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Review

Detection of internal fault in differential transformer protection based on fuzzy method

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Power transformers are vital and expensive components of electric power systems and it is necessary to protect them from internal faults. Differential protection is based on differential current. Occurrence of some phenomena such as inrush current, over excitation, saturation of current transformers and mismatch of current transformers cause the differential relay to operate incorrectly. In this paper, fuzzy logic is used as a powerful mathematic tool. In this method of protection, algorithm is based on ruled out non-internal fault phenomena. The results of simulations show that fuzzy protection system is able to detect occurrence of fault in less than half a cycle and this method improves protection system, satisfactorily.

Key words: Differential protection, power transformer, fuzzy logic.

INTRODUCTION

Differential protection is one of the most important and basic protection of power transformers. It is necessary to enhance speed, sensitivity and accuracy of operation of differential protection. A differential relay is based on the difference between current of low voltage and high voltage of the transformer. In normal operation mode, there is no significant differential current but while an internal fault occurs, the differential current will increase. Thus increase the differential current can be used as a sign of the internal fault. But occurrence of some phenol-mena such as inrush current, over excitation, saturation of current transformers and mismatch of current trans-formers cause the differential current increase and the differential relay operates incorrectly. Therefore the use of digital differential protection methods is developed in recent decades. These methods improve reliability, flexibility and performance of differential relay.

Some of the advanced digital algorithms that fully utilize the computational power of the digital relay (Kasztenny and Kezunovic, 1988; Habib and Marin, 2002) include: Fourier based methods (Rahman and Jeyasurya, 1988), Kalman filter techniques (Murty and Smolinski, 1988; Murty and Smolinski, 1990), flux-restrained current-differential relay (Phadke and Thorp, 1983), microprocessor-based relay (Sidhu et al., 1990) and opti-mal state observers (Murty et al., 1988). Some methods propose to use an adaptive scheme for protection of power transformers (Girgis et al., 1992).

The concept of inverse inductance utilizing both voltage and current information has been suggested (Inagaki et al., 1988; Sidhu and Sachdev, 1992). Faster and more reliable protection algorithms can be achieved by applying several elaborated protection principles together (Wiszniewski and Kasztenny, 1992). However conflicts may arise in doubtful cases; some criteria may recognize for example the inrush current, while others may support the occurrence of internal fault.

The problem addressed in this paper is how to resolve such conflict. Recently, the methods that have different structures in comparison other methods have been developed and improve speed and sensitivity of the protection. These methods of the protection are artificial neural network (Segatto and Coury, 2006; Pihler et al., 1997) and fuzzy logic (Wiszniewski and Kasztenny, 1995, 1993).

In this paper, fuzzy logic is used for internal fault detection

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in differential protection of power transformers. In this method of protection, algorithm of fault detection is based on ruled out non-internal fault phenomena. For internal fault detection are considered some criteria for inrush current, over excitation, saturation of current transformers and mismatch of current transformers and are defined appropriate membership functions and criteria signals. This algorithm for protection of power transformers is described followed by a test system.

THE CRITERIA OF NON-FAULT PHENOMENA DETECTION IN DIFFERENTIAL TRANSFORMER PROTECTION BASED ON FUZZY METHOD

For detection of non-fault phenomena according to the features will be used varied criteria and will be defined appropriate membership functions and criteria signals.

The inrush current case

Inrush current has different features. For detection of inrush current, different criteria have been developed.

Criterion 1: The value of the differential current is higher than the highest expected inrush current level

Comparing differential current caused by inrush current and differential current caused by internal fault shows that the value of differential current caused by internal fault is higher than differential current level caused by inrush current in some cases. Thus this criterion can be used for inrush current detection. For measuring this criterion, criteria signal is defined as follows:

$$\theta_1(n) = \max(I_{\Delta 1}(n), |i_{\Delta}(n)|)$$

$I_{\Delta 1}(n)$ - the amplitude of the n-th fundamental harmonic of differential current and $|i_{\Delta}(n)|$ - the amplitude of the n-th sampling instance differential current.

Figure 1 shows the membership function that is defined for this case.

