



基于模式分析的对称和非对称三相不接地系统故障测距算法研究

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摘要 基于模式分析理论,提出了不接地三相的两相短路、单相接地和两相接地故障测距的新算法. 计算机仿真和实际电网的模拟故障测距试验表明该算法有效.

关键词 不接地三相,故障测距,模式分析.

1 引言

文献[1—2]解决对称不接地三相的单相接地故障测距,算法建立在相坐标,运算量大. 作为研究的延续并结合实际课题,本文提出对称和非对称不接地三相的两相短路、单相接地和两相接地的模分量法故障测距新算法.

2 线路及其故障模型去耦

2.1 线路建模

线路建模可采用经典卡松公式,亦可利用近年提出的复数深度法^[3]. 本文研究的不接地三相线路结构如图1所示. 图1(a), (b)为对称线路. 图1(c)中相与两边相参数不相等,取其算术平均值. 对称线路传播矩阵记为

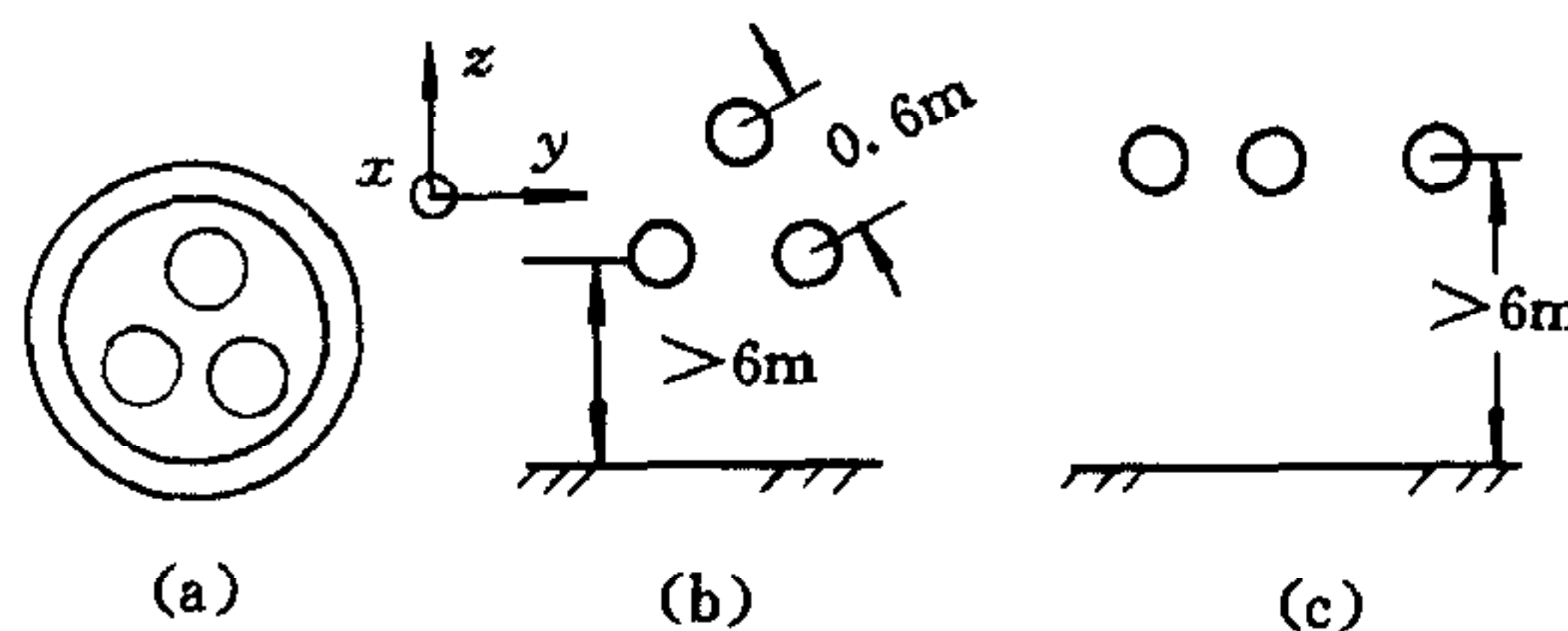


图1 线路结构

1) 邬大明现在昆明铁路机械学校.

