

# 基于小波分析的弱电源侧暂态量选相方案

李峰, 焦彦军, 马静

(华北电力大学电力系统保护与动态安全监控教育部重点实验室, 河北保定 071003)

**摘要:** 针对输电线路弱馈侧选相问题, 在分析各种故障类型模分量特征的基础上, 通过对输电线路各种短路故障情况进行分析, 提出了弱电源侧故障选相原理和算法, 该原理基于模量小波分析能量特征。并经过仿真计算和数据的验证表明该选相原理的正确性, 能满足现场弱馈选相的要求, 从而有效地解决了弱电源侧的选相问题。

**关键词:** 小波分析; 弱电源; 故障选相; 暂态量

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## 0 引言

目前, 国内数字式高压线路保护主要采用突变量选相和稳态量选相相结合的方法。对于弱电源侧保护, 在线路发生故障后, 能感受到的电流仅为零序电流, 因此靠电流突变量和电流量序分量进行选相很困难。以往通常利用电压故障分量进行选相, 但发现弱电源侧在保护起动一段时间以后, 不能准确地提取故障分量, 从而使得利用电压故障分量选相元件不能正确工作。

本文提出的弱馈侧选相, 选相判据用到的是模量小波分析能量特征, 避免使用突变量, 所以该选相判据的准确性较高, 能有效地解决弱电源侧的选相问题。ATP仿真结果验证了该选相判据的选相准确性<sup>[1]</sup>。

## 1 故障特征分析

当系统发生任何类型故障时各点的电流、电压均可分解为非故障分量和故障分量。根据叠加原理, 系统中故障分量可由在故障点叠加等效电源来求解。等效电源由故障点故障前电压及故障类型决定。由线性变换理论可知, 对故障分量网络仍可采用模分量进行分析。由于各模量相互独立, 因此当从故障边界条件中推导出各模量等效电源后, 就可分别求解各模量的独立网络, 以获得保护装置处各模故障分量<sup>[5]</sup>。

当采用克拉克模变换时, 其转换矩阵为

$$[S] = \frac{1}{3} \begin{bmatrix} 1 & 0 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \\ -1/2 & -\sqrt{3}/2 & 1 \end{bmatrix} \quad (1)$$

$$[S]^{-1} = \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix} \quad (2)$$

在故障附加网络中, 设故障点的故障前各相电压为  $U_A, U_B, U_C$ ;  $Z_1, Z_2, Z_0$  分别为从故障点看入的模量综合阻抗, 且假设  $Z_1 = Z_2$ 。

下面以 A 相为特殊相, 对各种类型故障的特征进行分析。

克拉克模变换:

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix} \quad (3)$$

1) A 相接地短路的边界条件为  $E_A = U_A, I_B = 0, I_C = 0$ ,

由 Clark 模变换得:

$$\begin{cases} E_1 + E_0 = 3E_A \\ I_1 = 2I_0 \\ I_0 = 0 \end{cases} \quad (4)$$

再利用模网络中基本关系式

$$\begin{cases} E_1 = Z_1 I_1 \\ E_2 = Z_2 I_2 \\ E_0 = Z_0 I_0 \end{cases} \quad (5)$$

可求得模量等效电源

$$\begin{cases} E_1 = 6Z_1 E_A / (2Z_1 + Z_0) \\ E_2 = 0 \\ E_0 = 3Z_0 E_A / (2Z_1 + Z_0) \end{cases} \quad (6)$$

2) BC 两相接地短路的故障边界条件  $E_B = U_B, E_C = U_C, I_A = 0$ 。

由克拉克模变换可得

$$\begin{cases} E_2 = 3U_A e^{-j90} \\ 2E_0 - E_1 = -3U_A \\ I_1 + I_0 = 0 \end{cases} \quad (7)$$

可求得模量等效电源

$$\begin{cases} E_1 = 3Z_1 U_A / (2Z_0 + Z_1) \\ E_2 = 3e^{-j90} U_A \\ E_0 = -3Z_0 U_A / (2Z_0 + Z_1) \end{cases} \quad (8)$$