Criterion 2: During the last half cycle, no sudden change of the voltage amplitude was observed

One of the features of the inrush current is that the inrush current was always caused by sudden change of the voltage amplitude (energizing the transformer). Therefore, measuring the changes of voltage amplitude can be useful for inrush current detection.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_2(n) = \frac{V(n)}{V(n-m/4)}$$

n is present sampling instance and m is the number of samples per cycle.

The membership function is shown in Figure 1a for this case.

Criterion 3: During the last cycle, no sudden change of the through current amplitude was observed

Studying the differential current caused by inrush current and the differential current caused by internal fault shows that the differential current caused by internal fault does not change with time, but the differential current caused by internal fault has considerable changes.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_3(n) = \frac{I_R(n)}{I_R(n-m)}$$

Figure 1a presents the membership function for this case.

Criterion 4: The second harmonic in the differential current is below 10% of its fundamental

Another important feature for inrush current detection is the second harmonic of the differential current. This criterion is used in classic relays as a restrained criterion for inrush current detection.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_4(n) = \frac{I_{\Delta 2}(n)}{I_{\Delta 1}(n)}$$

The membership function is shown in Figure 1a for this case.

Criterion 5: The wave shapes of the differential current shows certain fragments when the level of the current is close to zero

Comparing the wave shape of the differential current caused by inrush current with differential current caused by internal fault shows that the differential current caused by inrush current remains near zero (lasting no less than 1/6 of a cycle) while the level of the current is close to zero. Therefore, comparing these two parameters can also be used to relay decision making.

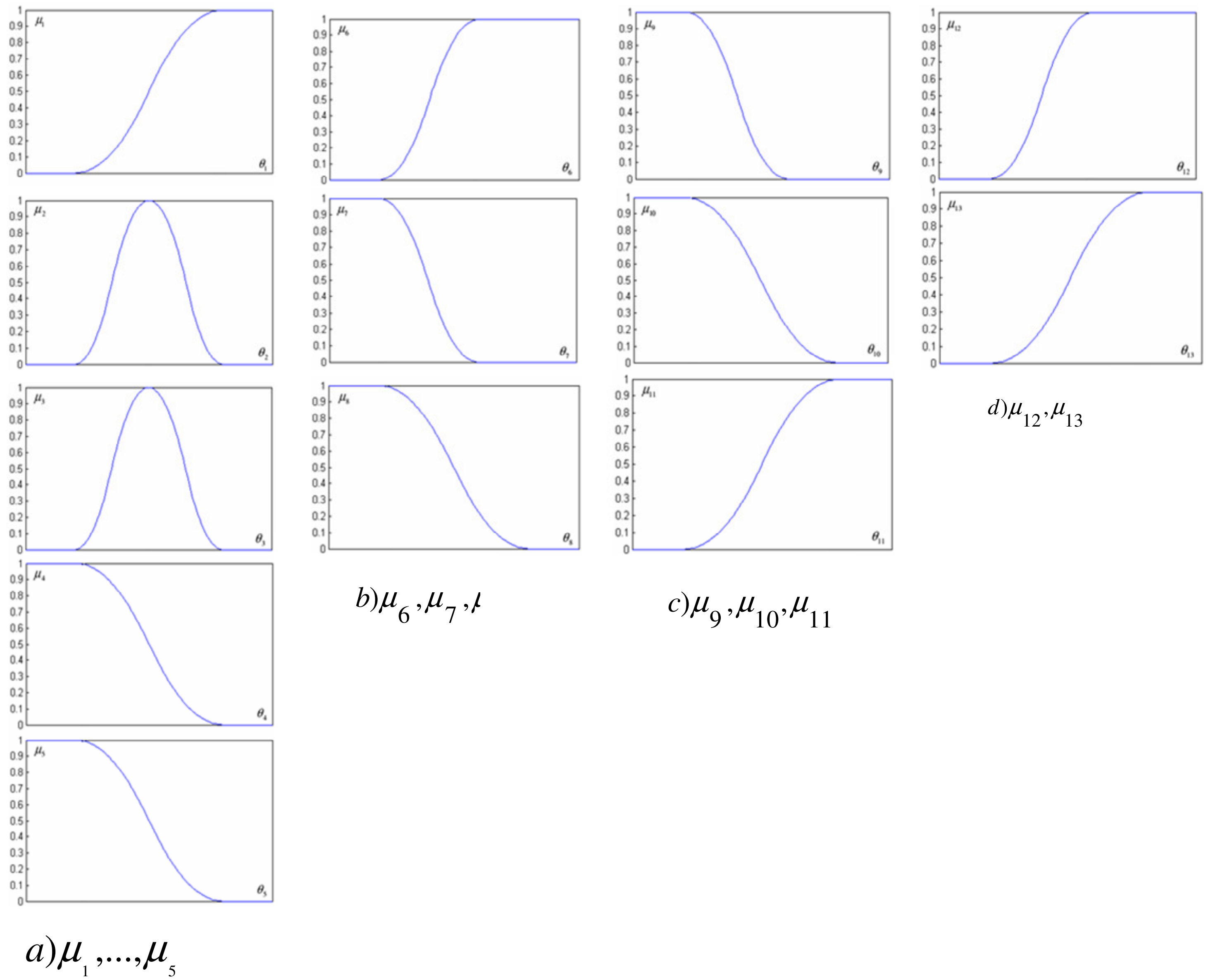

Figure 1. Membership functions for criteria of non-fault phenomena in differential transformer protection based on fuzzy method.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_5(n) = \min(\max(i_R(n-k-p)))$$

$$k = 0,\ldots,\frac{5m}{6},\ p = 0,\ldots,\frac{m}{6}$$

Figure 1a presents the membership function for this case.

The over excitation case

Over excitation has different feature. For detection of over excitation, different criteria have been developed.

Criterion 6: The level of the differential current is higher than expected in cases of over excitation

Comparing differential current caused by over excitation and differential current caused by internal fault shows that the value of differential current caused by internal fault is higher than differential current level caused by over excitation in some cases. Thus, this criterion can be used for over excitation detection. This criterion enhances the speed of the relay detection.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_6(n) = \theta_1(n)$$

Figure 1b shows the membership function for this criterion.

Criterion 7: The integral of the voltage for half a cycle which reflects the flux in the core, is below the saturation level

Over excitation always is associated with voltage increase thus the integral of the voltage for half a cycle shows the occurrence of over excitation.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_7(n) = T_i \sum_{k=o}^{m/2} V(n-k)$$

T_i is sampling period

Figure 1b presents the membership function for this case.

Criterion 8: The level of the fifth harmonic in the differential is below some 30% of its fundamental

The important criteria for over excitation is comparing fifth harmonic with its fundamental. The main problem of this criterion is the low speed of performance. In fact this criterion is enough for detecting over excitation and Criterions 6 and 7 help the speed of performance of the relay.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_8(n) = \frac{I_{\Delta 5}(n)}{I_{\Delta 1}(n)}$$

The membership function is shown in Figure 1b.

Saturation of the CTs

Saturation of the CTs has different features. For detection of saturation of the CTs different criteria have been developed.

Criterion 9: The large value of the through current did not exist during the cycle before the large value of the differential current was detected

For measuring this criterion, criteria signal is defined as follows:

$$\theta_9(n) = \max(|i_R(n-k)|)$$

$k = 0,...,m-1$

Figure 1c shows the membership function that is defined for this case.

Criterion 10: The level of the second harmonic of the differential current is below 20% of the fundamental one

The important feature for detection of saturation of the CTs is the second harmonic of the differential current. This criterion compares second harmonic with its fundamental for detection of saturation of the CTs.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_{10}(n) = \theta_4(n)$$

The membership function is shown in Figure 1c for this case

Criterion 11: The level of the differential current is greater than the greatest current expected during the external short circuit under CTs saturation

Comparing differential current caused by CTs saturation and differential current caused by internal fault shows that the value of differential current caused by internal fault is higher than differential current level caused by CTs saturation in some cases. Thus this criterion can be used for CTs saturation detection. This criterion enhances the speed of the relay detection.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_{11}(n) = \theta_1(n)$$

Figure 1c presents the membership function for this case.

