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**APPLICATION DES RÉSEAUX NEURONAUX FLOUS À
L'IDENTIFICATION ET LA PROTECTION D'UN
TRANSFORMATEUR TRIPHASÉ**

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Mise en garde/Advice

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To those who have filled my life with love

My wife, Mahin; my daughter, Shadi; my mother, Shahbano Nazemi;

and my mother-in-law, Fatemeh Kalantari

In loving memory of my father, Ali Asghar

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Résumé

Récemment, des systèmes avancés de reconnaissance et de prise de décision incorporant des éléments de logique floue et de réseaux de neurones artificiels ont été appliqués avec succès à l'identification, la commande et la protection des réseaux électriques. Le principal objectif de cette thèse consiste à explorer la capacité de systèmes neuro-flous, qui sont une combinaison des systèmes à réseaux de neurones et à logique floue, pour l'identification d'un transformateur triphasé, en vue de développer un modèle non-linéaire permettant de mieux protéger le transformateur contre les défauts internes.

Deux modèles, l'un direct et l'autre indirect, sont développés afin de prédire les courants secondaires en fonction des courants primaires et réciproquement. Un algorithme hybride d'apprentissage est utilisé pour entraîner les modèles. Celui-ci procède en deux étapes; premièrement, dans la passe en sens direct (des entrées vers les sorties) il impose des paramètres des prémisses et emploie l'estimateur aux moindres carrés pour ajuster les paramètres des conclusions. Ensuite, procédant en sens rétrograde (des sorties vers les entrées), il fixe les paramètres des conclusions et emploie un algorithme du gradient pour ajuster les paramètres des prémisses, de manière à minimiser l'erreur total des modèles.

Plusieurs fichiers de données d'apprentissage sont utilisés, afin de refléter toutes les conditions d'exploitation possibles: nominales, surcharges permanentes et transitoires,

défauts externes et courants d'appel lors de la mise sous tension. Cependant, ces fichiers d'apprentissage n'incluent aucune donnée de défaut interne.

Au terme de l'apprentissage, plusieurs nouveaux fichiers de données sont utilisés pour valider les modèles neuro-flous. On peut ainsi vérifier leur généralisation sur des données qu'ils n'ont pas vues durant leur entraînement. Au total, les modèles neuro-flous démontrent une bonne aptitude à prédire le comportement d'un transformateur de puissance de façon précise sous des conditions nominales, avec des erreurs de modèle direct et indirect relativement faibles. Cependant, ces erreurs augmentent substantiellement lors d'un défaut interne, ce qui permet de déterminer rapidement l'occurrence d'un tel défaut.

Abstract

Recently, advanced recognition and decision making techniques including *artificial neural networks* and *fuzzy set theory* have been used for the identification, control and protection of power systems. The principal objective of this thesis is to explore the capacity of *neuro-fuzzy systems*, which are the combination of artificial neural networks and fuzzy logic systems, for identification of a three-phase power transformer and development a model that can be employed for the protection of the power transformer against internal faults.

Two models, one direct and one indirect, are developed. A *hybrid learning algorithm* is used for the training of the models. The hybrid learning algorithm has two steps; First, in the forward pass, it fixes premise parameters and employs the *Least-Squares Estimator (LSE)* method to adjust consequent parameters. Then, in the backward pass, it fixes consequent parameters and utilizes the *Gradient Descent (GD)* method to adjust the premise parameters in order to minimize the error of the models.

Several training data files are used to train the models. These files include the rated condition, several over-load conditions, external faults and inrush current, however, they do not include any internal fault conditions.

After finishing of the training, several new data files are used to validate the neuro-fuzzy models. Therefore, the generalization of the neuro-fuzzy models can be verified and

tested by the unseen data files. The neuro-fuzzy models show that they can predict precisely the behavior of the power transformer under rated conditions. The amplitude of the errors of the direct and indirect models are small. However, these errors increase in amplitude when an internal fault occurs in the power transformer, allowing for rapid detection.

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Chapter 1

Introduction

1.1 Background

Power transformers were first included in power supply systems in the last decade of the nineteenth century to enable electricity to be distributed from central stations at relatively high voltages to consumers spread over quite wide areas. This practice, which proved to be economically sound, has been continued around the world.

With the growth of power systems, protection of their various components, especially power transformers, which have been installed all over, has become more and more important in order to avoid interruptions in service. Despite adequate design, care in erection, and proper maintenance of transformers, the possibility of a fault still exists. By fast disconnecting a faulty transformer from power systems, the damage can be limited. It is important that the faulted transformer be isolated as quickly as possible after the fault has occurred, not only to limit the damage to the transformer, but also to minimize the length of time the system voltage is depressed. Primary protection of a power transformer is intended for conditions which arise as a result of faults inside the protective zone. Electric power utilities use differential relays to detect winding faults in transformers rated at 10 MVA and above.

The procedure of protection by a differential relay consists of converting the primary and secondary currents to a common base and comparing them. During normal operation or external fault conditions, the differences between these currents are small and negligible. On the other hand, during a winding fault in a transformer, the differences are large.

However, differential relays may be operated when there is no internal fault. This may happen due to *magnetizing inrush current* and results in large differential currents causing differential relays to operate. The increased magnetizing currents associated with the more general use of higher permeability irons and the trend toward higher concentrations of system short-circuit capacity are factors which limit the sensitivity of differential protection.

To avoid the unnecessary trip by magnetizing inrush current, the second harmonic component is commonly used for blocking the relay operation. This method was invented more than 60 years ago [Kennedy L. F., