Testing Impedance Characteristics

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Abstract **– This paper presents a methodology to test Mho and Quadrilateral impedance characteristics. The methodology includes test criteria, selection of test points, and test conditions. This work also explores the challenges of selecting test voltages and currents considering impedance element directionality, current magnitude supervision, and test equipment capacity limitations. The calculations of voltage and current quantities in pre-fault, fault, and reset states are shown for each test point. The proposed methodology is implemented using Linear Ramp and Pulsed Linear Ramp algorithm. Finally, the test results are discussed, and recommendations are made.**

Index Terms – Distance protection, Mho characteristic, Quadrilateral characteristic, relay commissioning.

I. Introduction

A power systems protection relay only operates few times in its whole service life. However, failure to operate as anticipated can result in wide-ranging damage, prolonged power failure or loss of life. Therefore, commissioning of relays before integration with the system and routine test during service life are regulatory requirements. Mechanical inspection and functional test are two mandatory steps of relay testing.

This paper emphasizes on the protection function test of Mho and Quadrilateral distance element characteristics of the modern digital distance relay. The distance element operating characteristics are defined by reach, line angle, and supervision conditions. Manufactures recommend testing a relay at several given points inside and outside of the characteristic. Nevertheless, the implementation of those recommendations is not straightforward because of supervision conditions and multifunction trip equation [1]. This paper shows a methodology on how to compute the fault current and voltage quantities to trace the operating boundary for a given angle subject to functional and testing hardware constrains. The detail of the methodology is reviewed in Section II. The implementation of the proposed methodology using Linear Ramp and Pulsed Linear Ramp algorithm is presented in Section III. Section IV covers the test results along with recommendations for testing. Finally, concluding remarks are made in Section V.

II. Proposed Methodology

The proposed methodology includes the procedure to test the phase and ground distance function operating characteristics by applying AC phasor quantities at the inputs of the protective relay and sensing output of the relay. For each zone impedance characteristic, three test points are considered by varying test angle. Three states namely, pre-fault, fault/action, and reset are considered to mimic the fault condition for each test point. Test criteria, selection of test points, calculation of AC test quantities along with the associated test conditions, and various constraints as well as challenges are explained in the following Subsections.

A. Test Criteria

An ideal relay should operate for a point inside of the operating boundary and should block the operation for a point outside of that boundary. However, a practical relay has the tolerance margin due to hardware's performance precision [2]. The performance of the relay should be evaluated within the range of tolerance defined by relay manufacturer. The test compares the theoretical expected value with the experimental value obtained to verify that the value is within the tolerance levels.

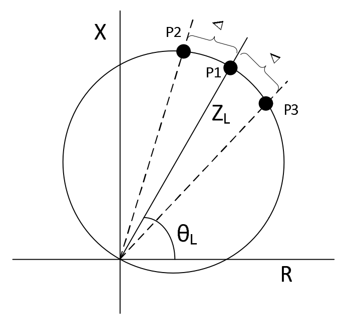

Figure 1: Three test points for Mho characteristic

B. Selection of Test Points

The test engineer/technician can select multiple test points. More points will increase the calculation burden and the testing time. That is why it is important to optimize the test point selection. At least three points should be tested to assess the performance of a non-linear characteristic. For Mho characteristic, the first test point is at maximum torque angle and other two points are selected at two sides of maximum torque angle as illustrated in Figure 1. The angles of the test points are θ_L, $\theta_L+\Delta$ and $\theta_L-\Delta$, respectively where θ_L represents maximum torque angle. The value of Δ is user defined and can be varied to shift the test points. The impedance function is more exposed to fail at the sharp edges of the operating curve due to overlapped tolerance area. That is why; the first test point is selected at the edge to ensure the correct performance of Quadrilateral characteristic as shown in Figure 2. Other two points are nominated by one from each side of the edge. The edge angle θ_e is calculated based on the Equations (1-5). Z_e, X_e, and R_e are impedance, inductance, and resistance, respectively for the edge. The tilt angle resulted from system non-homogeneity is represented by φ [3].