The mismatch of the CTs

The mismatch of the CTs can cause differential current of the differential relay and the relay operates incorrectly. Mismatch of the CTs has different features. For detection of mismatch of the CTs different criteria have been developed.

Criterion 12: The differential current is much greater than the through current (traditional percentage characteristic)

This criterion is very useful for detecting of differential current caused by mismatch of the CTs.

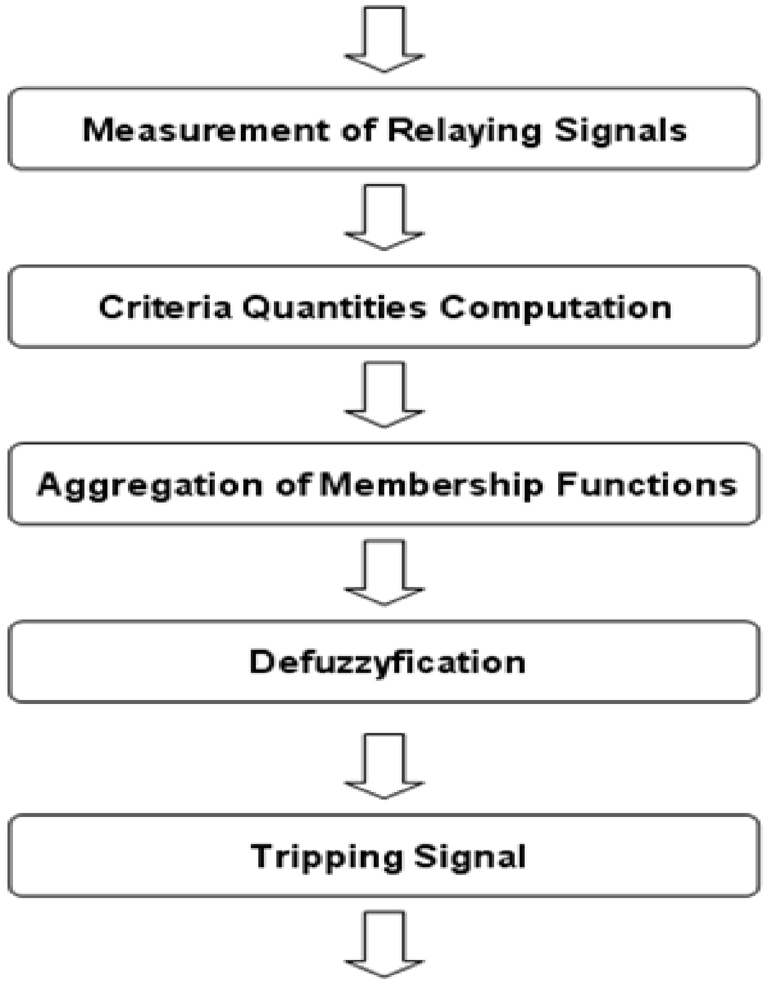

Figure 2. Flow chart of the protection algorithm based on fuzzy method.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_{12}(n) = \frac{I_{\Delta 1}(n)}{I_R(n)}$$

The membership function is shown in Figure 1d for this case.

Criterion 13: The differential current is greater than the greatest expected value of the current caused by near external fault and largest possible during the mismatch of the CTs

The value of differential current caused by internal fault is higher than differential current level caused by mismatch of the CTs in some cases. Thus this criterion can be used for over excitation detection. This criterion enhances the speed of the relay detection.

For measuring this criterion, criteria signal is defined as follows:

$$\theta_{13}(n) = \theta_1(n)$$

Figure 1d shows the membership function for this criterion.

