrac{1}{3}\left\{\left(\dot{E}_a - \dot{v}_a\right) + \alpha\left(\dot{E}_b - \dot{v}_b\right) + \alpha^2\left(\dot{E}_c - \dot{v}_c\right)\right\}$$
$$\dot{V}_2 = \tfrac{1}{3}\left\{\left(\dot{E}_a - \dot{v}_a\right) + \alpha^2\left(\dot{E}_b - \dot{v}_b\right) + \alpha\left(\dot{E}_c - \dot{v}_c\right)\right\}$$

より

$$\dot{V}_0 = \tfrac{1}{3}\left\{\left(\dot{E}_a + \dot{E}_b + \dot{E}_c\right) - \left(\dot{v}_a + \dot{v}_b + \dot{v}_c\right)\right\}$$
$$\dot{V}_1 = \tfrac{1}{3}\left\{\left(\dot{E}_a + \alpha\dot{E}_b + \alpha^2\dot{E}_c\right) - \left(\dot{v}_a + \alpha\dot{v}_b + \alpha^2\dot{v}_c\right)\right\}$$
$$\dot{V}_2 = \tfrac{1}{3}\left\{\left(\dot{E}_a + \alpha^2\dot{E}_b + \alpha\dot{E}_c\right) - \left(\dot{v}_a + \alpha^2\dot{v}_b + \alpha\dot{v}_c\right)\right\}$$

ここで, $\dot{E}_a = \dot{E}_a$, $\dot{E}_b = \alpha^2\dot{E}_a$, $\dot{E}_c = \alpha\dot{E}_a$ だから

$\dot{V}_0 = \frac{1}{3}\left\{\left(\dot{E}_a, +\alpha^2\dot{E}_a, +\alpha\dot{E}_a,\right) - \left(\dot{v}_a + \dot{v}_b + \dot{v}_c\right)\right\}$
$= -\frac{1}{3}\left(\dot{v}_a + \dot{v}_b + \dot{v}_c\right)$

$\dot{V}_1 = \frac{1}{3}\left\{\left(\dot{E}_a + \alpha\alpha^2\dot{E}_a + \alpha^2\alpha\dot{E}_a\right) - \left(\dot{v}_a + \alpha\dot{v}_b + \alpha^2\dot{v}_c\right)\right\}$
$= \dot{E}_a - \frac{1}{3}\left(\dot{v}_a + \alpha\dot{v}_b + \alpha^2\dot{v}_c\right)$

$\dot{V}_2 = \frac{1}{3}\left\{\left(\dot{E}_a + \alpha^2\alpha^2\dot{E}_a + \alpha\alpha\dot{E}_a\right) - \left(\dot{v}_a + \alpha^2\dot{v}_b + \alpha\dot{v}_c\right)\right\}$
$= -\frac{1}{3}\left(\dot{v}_a + \alpha^2\dot{v}_b + \alpha\dot{v}_c\right)$

発電機1相あたりの零相，正相，逆相インピーダンスを $\dot{Z}_0$，$\dot{Z}_1$，$\dot{Z}_2$ とし，$\dot{I}_0, \dot{I}_1, \dot{I}_2$ を零相，正相，逆相電流とすると，発電機各相電圧降下は

$\dot{v}_a = \dot{Z}_0\dot{I}_0 + \dot{Z}_1\dot{I}_1 + \dot{Z}_2\dot{I}_2$
$\dot{v}_b = \dot{Z}_0\dot{I}_0 + \alpha^2\dot{Z}_1\dot{I}_1 + \alpha\dot{Z}_2\dot{I}_2$
$\dot{v}_c = \dot{Z}_0\dot{I}_0 + \alpha\dot{Z}_1\dot{I}_1 + \alpha^2\dot{Z}_2\dot{I}_2$

よって，

$\dot{V}_0 = -\frac{1}{3}\left(\dot{v}_a + \dot{v}_b + \dot{v}_c\right) = -\frac{1}{3}3\dot{Z}_0\dot{I}_0 = -\dot{Z}_0\dot{I}_0$

$\dot{V}_1 = \dot{E}_a - \frac{1}{3}\left(\dot{v}_a + \alpha\dot{v}_b + \alpha^2\dot{v}_c\right)$
$= \dot{E}_a - \frac{1}{3}3\dot{Z}_1\dot{I}_1$

$\dot{V}_2 = -\frac{1}{3}\left(\dot{v}_a + \alpha^2\dot{v}_b + \alpha\dot{v}_c\right)$
$= -\frac{1}{3}3\dot{Z}_2\dot{I}_2$

以上から，三相交流発電機の基本式は

$\dot{V}_0 = \dot{E}_0 - \dot{Z}_0\dot{I}_0 = -\dot{Z}_0\dot{I}_0$
$\dot{V}_1 = \dot{E}_1 - \dot{Z}_1\dot{I}_1 = \dot{E}_a - \dot{Z}_1\dot{I}_1$
$\dot{V}_2 = \dot{E}_2 - \dot{Z}_2\dot{I}_2 = -\dot{Z}_2\dot{I}_2$

ここで，$\dot{E}_0, \dot{E}_1, \dot{E}_2$ は $\dot{E}_a, \dot{E}_b, \dot{E}_c$ の対称分

4.2.4 無負荷三相交流発電機の故障計算

[1] 一線地絡故障

a 端子で地絡故障発生。端子条件は

(i) $\dot{I}_b = \dot{I}_c = 0$

(ii) $\dot{V}_a = 0$

$\dot{I}_0 = \frac{1}{3}(\dot{I}_a + \dot{I}_b + \dot{I}_c) = \frac{1}{3}\dot{I}_a$
$\dot{I}_1 = \frac{1}{3}(\dot{I}_a + \alpha\dot{I}_b + \alpha^2\dot{I}_c) = \frac{1}{3}\dot{I}_a$,
$\dot{I}_2 = \frac{1}{3}(\dot{I}_a + \alpha^2\dot{I}_b + \alpha\dot{I}_c) = \frac{1}{3}\dot{I}_a$

$\dot{I}_0 = \dot{I}_1 = \dot{I}_2$ (iii)

(ii) 式に，発電機の基本式を代入

$\dot{V}_a = \dot{V}_0 + \dot{V}_1 + \dot{V}_2 = -\dot{Z}_0\dot{I}_0 + \dot{E}_a - \dot{Z}_1\dot{I}_1 - \dot{Z}_2\dot{I}_2$
$= \dot{E}_a - (\dot{Z}_0\dot{I}_0 + \dot{Z}_1\dot{I}_1 + \dot{Z}_2\dot{I}_2) = 0$

(iii) 式を代入

$\dot{I}_0 = \dot{I}_1 = \dot{I}_2 = \dfrac{\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2} = \frac{1}{3}\dot{I}_a$ だから

$$\dot{I}_a = \frac{3\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}$$

a 端子からみた発電機の内部インピーダンスは

$$\frac{\dot{E}_a}{\dot{I}_a} = \frac{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}{3}$$

健全相 b,c の端子電圧は，$\dot{V}_0, \dot{V}_1, \dot{V}_2$ から求める

$$\dot{V}_0 = -\dot{Z}_0\dot{I}_0 = -\frac{\dot{Z}_0\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}$$

$$\dot{V}_1 = \dot{E}_a - \dot{Z}_1\dot{I}_1 = \dot{E}_a - \frac{\dot{Z}_1\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2} = \frac{(\dot{Z}_0 + \dot{Z}_2)\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}$$

$$\dot{V}_2 = -\dot{Z}_2\dot{I}_2 = -\frac{\dot{Z}_2\dot{E}_a}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}$$

端子電圧は

$$\dot{V}_a = \dot{V}_0 + \dot{V}_1 + \dot{V}_2 = 0$$

$$\dot{V}_b = \dot{V}_0 + \alpha^2\dot{V}_1 + \alpha\dot{V}_2 = \frac{(\alpha^2 - 1)\dot{Z}_0 + (\alpha^2 - \alpha)\dot{Z}_2}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}\dot{E}_a$$

$$\dot{V}_c = \dot{V}_0 + \alpha\dot{V}_1 + \alpha^2\dot{V}_2 = \frac{(\alpha - 1)\dot{Z}_0 + (\alpha - \alpha^2)\dot{Z}_2}{\dot{Z}_0 + \dot{Z}_1 + \dot{Z}_2}\dot{E}_a$$