3) BC两相短路的故障边界条件为  $E_B - E_C = U_{BC}$ ,  $I_B = -I_C$ ,  $I_A = 0$ 。

由克拉克模变换可得

$$\begin{cases} I_1 = 0 \\ I_0 = 0 \\ E_2 = 3U_A e^{-j90} \end{cases} \quad (9)$$

可求得模量等效电源

$$\begin{cases} E_1 = 0 \\ E_2 = 3U_A e^{-j90} \\ E_0 = 0 \end{cases} \quad (10)$$

4) 三相接地电源的故障边界条件  $E_A = U_A$ ,  $E_B = U_B$ ,  $E_C = U_C$ 。

由克拉克模变换可求得模量等效电源

$$\begin{cases} E_1 = 3E_A \\ E_2 = 3e^{-j90} E_A \\ E_0 = 0 \end{cases} \quad (11)$$

以上分析了以 A 相为故障特殊相,模变换也是以 A 相为基准的情况。当故障是以 B 相或 C 相为特殊相时,则采用以 B 相或 C 相为基准的模变换将具有与前述完全对应的结果。

## 2 小波分析

空间序列  $\{V_j\}_{j \in \mathbf{Z}}$ , 存在函数  $\psi(t)$ ,  $V_0$ , 使它的整数平移系  $\{\psi(2^{-j/2}t - k) \mid k \in \mathbf{Z}\}$  构成  $V_j$  的规范正交基, 称  $\psi(t)$  为尺度函数, 定义为  $\psi(t) = 2^{-j/2} \psi(2^{-j}t - k)$   $j, k \in \mathbf{Z}$ 。

$\psi_k = 2^{-j/2} \psi(2^{-j}t - k)$   $j, k \in \mathbf{Z}$  函数系  $\{\psi_k(t) \mid k \in \mathbf{Z}\}$  是正交。

设以  $V_j$  表示图 1 中分解中的低频部分  $A_j$ ,  $W_j$  表示分解中的高频部分  $D_j$ , 则  $W_j$  是  $V_j$  在  $V_{j+1}$  中的正交补, 即:

$$V_j \otimes W_j = V_{j+1} \quad j \in \mathbf{Z}$$

显然

$$V_j \otimes W_j \otimes W_{j+1} \otimes \dots \otimes W_{j+m} = V_{j+m}$$

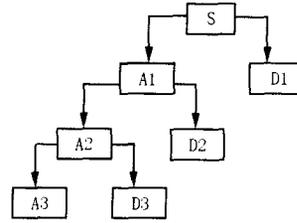


图 1 多尺度分析结构图

Fig 1 Structure of multiple-dimension analysis

则多分辨分析的子空间  $V_0$  可以用有限个子空间来逼近, 即有

$$V_0 = V_1 \otimes W_1 = V_2 \otimes W_2 \otimes W_1 = \dots V_N \otimes W_N \otimes W_{N-1} \otimes \dots \otimes W_2 \otimes W_1$$

## 3 利用小波分析构成选相原理

由于保护处各模故障分量完全由故障点叠加的等效电源来决定, 因此各独立模量网络中由故障产生的暂态电流或电压量也完全由此等效电源来决定。而根据以上分析可知, 不同的故障类型所对应的各模量网络中等效电源也各不相同, 从而导致暂态电流或电压量出现特征差异。

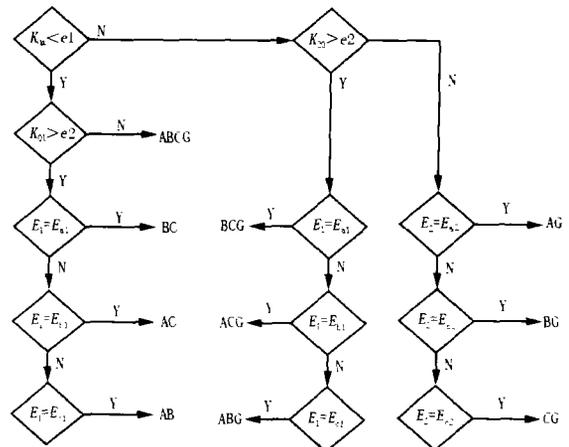


图 2 选相判据流程图

Fig 2 Flow chart of fault phase selector

小波分析是时频分析, 在选择频段上比较灵活, 因此对以 A, B, C 相为基准的各模量经 db3 小波分析后的第二尺度在固定的时间窗内进行求取能量  $E$  (经多次仿真发现信号第二尺度所能达到的选相效果最佳)。