DIFFERENTIAL PROTECTION BASED ON FUZZY METHOD

Previously defined criteria for power transformer protection, their settings, and the aggregation method are described here. In fuzzy method, there are a number of criteria which are being used to differentiate between a fault and non-internal fault cases. In this method, the symptoms qualify a case to the group "internal fault" with the membership function μ. If μ is zero, it is certainly no internal fault. If μ = 1, it is certainly an internal fault. If 0< μ <1 it is a doubtful case. Fuzzy method became a very powerful mathematical tool to solve this problem. With reference to the protection flow chart (Figure 2) at

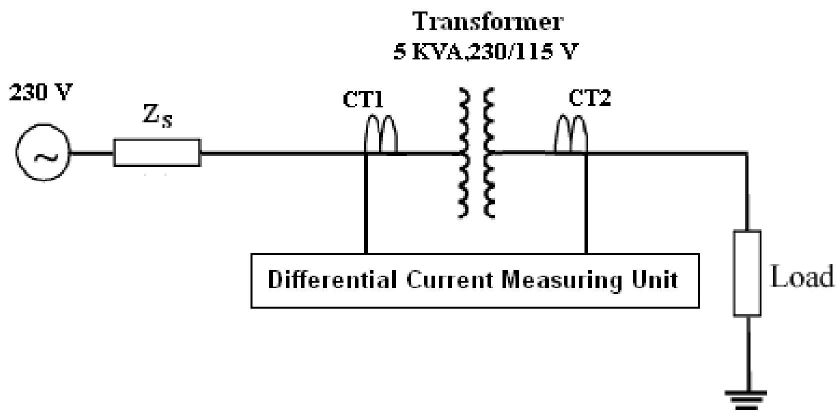

Figure 3. The test system with the protected transformer.

first relaying signals are measured and then criteria quantities are computed. The aggregation of membership function $(\mu_1,...,\mu_{13})$ gives the fuzzy output for each non-fault phenomena. The tripping signal is obtained by defuzzyfication of final fuzzy output using a constant threshold.

The operation performed after detecting a significant value of the differential current is to compute the criteria signals and to compare them with their settings in order to obtain the levels of satisfaction for all the criteria.

In fuzzy method for non-fault phenomena detection multi-criteria system is used. In this method, the fault detection is based on ruled out non-internal fault cases. There are differences between the quality of criteria of non-fault phenomena. Some criteria may be more reliable than others. For the proper use of all these criteria, weighting factors are defined. Weighting factors describe the strength of the criteria. Thus for each non-fault phenomena is obtained final fuzzy output. The aggregation of (membership functions of the fuzzy setting for relevant criteria) must be performed for each group of criteria separately, so that the supports for the corresponding aspects of transformer operation are obtained.

If the relay detects the differential current, before making a trip decision, the relay ought to rule out the non-fault cases:

Inrush current ruled out

$$\omega_1(n) = w_1\mu_1(n) + w_2\mu_2(n) + w_3\mu_3(n) + w_4\mu_4(n) + w_5\mu_5(n)$$

$$\sum_{k=1}^{5} w_k = 1$$

where: $w_1,...,w_5$ - weighting factors describing the strength.

The criterion 1,…, criterion 5 used to exclude the inrush current case (The strength of criteria determines the value of the weighting factors) and $\mu_1,...,\mu_5$ - levels of satisfaction for the criterion 1,…, criterion 5.

Over excitation ruled out

$$\omega_2(n) = w_6\mu_6(n) + w_7\mu_7(n) + w_8\mu_8(n)$$

$$\sum_{k=6}^{8} w_k = 1$$

Saturation of the CTs ruled out

$$\omega_3(n) = w_9\mu_9(n) + w_{10}\mu_{10}(n) + w_{11}\mu_{11}(n)$$

$$\sum_{k=9}^{11} w_k = 1$$

Mismatch of the CTs ruled out

$$\omega_4(n) = w_{12}\mu_{12}(n) + w_{13}\mu_{13}(n)$$

$$\sum_{k=1}^{13} w_k = 1$$

Internal fault hypothesis means that all the cases have to be ruled out. Thus, the total support for "internal fault" (δ) resulting from all the thirteen criteria must be computed as:

$$\delta(n) = \min(\omega_1(n), \omega_2(n), \omega_3(n), \omega_4(n))$$

Fuzzy differential relay will operate if: $\delta(n) > \Delta$

The value of Δ is determined according to the membership functions and weighting factors for all the criteria and is considered 0.8.