$$P = ZY = \begin{bmatrix} z_s & \text{(对称)} \\ z_m & z_s \\ z_m & z_m & z_s \end{bmatrix} \begin{bmatrix} y_s & \text{(对称)} \\ y_m & y_s \\ y_m & y_m & y_s \end{bmatrix}, \quad (1)$$

非对称三相传播矩阵记为

$$P = ZY = \begin{bmatrix} z_{11} & \text{(对称)} \\ z_{12} & z_{22} \\ z_{13} & y_{12} & z_{11} \end{bmatrix} \begin{bmatrix} y_{11} & \text{(对称)} \\ y_{12} & y_{22} \\ y_{13} & y_{12} & y_{11} \end{bmatrix} = \begin{bmatrix} p_a & p_b & p_c \\ p_d & p_e & p_d \\ p_c & p_b & p_a \end{bmatrix}. \quad (2)$$

2.2 线路去耦

利用模式分析(亦称模分量法),相互耦合的相空间三相线路去耦为模量上相互独立的三根模量线.相模变换关系为

$$\dot{V}^p = S\dot{V}^m, \dot{I}^p = Q\dot{I}^m \text{ 和 } Z_{012} = s^{-1}ZQ, Y_{012} = Q^{-1}YS, \quad (3)$$

其中上角标 p 代表相空间, m 代表模空间, s 和 Q 分别为电压和电流变换矩阵. 每公里的模阻抗为 z_{012} 、模导纳为 Y_{012} , 模量上传播常数为 $\gamma_m = (Z_m Y_m)^{1/2}$, 特征阻抗为 $Z_{cm}, m=0, 1, 2$.

对称三相,若采用 Wedepohl 变换,即有

$$S = Q = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0 & -2 \\ 1 & -1 & 1 \end{bmatrix}, S^{-1} = Q^{-1} = \frac{1}{6} \begin{bmatrix} 2 & 2 & 2 \\ 3 & 0 & -3 \\ 1 & -2 & 1 \end{bmatrix}. \quad (4)$$

不对称三相,由其传播矩阵(2)可得传播常数之平方为

$$\gamma_0^2 = (p_a + p_c + p_e)/2 + \frac{1}{2}[(p_a + p_c - p_e)^2 + 8p_d p_b]^{1/2}, \quad (5a)$$

$$\gamma_1^2 = p_a - p_c, \quad (5b)$$

$$\gamma_2^2 = (p_a + p_c + p_e)/2 - \frac{1}{2}[(p_a + p_c - p_e)^2 + 8p_d p_b]^{1/2}. \quad (5c)$$

由此可得模电压和电流变换矩阵为

$$S = \begin{bmatrix} 1 & 1 & 1 \\ s_1 & 0 & s_2 \\ 1 & -1 & 1 \end{bmatrix}, Q = \begin{bmatrix} 1 & 1 & 1 \\ Q_1 & 0 & Q_2 \\ 1 & -1 & 1 \end{bmatrix}, \quad (6a)$$

其中

$$s_{1,2} = -\frac{p_a + p_c - p_e}{2p_b} \pm \left[\left(\frac{p_a + p_c - p_e}{2p_b} \right)^2 + \frac{2p_d}{p_b} \right]^{1/2}, \quad (6b)$$

$$Q_{1,2} = -2/s_{2,1}, \text{ 且 } s_1 s_2 = -2p_d/p_b, Q_1 Q_2 = -2p_b/p_d. \quad (6c)$$

2.3 故障模型去耦

不接地三相及其故障模型如图2(a), G_f 为过渡电导矩阵. 线路末端降压变之原端子诊信频率下的等值阻抗为 Z_L (图2(b)). G_f 用 $\dot{I}_{f,abc}$ 置换后,故障模型去耦为图2(c),且 $Y_L^{(0)} = 0, Y_L^{(1)} = Y_L^{(2)} = 1/Z_L$.

3 故障测距算法

本文算法是,离线于故障线路加诊信,若线路始端安装阻波器,亦可在线加音频诊信.

