一种用于线路开断修改节点阻抗矩阵的简便方法

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【摘要】 本文推导出线路开断时一次性修改节点阻抗矩阵的公式。计算简便、易于编程。它已用于故障计算程序中。

【关键词】 纵向故障　节点阻抗矩阵　互感线路

前言

计算电力系统复杂故障时, 获取故障端口阻抗矩阵十分重要, 它由故障前节点阻抗矩阵中元素计算得到[1]。当计算纵向故障时, 或考虑继电保护相继动作时, 必须求取线路开断后的节点阻抗矩阵。以往程序中对此处理为: 先切除欲开断的线路, 再追加一条树支[2], 计算公式、编程较复杂, 尤其是互感线路。所以一次性修改开断后的节点阻抗矩阵显得有意义。本文下面分别推导线路首、末端开断后修改节点阻抗矩阵的公式, 并予以分析。

1　有互感线路首端开断

设线路开断前网络节点数为 n, 且断口处在某互感支路组(互感支路条数为 $m+1$) 中 $I-J$ 线路的首端(I 节点侧), 则互感支路组支路方程为

$$\begin{bmatrix} U_{PQ} \\ U_{IJ} \end{bmatrix} = \begin{bmatrix} Z_{PQ-PQ} & Z_{PQ-IJ} \\ Z_{IJ-PQ} & Z_{IJ-IJ} \end{bmatrix} \begin{bmatrix} I_{PQ} \\ I_{IJ} \end{bmatrix} \tag{1}$$

或

$$\begin{bmatrix} I_{PQ} \\ I_{IJ} \end{bmatrix} = \begin{bmatrix} Y_{PQ-PQ} & Y_{PQ-IJ} \\ Y_{IJ-PQ} & Y_{IJ-IJ} \end{bmatrix} \begin{bmatrix} U_{PQ} \\ U_{IJ} \end{bmatrix} \tag{2}$$

式中

$$\begin{bmatrix} Y_{PQ-PQ} & Y_{PQ-IJ} \\ Y_{IJ-PQ} & Y_{IJ-IJ} \end{bmatrix} = \begin{bmatrix} Z_{PQ-PQ} & Z_{PQ-IJ} \\ Z_{IJ-PQ} & Z_{IJ-IJ} \end{bmatrix}^{-1}$$

$$Z_{PQ-PQ} = \begin{bmatrix} z_{p1q1-p1q1} & z_{p1q1-p2q2} & \cdots & z_{p1q1-pmqm} \\ z_{p2q2-p1q1} & z_{p2q2-p2q2} & \cdots & z_{p2q2-pmqm} \\ \vdots & & & \\ z_{pmqm-p1q1} & z_{pmqm-p2q2} & \cdots & z_{pmqm-pmqm} \end{bmatrix} \qquad Z_{PQ-IJ} = \begin{bmatrix} z_{p1q1-IJ} \\ z_{p2q2-IJ} \\ \vdots \\ z_{pmqm-IJ} \end{bmatrix}$$

$$Z_{IJ-PQ} = Z_{PQ-IJ}$$

$$Z_{IJ-IJ} = z_{IJ-IJ}$$

$P-Q$ 为等值互感支路, $I-J$ 为断口所在支路。假设在断口处串联一对符号相反的阻抗 $-z$ 和 z, 见图 1。网络新增两个节点: $(n+1)$、$(n+2)$, 其中$(n+1)$ 节点是断口处开断后线路侧新增节点; $(n+2)$ 节点是为推导公式方便虚设节点。下面讨论新增节点对其它节点的互阻抗及自阻抗。

1.1　$(n+1)$ 节点对 1～ n 节点的互阻抗和自阻抗

$(n+1)$ 节点与 I 节点对外电路完全等效, 有

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$$Z_{(n+1),k} = Z_{i,k} \qquad k = 1, \cdots, n \quad (3)$$