TEST SYSTEM

Figure 3 shows the test system with differential transformer

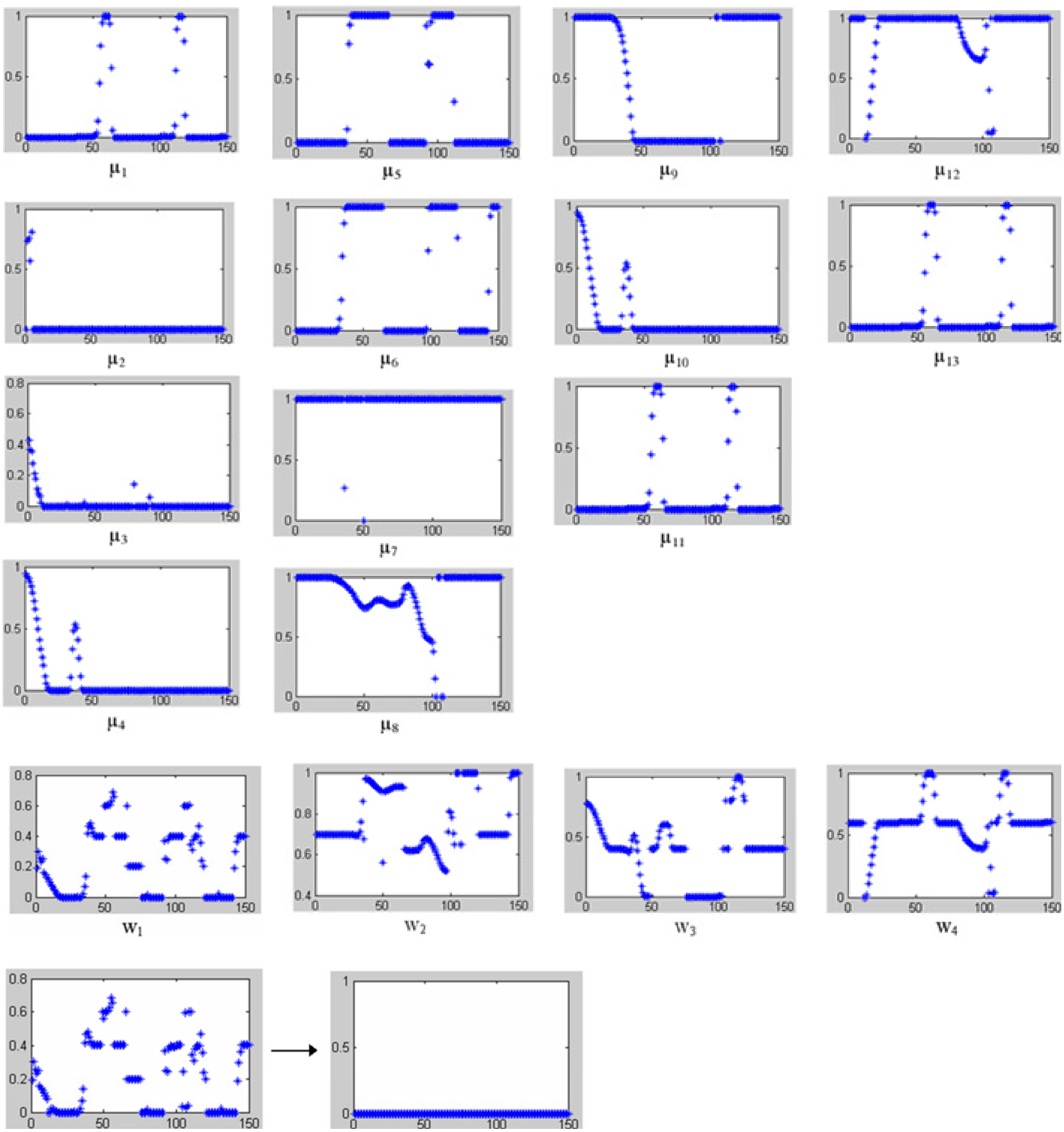

Figure 4. The tripping signal and the continuous logic signals involved with the decision making in the case of an inrush current.

protection based on fuzzy method.