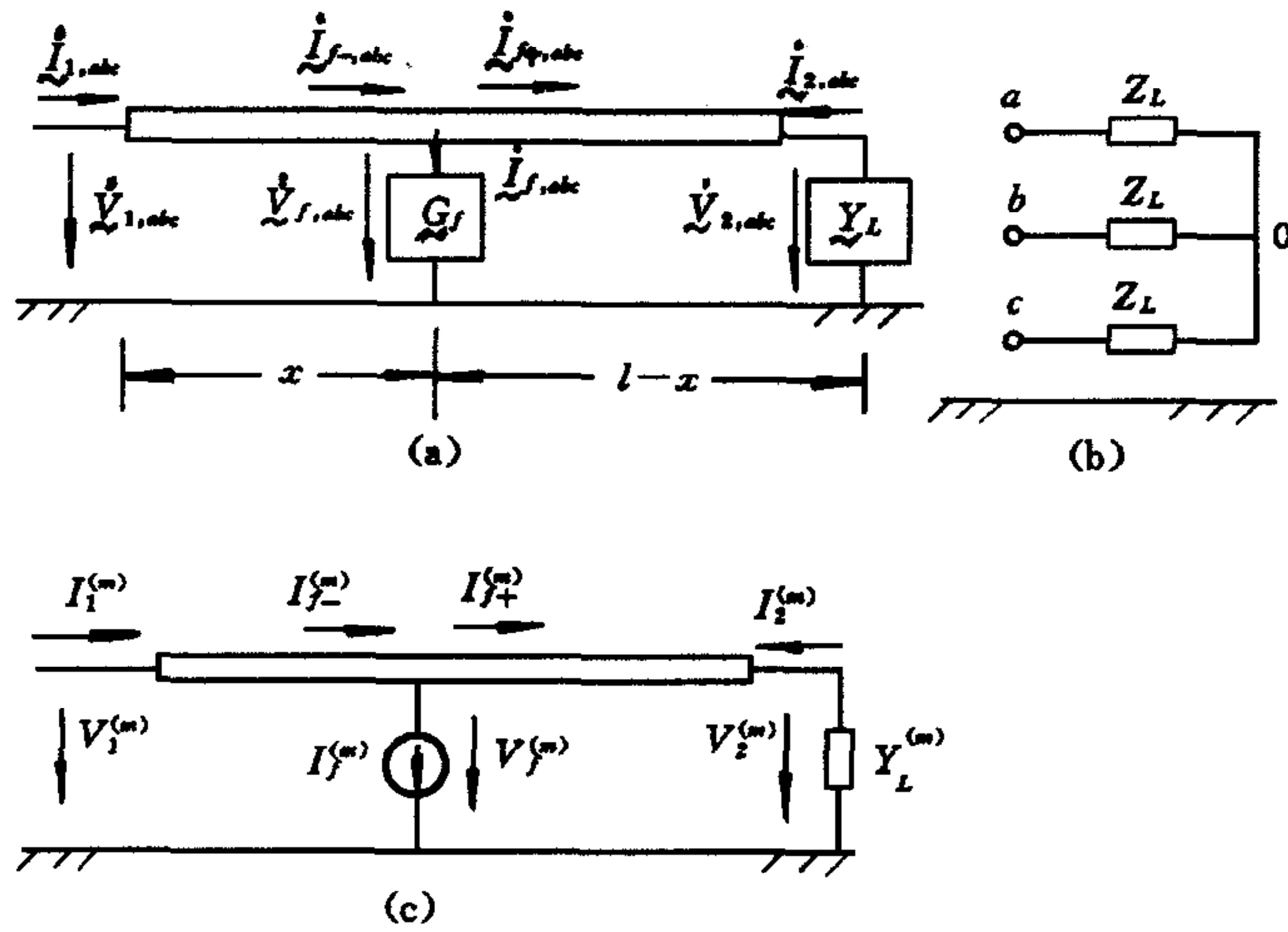


图2 故障模型解耦(m=0,1,2)

待电路稳定后检测线路始端电压电流 $V_{1,abc}$ 和 $I_{1,abc}$, 并借此迭代求解测距方程, 实现故障定位. 为排除线路上杂波干扰, 应具有数字滤波环节.