$$Z_{n+1,n+1} = Z_{i,i}$$

1.2 $(n+2)$ 节点对 1～$(n+1)$ 节点互阻抗和自阻抗

$(n+2)$ 节点对其它节点的互阻抗及自阻抗是在 k 节点注入单位电流, 流出 I 侧电流 I_k 乘以 z 加上 $Z_{i,k}$, 见图 1。有

$$\frac{U_i - U_{n+a}}{-z} = I_k \quad \text{即}$$

$$Z_{n+2,k} = Z_{i,k} + zI_k \quad (4)$$

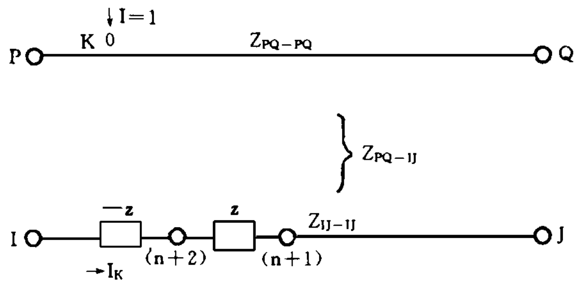


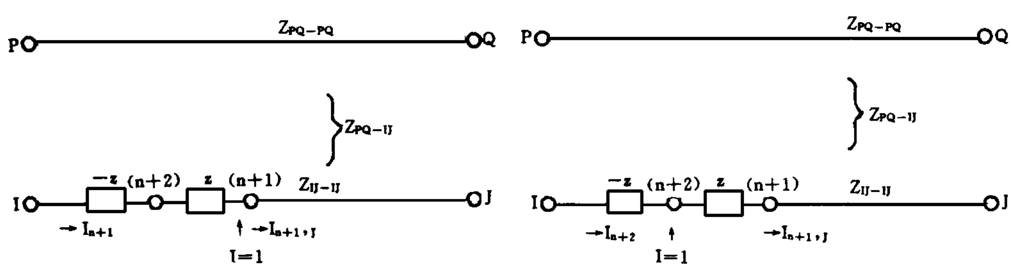
图 1 I 侧开断示意图

式中 $I_k = Y_{IJ-IJ}(Z_{i,k} - Z_{j,k}) + Y_{IJ-PQ}(Z_{P,K} - Z_{Q,K}) \qquad k = 1, \cdots, n \qquad (5)$

$$Y_{IJ-PQ}(Z_{P,K} - Z_{Q,K}) = \left(y_{ij-p1q1}\ y_{ij-p2q2} \cdots y_{ij-pmqm}\right)\begin{bmatrix} Z_{p1,k} - Z_{q1,k} \\ Z_{p2,k} - Z_{q2,k} \\ \vdots \\ Z_{pm,k} - Z_{qm,k} \end{bmatrix}$$

当 $k = n+1$ 时, 见图 2a, 由 $(n+1)$ 节点注入单位电流, I 侧流出电流 I_{n+1} 为

$$I_{n+1} = I_{n+1,J} - 1$$



(a) $(n+1)$ **节点注入单位电流** (b) $(n+2)$ **节点注入单位电流**

图 2 $k > n$ 时电流分布图

而 $I_{n+1,J}$ 即为 I 节点注入单位电流时的 I_i, 有

$$I_{n+1} = I_i - 1$$

$$= Y_{IJ-IJ}(Z_{ii} - Z_{ji}) + Y_{IJ-PQ}(Z_{Pi} - Z_{Qi}) - 1 \qquad (6)$$

同理, 当 $k = n+2$ 时, 见图 2b, 有

$$I_{n+2} = I_{n+1,J} - 1$$

$$= Y_{IJ-IJ}(Z_{n+2,n+1} - Z_{n+2,j}) + Y_{IJ-PQ}(Z_{n+2,P} - Z_{n+2,Q}) - 1 \qquad (7)$$

1.3 在 $(n+1)$ 与 $(n+2)$ 追加支路阻抗为 $-z$ 的链支, 以断开线路 $I-J$ 的 I 侧

$$ZL_k = Z_{n+1,k} - Z_{n+2,k} = Z_{j,k} - Z_{j,k} - zI_k = -zI_k \qquad k = 1, \cdots, (n+1)$$

$$ZLL = Z_{n+1,n+1} + Z_{n+2,n+2} - 2Z_{n+1,n+2} - z$$

$$= z(I_i + I_{n+2} - 2I_{n+1} - 1)$$

代入式 6 和 7 及 $I_{n+1} = I_i - 1$

$$ZLL = z(I_{n+2} - I_{n+1})$$

$$= z^2\left[Y_{IJ-IJ}(I_{n+1} - I_j) + Y_{IJ-PQ}(I_P - I_Q)\right]$$

开断后的节点阻抗矩阵 Z ′为

$$Z_{s,t}'= Z_{s,t} - \frac{ZL_s \cdot ZL_t}{ZLL}$$

$$= Z_{s,t} - \frac{I_s \cdot I_t}{Y_{IJ-IJ}(I_{n+1} - I_j) + Y_{IJ-PQ}(I_P - I_Q)} \quad s,t = 1,\cdots,(n+1) \qquad (8)$$