在时刻  $n$ , 固定时间窗  $N$  内的能量公式如下:

$$E_i(n, T) = \sum_{k=n-M}^n \hat{I}_i^2(k, T) T \quad K = n - M \quad (12)$$

式中  $M$  为窗口中采样数;  $T$  为步长时间。

根据各暂态电流模量小波分析的第二尺度能量,通过比较其大小选择故障相(以 A 相为基准的模一量),流程图见图 2。

令:

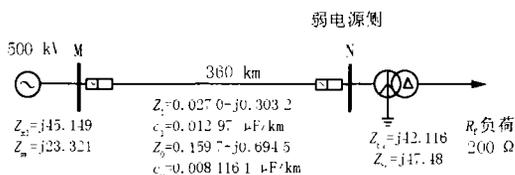
$$E_1 = \min\{E_{a1}, E_{b1}, E_{c1}\}, E_2 = \min\{E_{a2}, E_{b2}, E_{c2}\}, E_{\max} = \max\{E_{a1}, E_{b1}, E_{c1}, E_{a2}, E_{b2}, E_{c2}, E_0\},$$

$$K_{01} = E_0 / E_1, K_{20} = E_2 / E_0, K_{0m} = E_0 / E_m,$$

其中判据中的两个门限值为:  $e_1 = 0.001, e_2 = 0.03$ 。

### 4 仿真参数和结果

系统仿真模型如图 3 所示,其中 N 侧为线路保护弱电源侧。



注:接地故障点  $d_1, d_2, d_3$  分别位于 MN 线路的 10%, 50%, 90% 处,过渡电阻分别为 0、100、200、400。

图 3 系统仿真模型

Fig 3 Model of system simulation

母线 M 端背后的系统参数为  $Z_{m1} = j45.149$ ,  $Z_{m0} = j23.321$ , 弱馈侧变压器参数为  $Z_{b1} = j42.116$ ,  $Z_{b0} = j47.48$ ,  $R_f$  为负荷阻抗,线路为 360 km, 500 kV 的超高压输电线路,采用的耦合参数为  $R_1 = 0.0270 / \text{km}$ ,  $l_1 = 0.3032 / \text{km}$ ,  $R_0 = 0.1597 / \text{km}$ ,  $l_0 = 0.6945 / \text{km}$ 。

选取的采样频率为  $f = 200 \text{ kHz}$ , 负荷阻抗  $R_f$  取 200, 选取第 2 个尺度, 取能量窗宽  $N$ 。得不同故障类型、不同过渡电阻、不同故障位置时的选相结果。