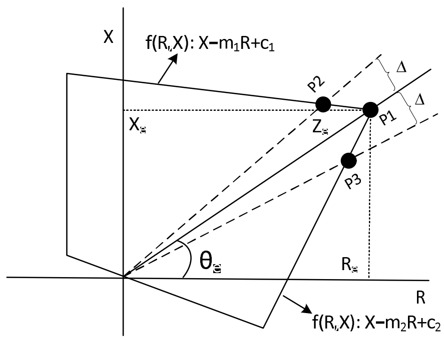

Figure 2: Three test points for Quadrilateral characteristic

$$m_1 = \tan(\varphi) \quad (1)$$

$$m_2 = \tan(\theta_L) \quad (2)$$

$$R_e = \frac{c_1 - c_2}{m_2 - m_1} \quad (3)$$

$$X_e = m_1 * R_e + c_1 \quad (4)$$

$$\theta_e = \arctan\left(\frac{R_e}{X_e}\right) \quad (5)$$

For three-phase fault, test points must be selected out of the load encroachment area to avoid the blocking or reach needs to adjusted according to the load encroachment setting.

C. *Calculations and Test Conditions*

The calculations of current quantities depend on the test conditions. Modern distance protection relays are complex multifunctional devices based on classical or advanced operating principles that impose special requirements for their testing. For multi-function relay output, it is important to enable only the element which is selected to test. Fortunately, modern relay facilitates element enable-disable function. Moreover, the test currents and voltages should be injected in such a manner so that the elements other than selected one remain deactivated. In this paper, the test current and voltage quantities are calculated based on the following test conditions:

1) Built-in element enable-disable option in the relay.
2) Three-phase voltage is applied for all three states.
3) Pre-fault and post-fault currents are injected in three phases.
4) Fault current is injected only in the selected phases for phase element tests.
5) Fault current is injected only in one phase for ground element tests.
6) Voltage drops only on faulted phases.

The calculations of the test current and voltage quantities in different states for each test point are illustrated below.

Pre-fault State: In pre-fault state, phase currents are equal in magnitude and 120 degrees apart from each other. The voltages are equal to rated voltage in magnitude and 120 degrees apart from each other. The default value and range are mentioned in Table I.

TABLE I
DEFAULT VALUE AND RANGE OF CURRENT AND VOLTAGE IN PRE-FAULT STATE

Quantities	Default Value	Range
Phase current	Nominal load current	0 to nominal load current
Phase voltage	Rated voltage	-

Reset State: In reset state, phase currents are also equal in magnitude and 120 degrees apart from each other. The voltages in reset state are considered equal to zero. The default value and range are mentioned in Table II.

TABLE II
DEFAULT VALUE AND RANGE OF CURRENT AND VOLTAGE IN RESET STATE

Quantities	Default Value	Range
Phase current	0	0 to nominal load current
Phase voltage	0	-

Fault/Action State: In this state, the desired fault event is simulated on the zone operating boundary to check the response of the relay. The fault event can be simulated either by varying the fault voltages slowly while the fault currents are kept constant; or by varying the fault currents keeping the fault voltages constant, until the operating boundary at a given point. In this paper, the fault currents are varied and the fault voltages are kept constant. For each test point, the expected fault voltages and currents depend on impedance reach and the type of fault. Equation (6) shows the relationship between fault current (I_p), fault voltage (V_p), and impedance (Z) for single phase fault.

$$Z = \frac{V_p}{(1+k)I_p} = \frac{|V_p|}{|(1+k)I_p|}\angle\theta \quad (6)$$

In Equation (6), k is the zero-sequence compensation factor and θ represents angle of the test point. For phase-phase fault, the relationship between fault current (I_p), fault voltage (V_{pp}), and impedance (Z) can be expressed as Equation (7).

$$Z = \frac{V_{pp}}{2I_p} = \frac{|V_{pp}|}{2|I_p|}\angle\theta \quad (7)$$

Equation (8) shows the relationship between fault current (I_p), fault voltage (V_p), and impedance (Z) for three-phase fault.

$$Z = \frac{V_p}{I_p} = \frac{|V_p|}{|I_p|}\angle\theta \quad (8)$$

The expected fault current and fault voltage can be calculated from Equations (6-8) for any desired fault event. In each equation there are two unknown which include the fault voltage and the fault current magnitude. In this paper, the expected fault current (test current) magnitude is assumed within given constraints to calculate the fault voltage for the sake of mathematical simplicity.