[2] 二線地絡故障

a 端子で地絡故障発生。端子条件は

(i) $\dot{V}_b = \dot{V}_c = 0$

(ii) $\dot{I}_a = 0$

(i) と $\begin{matrix} \dot{V}_b = \dot{V}_0 + \alpha^2 \dot{V}_1 + \alpha \dot{V}_2 = 0 \\ \dot{V}_c = \dot{V}_0 + \alpha \dot{V}_1 + \alpha^2 \dot{V}_2 = 0 \end{matrix}$

より $\dot{V}_0 = \dot{V}_1 = \dot{V}_2$

3 相交流発電機の基本式より

$\dot{E}_a - \dot{Z}_1 \dot{I}_1 = -\dot{Z}_0 \dot{I}_0 = -\dot{Z}_2 \dot{I}_2$ だから

$\dot{I}_0 = -\dfrac{\dot{E}_a - \dot{Z}_1 \dot{I}_1}{\dot{Z}_0}$, $\dot{I}_2 = -\dfrac{\dot{E}_a - \dot{Z}_1 \dot{I}_1}{\dot{Z}_2}$

$\dot{I}_a = \dot{I}_0 + \dot{I}_1 + \dot{I}_2 = 0$ だから,

$$\dot{I}_0 = \frac{-\dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

$$\dot{I}_1 = \frac{\dot{Z}_0 + \dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

$$\dot{I}_2 = \frac{-\dot{Z}_0}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

基本式より

$$\dot{V}_0 = -\dot{Z}_0 \dot{I}_0 = \frac{\dot{Z}_0 \dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a = \dot{V}_1 = \dot{V}_2$$

端子電圧は

$$\dot{V}_a = \dot{V}_0 + \dot{V}_1 + \dot{V}_2 = \frac{3 \dot{Z}_0 \dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

故障電流は

$$\dot{I}_b = \dot{I}_0 + \alpha^2 \dot{I}_1 + \alpha \dot{I}_2 = \frac{(\alpha^2 - \alpha)\dot{Z}_0 + (\alpha^2 - 1)\dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

$$\dot{I}_c = \dot{V}_0 + \alpha \dot{I}_1 + \alpha^2 \dot{I}_2 = \frac{(\alpha - \alpha^2)\dot{Z}_0 + (\alpha - 1)\dot{Z}_2}{\dot{Z}_0 \dot{Z}_1 + \dot{Z}_0 \dot{Z}_2 + \dot{Z}_1 \dot{Z}_2} \dot{E}_a$$

[3] 二線短絡故障

bc 端子で短絡故障発生。端子条件は

(i) $\dot{V}_b = \dot{V}_c$

(ii) $\dot{I}_a = 0$

(ii) $\dot{I}_b = -\dot{I}_c$

$\dot{I}_1 = \dfrac{\dot{E}_a}{\dot{Z}_1 + \dot{Z}_2}$, $\dot{V}_1 = \dfrac{\dot{Z}_2}{\dot{Z}_1 + \dot{Z}_2} \dot{E}_a$

$\dot{I}_b = \dfrac{-\mathrm{j}\sqrt{3}\dot{E}_a}{\dot{Z}_1 + \dot{Z}_2}$, $\dot{V}_a = \dfrac{2\dot{Z}_2}{\dot{Z}_1 + \dot{Z}_2} \dot{E}_a$

[4] 三線短絡故障

(i) $\dot{I}_a + \dot{I}_b + \dot{I}_c = 0$

(ii) $\dot{V}_a = \dot{V}_b = \dot{V}_c$

$\dot{V}_0 = -\dot{Z}_0 \dot{I}_0 = 0$

$\dot{V}_1 = 0$

$\dot{V}_2 = 0$

$\dot{I}_a = \dfrac{\dot{E}_a}{\dot{Z}_1}$