选相中模分量的小波分析如图 4~图 7 (以 A 相 50% 处金属性接地故障为例, 模变换以 A 相为基准), 选相结果见表 1~表 3。

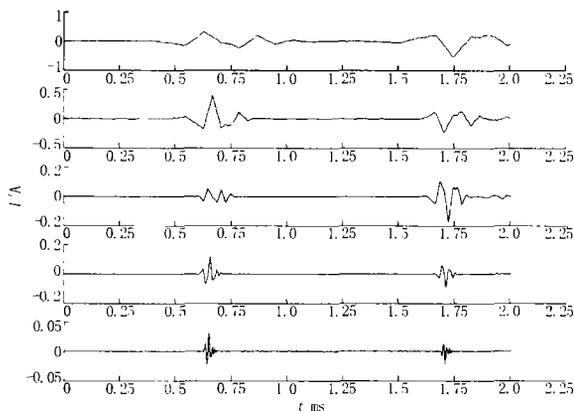


图 4 模 0 的小波分析五尺度

Fig 4 Wavelet analysis five dimensions of modular 0

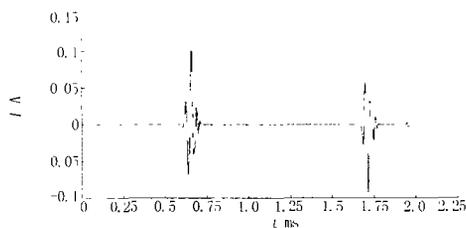


图 5 模 0 的第二尺度

Fig 5 Second dimension of modular 0

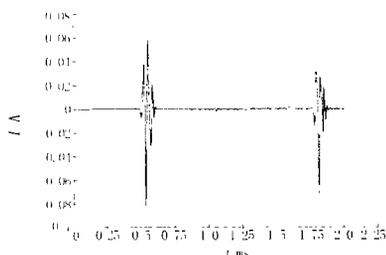


图 6 模 1 的第二尺度

Fig 6 Second dimension of modular 1

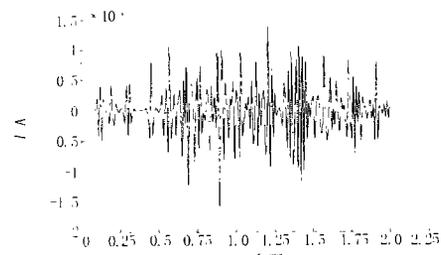


图 7 模 2 的第二尺度

Fig 7 Second dimension of modular 2

表 1 180 km 处不同故障类型的选相结果 ( $R = 0$ )

Tab 1 Result of fault phase selecting under different faults ( $L = 180 \text{ km}, R = 0$ )

故障类型	$E_1$	$E_2$	$E_{\max}$	$E_0$	$K_{0m}$	$K_{01}$	$K_{20}$	选相结果
AG	0.0428	$3.0814 \times 10^{-4}$	0.2867	0.2867	1	6.7068	0.0011	AG
BC	$9.535 \times 10^{-5}$	$3.230 \times 10^{-3}$	$1.292 \times 10^{-4}$	$9.616 \times 10^{-5}$	$7.443 \times 10^{-9}$	1.0085	$3.358 \times 10^{-7}$	BC
ABG	$4.793 \times 10^{-2}$	$6.793 \times 10^{-2}$	$3.154 \times 10^{-3}$	$1.175 \times 10^{-3}$	0.3726	2.4527	0.5779	ABG
ABC	0.6131	$3.155 \times 10^{-3}$	$1.292 \times 10^{-4}$	$1.443 \times 10^{-4}$	$1.116 \times 10^{-8}$	$2.3537 \times 10^{-4}$	$2.186 \times 10^{-7}$	ABC

表 2 180 km 处 A 相经不同过渡电阻接地短路故障类型的选相结果

Tab 2 Result of fault phase selecting through different resistances (A phase ground,  $L = 180$  km)

过渡电阻	$E_1$	$E_2$	$E_{max}$	$E_0$	$K_{0m}$	$K_{01}$	$K_{20}$	选相结果
0	0.042 8	3.081 4e - 4	0.286 7	0.286 7	1	6.706 8	0.001 1	AG
100	0.014 5	3.698 4e - 4	0.091 7	0.091 7	1	6.328 0	0.004 0	AG
200	0.007 5	3.793 6e - 4	0.045 0	0.045 0	1	5.991 3	0.008 4	AG
400	0.003 5	3.083 7e - 4	0.018 5	0.018 5	1	5.352 2	0.016 7	AG

表 3 在不同处 A 相接地短路故障类型的选相结果

Tab 3 Result of fault phase selecting on different positions (A phase ground,  $R = 0$ )

距离	$E_1$	$E_2$	$E_{max}$	$E_0$	$K_{0m}$	$K_{01}$	$K_{20}$	选相结果
10%	0.010 1	2.560 1e - 4	0.041 3	0.024 4	0.590 7	2.423 1	0.010 5	AG
50%	0.042 8	3.081 4e - 4	0.286 7	0.286 7	1	6.706 8	0.001 1	AG
90%	0.089 8	4.647 9e - 4	0.358 8	0.293 0	0.816 6	3.262 5	0.001 6	AG