D. Constraints and Challenges

The key challenge of the fault current and voltage selection is to satisfy various constraints [2]. The arbitrary assumption of fault current may result in the failure of the test because of one or more unsatisfied constraints. The following constraints must be considered to select the fault current for any test point.

1) When the impedance element is supervised by the fault current magnitude then the impedance element is only picked up if the fault current is greater than a specific threshold value.
2) The maximum possible value of the fault current depends on the capacity of the Power System Simulator used to simulate the fault event.
3) The practical fault voltage must be smaller than the rated phase voltage. According to Equations (6-8), the value of the fault voltage depends on the fault current magnitude for a given test point. Therefore, the fault current should be selected within a range so that the fault voltage satisfies the constraint.
4) The ground impedance element is supervised by directional conditions described in [2, 4]. The values of the fault current and the fault voltage should be chosen to satisfy the conditions of ground directionality.

III. IMPLEMENTATION

The proposed test methodology can be implemented in various algorithms like State Simulator, Linear Ramp (LR) and Pulsed Linear Ramp (PLR), etc. This paper only considers LR and PLR search algorithm. LR search algorithm changes the current in single step to move from Pre-fault to Offset and then it changes current in small steps until the element pickup. Each step size is denoted by Delta Current and Delta Time represents time for each step. The overview of LR working principle for zone1 test is shown in Figure 3.

PLR search algorithm also changes the current in single step to move from Pre-fault to Offset and then it uses current pulse instead of step to reach expected operating boundary. At the end of each pulse, it moves to Offset point and stays for a time period which is called Wait Time. The overview of PLR working principle for zone1 test is shown in Figure 4 where the solid arrow lines indicate the trajectory of each pulse. The fault voltages for all test points are assumed to be equal and calculated based on the point which has highest impedance reach value. For Mho characteristic, highest reach value is found at maximum torque angle. For Quadrilateral characteristic, the edge of the characteristic results in highest reach value as shown in Figure 2. The calculations of Test Parameters for LR and PLR algorithms are shown in Table III and Table IV, respectively.

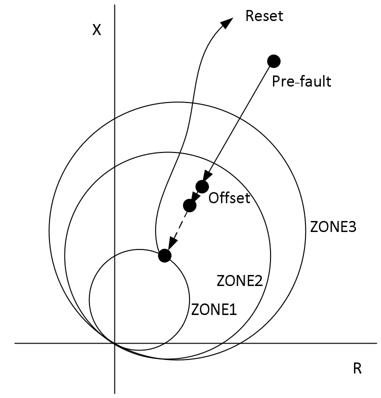

Figure 3: Working principle of LR algorithm for zone 1 test

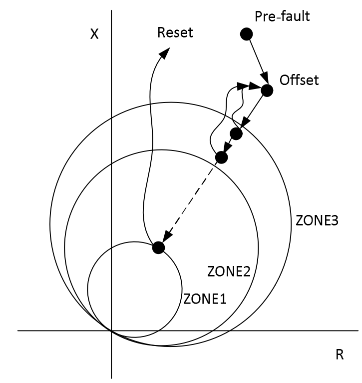

Figure 4: Working principle of PLR algorithm for zone 1 test

TABLE III
TEST PARAMETERS CALCULATION FOR LR

Offset Current	50-95% of the Minimum Expected Current of selected test points
Offset Duration	≥5 cycle
Delta Current	>0.0 A (higher value requires higher delta time)
Delta Time	≤(Time delay + 5) cycle
Current Limit	120% of Maximum Expected Current of the selected test points

TABLE IV
TEST PARAMETERS CALCULATION FOR PLR

Offset Current	Load current
Offset Duration	≥5 cycle
Initial Pulse Current	90-95% of the Minimum Expected Current of selected test points
Pulse Duration	(Time delay + 5) cycle
Wait Time	≥5 cycle
Delta Current	>0.0 A (higher value requires higher delta time)
Current Limit	120% of Maximum Expected Current of the selected test points