In this protection system, δ is the total support for tripping. The Boolean tripping signal is generated by defuzzyfication of δ using a constant threshold. The relay sampling frequency is 1 KHZ. The results have been simulated by using MATLAB software.

Figure 4 shows the tripping signal and continuous logic signals involved with decision making in the case of energizing of the transformer. This figure shows the levels of satisfaction for the criteria $(\mu_1,...,\mu_{13})$, their aggregation $(\omega_1,\omega_2,\omega_3,\omega_4)$, and the total support for tripping (δ) and eventually the Boolean tripping signal is

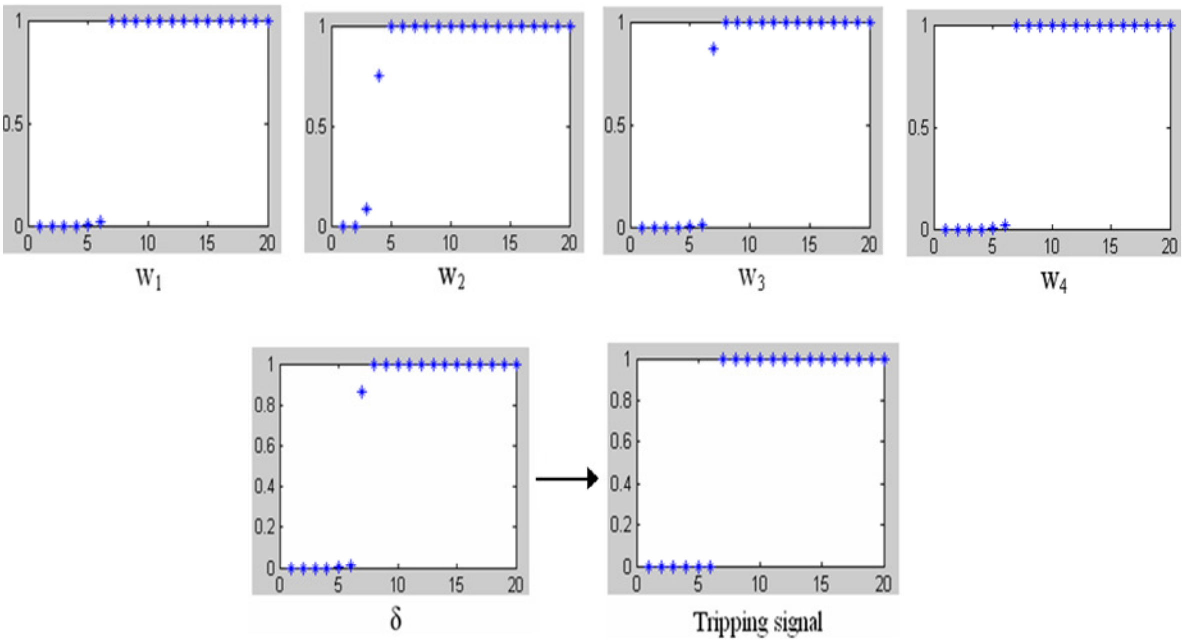

Figure 5. The tripping signal and some of the continuous logic signals involved with the decision making in the case of an internal fault.

generated by defuzzyfication of (δ) using a constant threshold. In this case the trip command is not exported.

Figure 5 shows the tripping signal and some of the continuous logic signals involved with decision making in the case of an internal fault (Aggregations of criteria $(\omega_1, \omega_2, \omega_3, \omega_4)$, the total support for tripping (δ) and the Boolean tripping signal). In this case, the trip command is reached at 7 th sample (7 ms) since the fault inception.

Conclusion

In this paper, the design and implementation of a differential transformer protection based on fuzzy method is presented. The criteria have been aggregated and combined in order to generate more reliable tripping signal. This differential relay applied for digital protection of a transformer has following advantages:

1. In this method, the evaluation is done by different criteria, so this method has more accuracy and confidence.
2. The results of simulations show the protective system operates correctly in fault and non-fault cases.
3. The results of simulations show that fuzzy protection system is able to detect occurrence of fault in less than half a cycle and this method improves protection system, satisfactorily.

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