由图2(c)得

$$V_f^{(m)} = V_1^{(m)} \text{ch} \gamma_m x - Z_{cm} I_1^{(m)} \text{sh} \gamma_m x, m = 0, 1, 2, \tag{7a}$$

$$I_f^{(0)} = (I_1^{(0)} \text{ch} \gamma_0 l - V_1^{(0)} / Z_{c0} \text{sh} \gamma_0 l) / \text{ch} \gamma_0 (l - x), \tag{7b}$$

$$I_f^{(m)} = \frac{[Z_{cm} I_1^{(1)} - Z_L V_1^{(1)} / Z_{cm}] \text{sh} \gamma_m l + [Z_L I_1^{(1)} - V_1^{(1)}] \text{ch} \gamma_m l}{Z_{cm} \text{sh} \gamma_m (l - x) + Z_L \text{ch} \gamma_m (l - x)}, m = 1, 2, \tag{7c}$$

由图2(a)可得故障边界电压电流约束为

$$I_{f,abc} = G_f V_{f,abc}, \tag{8}$$

模量表示为

$$\text{col}(I_f^{(m)}, m = 0, 1, 2) = Q^{-1} G_f s \text{col}(V_f^{(m)}, m = 0, 1, 2). \tag{9}$$

由式(9)建构对称三相故障测距方程如表1.

表1 对称线路故障测距方程

类型	BC	A-G	BC-G
故障			
导纳矩阵 G_f	$\frac{1}{R_f} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{bmatrix}$	$\frac{1}{R_f} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$	$\frac{1}{R_f^2 + 2R_f R_d} \begin{bmatrix} 0 & 0 & 0 \\ 0 & R_f + R_d & -R_d \\ 0 & -R_d & R_f + R_d \end{bmatrix}$
过渡电阻 R_f	$[V_f^{(1)} - 3V_f^{(2)}] / (2I_f^{(1)})$	$\frac{1}{3} (\sum_{m=0}^2 V_f^{(m)}) / I_f^{(0)}$	$R_f + 2R_d \left \frac{1}{3} [2V_f^{(0)} - V_f^{(1)} - V_f^{(2)}] / I_f^{(0)} \right.$
测距方程	$I_m(R_f) = 0$	$I_m(R_f) = 0$	$I_m(R_f + 2R_d) = 0$

对于非对称三相, 相模变换采用式(6), 且考虑 $|Z_L|$ 比 $|Z_{cm}|$ 大十多倍, 令 $Y_L^{(m)} = 0, m = 0, 1, 2$, 则

$$I_f^{(m)} = (I_1^{(m)} \operatorname{ch} \gamma_m l - V_1^{(m)} / Z_{cm} \operatorname{sh} \gamma_m l) / \operatorname{ch} \gamma_m (l - x), m = 0, 1, 2 \quad (10)$$

BC 和 A-G 故障定位方程为

$$I_m \left(\frac{(s_1 - 1)V_f^{(0)} + V_f^{(1)} + (s_2 - 1)V_f^{(2)}}{I_f^{(1)}} \right) = 0, \quad I_m \left[\frac{\sum_{m=0}^x V_f^{(m)}}{I_f^{(1)}} \right] = 0. \quad (11)$$

BC-G 故障的诊断方程为

$$D(x) = \operatorname{col}(D_m(x), m = 1, 2, 3) = \operatorname{col}(I_m(F_m(x), m = 1, 2, 3)) = 0, \quad (12)$$

其中 $x = \operatorname{col}(x \quad R_f \quad R_d)$, 且

$$F_1(x) = z_a V_f^{(0)} + z_b V_f^{(1)} + z_c V_f^{(2)} - 2(\theta_1 - \theta_2)(R_f^2 + 2R_f R_d) I_f^{(0)},$$

$$F_2(x) = z_d V_f^{(0)} + z_e V_f^{(1)} + z_f V_f^{(2)} - 2(\theta_1 - \theta_2)(R_f^2 + 2R_f R_d) I_f^{(1)},$$

$$F_3(x) = z_g V_f^{(0)} + z_h V_f^{(1)} + z_i V_f^{(2)} - 2(\theta_1 - \theta_2)(R_f^2 + 2R_f R_d) I_f^{(2)},$$