IV. Results and Discussions

The proposed test methodology is implemented in Linear Ramp (LR) and Pulsed Linear Ramp (PLR) search algorithm and tested for single-function and multi-function outputs by varying zone impedance reaches. The sample results are shown in Figures 5-8. The results show that PLR successfully operate within the tolerance range for both single-function and multi-function relay output irrespective of zone reach. However, LR only operates successfully within the tolerance range for single-function relay output while frequently operates out of the tolerance range for multi-function output. Multi-function output consists of several zone elements as the example shown in Equation (9).

$$OUT\ XXX = Z1T\ OR\ Z2T\ OR\ Z3T \tag{9}$$

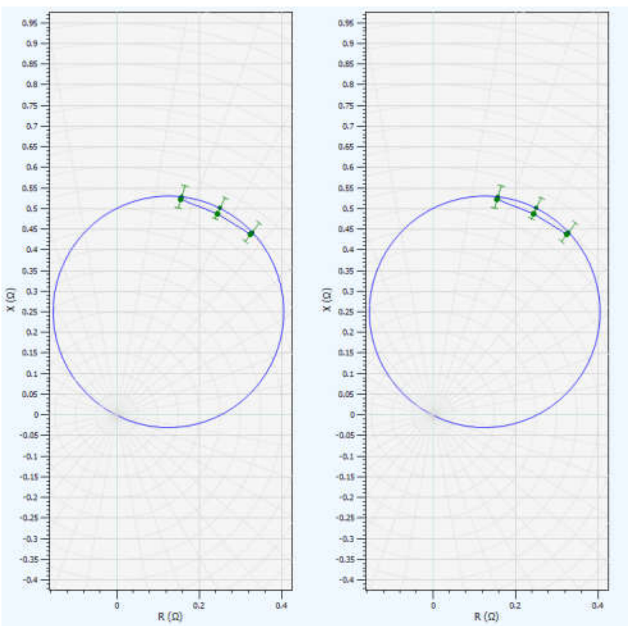

Figure 5: Single-function test results for Mho characteristics using LR algorithm (left) and PLR algorithm (right)

The time delays of Zone1, Zone2, and Zone3 are T_1, T_2, and T_3, respectively and they are related as Equation (10).

$$T_1 < T_2 < T_3 \tag{10}$$

As shown in Figure 3, for Zone1 test the impedance moves from Pre-fault to Offset state which is within in the range of Zone2 and finally it moves to the operating boundary of Zone1 by multiple small jumps. If the required time to move from Offset to operating boundary of Zone 1 is higher than T_2, Zone2 element will operate even before the impedance reaches in Zone 1 operating boundary and subsequently, the test will fail. This issue is more acute for Quadrilateral characteristic. The higher value of Offset current (98% of the Minimum Expected Current of selected test points) improves the situation for single point test cases; although, it may result in the pickup of the element in Offset state if the zone time delay is small or zero. For same reason, all other zone elements fail. The higher value of the Delta Current and lower value of the Delta Time may address the issue in some extent. However, the Test Simulator requires higher delta time for higher delta current.

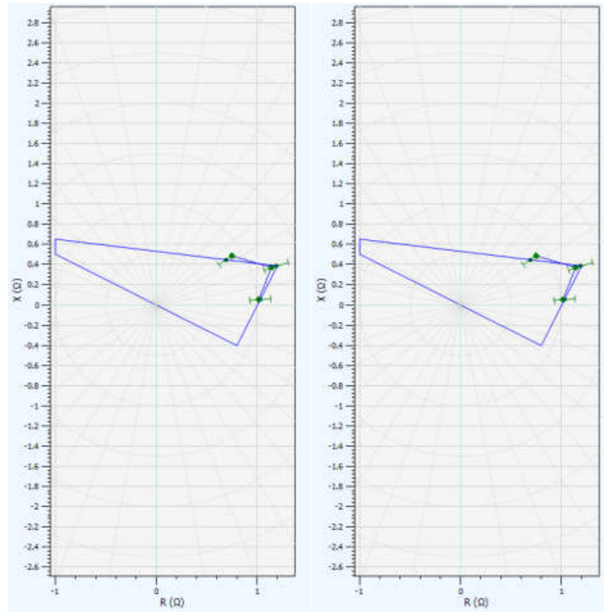

Figure 6: Single-function test results for Quadrilateral characteristic using LR algorithm (left) and PLR algorithm (right)