式中 I_s, I_t 由式5和式6计算。可见一次性修改公式简便,易于编程。

2　有互感线路末端开断

同 I 侧开断类似,在 J 侧串联 $-z, z$,增加 $(n+1)$, $(n+2)$ 两节点,见图3。

2.1　$(n+1)$ 节点对1～n 节点互阻抗,自阻抗

$$Z_{n+1,k} = Z_{j,k} \qquad k = 1,\cdots,n$$

$$Z_{n+1,n+1} = Z_{j,j} \qquad (9)$$

2.2　$(n+2)$ 节点对其它节点互阻抗,自阻抗

定义 I_k 为 k 节点注入单位电流,流出 j 侧的电流,见图3。有

$$Z_{n+2,k} = Z_{j,k} + zI_k \qquad (10)$$

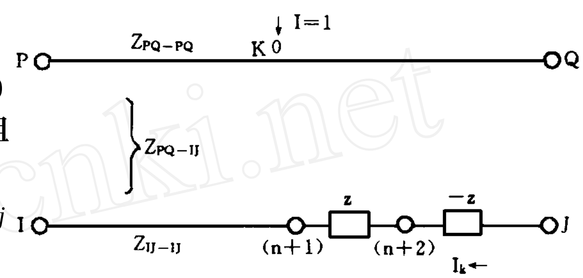


图3　J 侧开断示意图

由于 I_k 与 I_{IJ} 方向相反,则

$$I_k = -Y_{IJ-IJ}(Z_{i,k} - Z_{j,k}) - Y_{IJ-PQ}(Z_{P,K} - Z_{Q,K})$$

$$= Y_{IJ-IJ}(Z_{i,k} - Z_{j,k}) - Y_{IJ-PQ}(Z_{P,K} - Z_{Q,K})$$

$$k = 1,\cdots,n \qquad (11)$$

$k = n+1$ 时,类似 I 侧开断,有

$$I_{n+1} = I_j - 1 = -Y_{IJ-IJ}(Z_{i,j} - Z_{j,j}) - Y_{IJ-PQ}(Z_{p,j} - Z_{Q,j}) - 1$$

$$= Y_{IJ-IJ}(Z_{j,j} - Z_{i,j}) - Y_{IJ-PQ}(Z_{p,j} - Z_{Q,j}) - 1 \qquad (12)$$

$$I_{n+2} = -Y_{IJ-IJ}(Z_{n+2,i} - Z_{n+2,n+1}) - Y_{ij-PQ}(Z_{n+2,P} - Z_{n+2,Q}) - 1 \qquad (13)$$

2.3　在 $(n+1)$、$(n+2)$ 间追加阻抗为 $-z$ 的链支

$$ZL_k = Z_{n+1,k} - Z_{n+2,k} = -zI_k \qquad k = 1,\cdots,(n+1)$$

$$ZLL = Z_{n+1,n+1} + Z_{n+2,n+2} - 2Z_{n+2,n+1} - z$$

$$= z(I_j + I_{n+2} - 2I_{n+1} - 1)$$

代入 $I_{n+1} = I_j - 1$ 及式12和式13得

$$ZLL = z(I_{n+2} - I_{n+1})$$

$$= z^2[-Y_{IJ-IJ}(I_i - I_{n+1}) - Y_{IJ-PQ}(I_P - I_Q)]$$

$$= z^2[Y_{IJ-IJ}(I_{n+1} - I_i) - Y_{IJ-PQ}(I_P - I_Q)]$$

断开后的节点阻抗矩阵 Z ′为

$$Z_{s,t}' = Z_{s,t} - \frac{ZL_s \cdot ZL_t}{ZLL}$$

$$= Z_{s,t} - \frac{I_s \cdot I_t}{Y_{IJ-IJ}(I_{n+1} - I_i) - Y_{IJ-PQ}(I_P - I_Q)} \quad s,t = 1,\cdots,(n+1) \qquad (14)$$