其中

$$z_a = (2s_1 - Q_2)R_f + (2 + Q_2)(s_1 - 1)R_d, z_b = Q_2 R_f + (2 + Q_2)R_d,$$

$$z_c = (2s_2 - Q_2)R_f + (2 + Q_2)(s_2 - 1)R_d, z_d = (Q_2 - Q_1)R_f + (Q_1 - Q_2)(s_1 - 1)R_d,$$

$$z_e = (Q_1 - Q_2)(R_f + R_d), z_f = (Q_2 - Q_1)R_f + (Q_1 - Q_2)(s_1 - 1)R_d,$$

$$z_g = (Q_1 - 2s_1)R_f - (2 + Q_1)(s_1 - 1)R_d, z_h = -Q_1 R_f - (2 + Q_1)R_d,$$

$$z_i = (Q_1 - 2s_2)R_f - (2 + Q_1)(s_2 - 1)R_d.$$

方程(12)为三元非线性方程, 可选用修正的 NR 法. 在满足线长小于四分之一诊信波长条件下, 从(0.5l, 0, 0)开始迭代7, 8次即可收敛($\epsilon \leq 10^{-2} \text{m}$).

对于平行线路, 无论是输电线还是配电馈线, 无论对称还是不对称, 若有代价实现近远端之间同步采样, 则一切横向故障的测距方程可为算式

$$x = 0.5 \gamma_m^{-1} \ln \frac{A^{(m)} - B^{(m)}}{A^{(m)} + B^{(m)}}, m = 0, 1, \dots, n - 1, \quad (13)$$

其中

$$A^{(m)} = Z_{cm} I_2^{(m)} \operatorname{ch} \gamma_m l - V_2^{(m)} \operatorname{sh} \gamma_m l + Z_{cm} I_1^{(m)}, \quad (14a)$$

$$B^{(m)} = V_2^{(m)} \operatorname{ch} \gamma_m l - Z_{cm} I_2^{(m)} \operatorname{sh} \gamma_m l - V_1^{(m)}, \quad (14b)$$

单相接地选零模, 其余选空间模.

4 算例

l=20km 的某三相对称线路故障测距结果见表2.

表2 对称三相故障测距的计算机仿真

类型	假设故障		诊断结果	
	x(km)	R(Ω)	x(km)	R(Ω)
BC	5	10	5010	9.9
		100	4995	99.5
	10	10	10010	9.9
		100	9974	99.1
	15	10	14998	9.9
		100	14998	99.8

续表2 对称三相故障测距的计算机仿真

类型	假设故障			诊断结果	
	$x(\text{km})$	$R(\Omega)$		$x(\text{km})$	$R(\Omega)$
A-G	5	10		5015	10.0
		100		5015	100.0
	10	10		10023	10.0
		100		10034	99.8
	15	10		15039	10.3
		100		15035	100.1
BC-G	$x(\text{km})$	$R_f(\Omega)$	$R_d(\Omega)$	$x(\text{m})$	R_f+2R_d
	5	10	10	5007	30.6
		100	100	5018	299.3
	10	10	10	10034	30.2
		100	100	10048	299.8
	15	10	10	15053	27.7
		100	100	14971	300.1

5 结 论

1)采用分布参数模型,为精确定位故障奠定基础;2)采用模量分离解法,运算量小;3)线长小于四分之一波长时,不存在伪根.

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A STUDY ON ALGORITHMS OF FAULT LOCATION FOR (A) SYMMETRIC UNGROUNDED 3-PHASE SYSTEM BASED ON MODAL ANALYSIS THEORY

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Abstract Based on distributed parameter circuit theory and modal analysis theory, a number of new algorithms of line-to-line, single-line-to-ground & double-line-to-ground fault location for (a) symmetric ungrounded 3-phase system are proposed in accordance with the characteristic of the system. Simulation of fault location by computer and tests on the fault model simulation lines show that the algorithms presented in the paper are effective.

Key words Symmetric 3-phase system, asymmetric 3-phase, ungrounded system, fault location, modal analysis.