## 5 结论

针对目前所用选相元件在弱电源侧选相困难的现状,利用输电线路弱电源侧电流模量小波分析能量特征,提出了弱电源侧的选相新原理。该原理选相可靠性很高,且不受故障距离及过渡电阻等的影响,有效地解决了弱电源侧的选相问题。该选相原理通过了 ATP 仿真,选相结果可靠有效。

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作者简介:

李峰(1980-),男,硕士研究生,研究方向为电力系统微机保护; E-mail: yytk991@you.com

焦彦军(1966-),男,博士,副教授,从事电力系统微机保护教学、科研工作;

马静(1981-),男,博士研究生,研究方向为电力系统微机保护。

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作者简介:

俞晓冬 (1974 - ), 女, 讲师, 主要研究方向是电力系统的运行与控制; E-mail: xiaodongyu2001@163.com

马凤英 (1971 - ), 女, 讲师, 主要研究方向是自动控制领域;

臧宏志 (1971 - ), 男, 主要研究方向是电力系统的运行与控制。

### Rough sets theory and artificial neural networks applied in the transformer fault diagnosis

YU Xiao-dong<sup>1</sup>, MA Feng-ying<sup>1</sup>, ZANG Hong-zhi<sup>2</sup>

(1. Shandong Light Industry College, Jinan 250061, China; 2. Shandong Electric Power Research Institute, Jinan 250061, China)

**Abstract:** Rough set theory is a new intelligent information process technology. It can analyse and deduce all kinds of incomplete data, find the relationship between the data, pick up the useful characters and reduce the information process. Artificial neural networks has the essential nonlinear character, parallel processing ability, and the ability of self organization and self-learning. But when only using ANN to solve a problem, it often has some shortcomings. This paper combines rough set theory with artificial neural networks, applying it in the transformer fault diagnosis. It can fully develop the two methods' advantages, learn from other's strong points to offset one's weakness. Rough set theory can efficiently process the reduction of stylebook collection, so it simplifies the networks' structure, reduces the networks' training epochs and improves the judgement accuracy. Simulation experiment verifies the validity of this method.

**Key words:** transformer; fault diagnosis; rough sets(RS); artificial neural networks(ANN)

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### Transient energy fault phase selecting scheme on the weak feed backside of transmission line based on wavelet analysis

LI Feng, JIAO Yan-jun, MA Jing

(Key Laboratory of Power System Protection and Dynamic Security Monitoring and Control under Ministry of Education, North China Electric Power University, Baoding 071003, China)

**Abstract:** This paper is to solve problem of fault phase selecting on the weak feed backside of transmission line. Based on the results of various model component analysis, it analyzes different short faults of transmission line and proposes an efficient principle and algorithm to determine the fault phase on weak feed side. The principle is based on model component analysis. The ATP simulation calculation and the data certification show that the principle is correct and can meet the requirement of phase-selection on the weak feed backside to effectively resolve problem of fault phase selecting.

**Key words:** wavelet analysis; weak feed backside of transmission line; fault phase selecting; transient energy

(上接第 9 页 continued from page 9)

(Tsinghua University, Beijing 100084, China)

**Abstract:** After an external fault of transformer is cleared, the transient flux may enter into the saturation region, and a recovery inrush may be produced. At the same time, the aperiodic component in the fault current usually has a high value during the fault, so that the CT may also enter into the saturation region. Both of them may cause the maloperation of the differential protection. In this paper, the flux of the transformer is obtained by theoretical derivation, then models of transformer and CT are built for simulation, and an experiment is done to prove the results. The factors that affect the inrush are analyzed. The influence on the inrush of the differential protection is investigated and the saturation of CT is studied as well. At last, considering the inrush and the saturation of CT together, the main cause of the maloperation is discussed.

**Key words:** external fault; recovery inrush; saturation of CT; transformer differential protection; maloperation