式中 I_s, I_t 由式11或式12计算。

将 I 侧开断公式5、6、8与 J 侧开断公式11、12、14比较,可以看出: J 侧开断时,只需将 I 侧

开断公式中 I、J 互换, 且将公式中 Y_{IJ-PQ} 取负即可。这也证实了作者以前采用先切除互感支路 $I-J$, 再追加 I, $(n+1)$ 互感树支, 以开断 J 侧; 追加 $(n+1)$、J 互感树支, 以开断 I 侧, 共用一套计算公式, I、J 互换, Y_{IJ-PQ} 取反的结论。究其原因, 是 I 和 $P(p_1, p_2, \cdots, p_m)$ 同名端, J 和 $Q(q_1, q_2, \cdots, q_m)$ 同名端, 当 I, J 互换时, 理应 P、Q 也互换才能保证极性。而 P、Q 不互换, 可通过 Y_{IJ-PQ} 取负号达到计算正确的目的。

3 无互感支路的开断

无互感支路为有互感支路的特例, 即 $Y_{IJ-PQ}=0$, $Y_{IJ-IJ}=\frac{1}{z_{IJ-IJ}}$, z_{IJ-IJ} 为断口所在支路阻抗。

I 侧开断计算公式

$$I_k=\frac{Z_{i,k}-Z_{j,k}}{z_{IJ-IJ}} \qquad k=1, \cdots, n \tag{15}$$

$$I_{n+1}=I_i-1=\frac{Z_{ii}-Z_{ji}-z_{IJ-IJ}}{z_{IJ-IJ}} \tag{16}$$

I 侧开断后节点阻抗矩阵 Z' 为

$$Z_{s,t}'=Z_{s,t}-\frac{I_s \cdot I_t}{I_{n+1}-I_j} \cdot z_{IJ-IJ} \qquad s, t=1, \cdots, (n+1) \tag{17}$$

当 J 侧开断时, 只需将式 15、16、17 中 I, J 互换即可。

4 结论

本文推导的线路开断一次性修改节点阻抗矩阵的计算公式, 对纵向故障、线路相继动作及包含断线的复杂故障计算有一定意义, 具有公式简洁, 易于编程的特点。

参考文献

1 王春, 柳焕章. 电力系统不对称状态计算. 中国电机工程学报, 1993. 6
2 陈辉华, 余乐. 继电保护整定用短路和分支系数计算程序. 1989. 7
3 电力系统故障分析. 华北电力学院主编. 水利电力出版社, 1984. 6, P261～273

RELAY

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CONTENTS AND ABSTRACTS (Partial)

THEORETICAL STUDY AND CALCULATION

The influence of distributed Capacitance of UHV distant transmission line to current differential protection is analyzed and the corresponding capacitance current compensation scheme is presented in this paper. The scheme is simple and practical, not only increasing security during short- circuit beyond protected zone but also improving sensitivity at fault within the protected zone.

Key words: Distributed capacitance Current differential protection Capacitance current compensation

A new concept of whole line fault high speed clearing protection is introduced according to the structure of urban distribution power system and requirement of power supplying. Feasibility study on this protection is carried out. A practical implement scheme of this protection, which measures the electrical signal on both sides of the protected line is presented.

Key words: Distribution power system Line protection High speed relay Feasibility

The computating formulas for modifying bus- impedance matrix in open circuit state are derived in this paper. They are convenient to calculate and easily programmed. They have been used in fault- calculating program.

Key words: Open circuit fault Bus- impedance matrix Line with zero- sequence mutual impedance

A new method of deriving magnetization curve of transformer- - the approximating function optimization is presented to meet the requirement of using magnetic flux characteristic to discriminate the energization inrush current in transformer. Actual calculation shows that the magnetization curve derived by the method is of high accuracy and its error is within 1%, thus it can meet the requirement of transformer differential protection.

Key words: Power transformer Magnetization curve Energization inrush

NEW TECHNICAL RESEARCH AND APPLICATION

A microcomputer protection and supervisory control system for substation by using the two- model redundancy technology is briefly described. With reference to the system, the reliability of the two- model redundancy system is analyzed and effect of fault- tolerant technique in improving the reliability of the system is also discussed.

Key words: Redundancy Fault- tolerant Substation Microcomputer supervisory control

A new method to realize the digital impedance relay based on microcomputer is described in this paper. The new method utilizes ANN (artificial neural network) and is available for all kinds of relay characteristics which are used in power system. Some examples are used to test the new algorithm and the results show the algorithm performs well.

Key words: ANN Impedance relay Distance protection

A single phase earthed protection of generator stator winding is presented in this paper. It is realized by de-