On the other hand, PLR algorithm does not face above-mentioned incorrect operations because PLR uses single big jump as shown in Figure 4 to move from Offset to the expected operating boundary in each pulse. The above feature allows setting the offset point out of any zone operating area and therefore, the timers of the zone elements get reset.

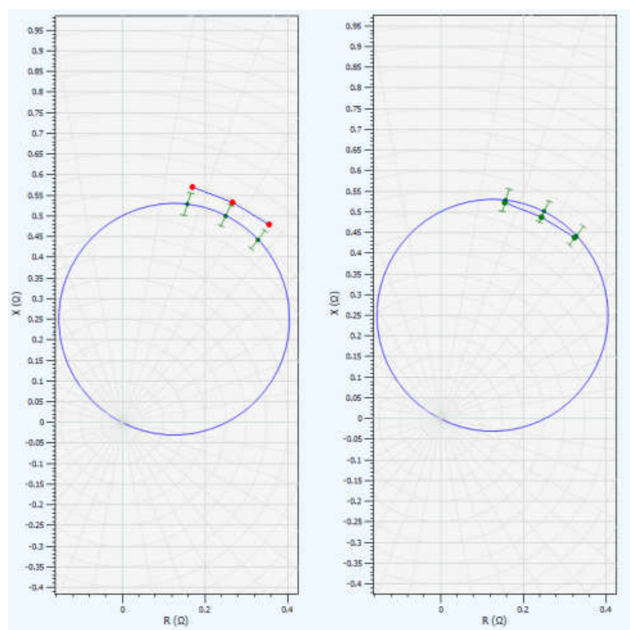

Figure 7: Multi-function test results for Mho characteristics using LR algorithm (left) and PLR algorithm (right)

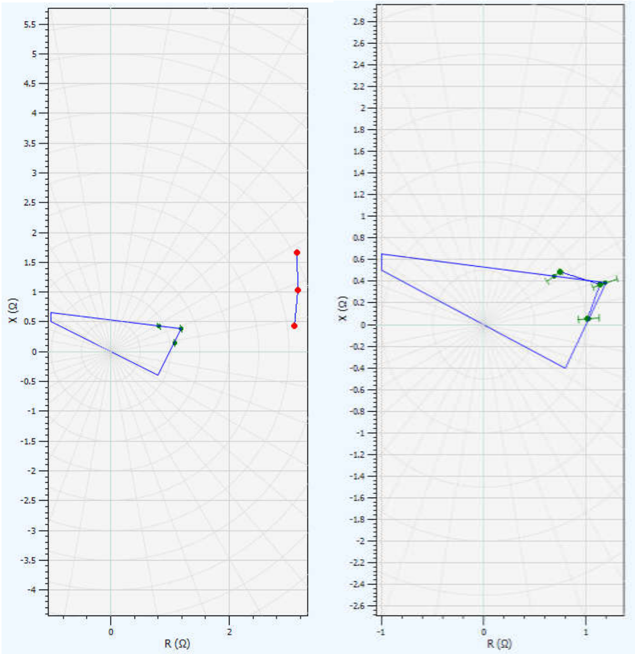

Figure 8: Single-function test results for Quadrilateral characteristic using LR algorithm (left) and PLR algorithm (right)

IV. Concluding Remarks

The paper proposes a methodology to test impedance operating characteristics at multi-points of its boundary. The article also explores two search algorithms to implement the methodology in Power System Test Simulator. The analysis suggests that Pulsed Linear Ramp (PLR) algorithm is much appropriate one to implement the proposed impedance test methodology while Linear Ramp (LR) can be limitedly applied for single-element relay output test. The performance of the proposed methodology implemented in LR algorithm is vastly depends on the tuning of the test parameters such as Offset current, Delta current, and Delta time.

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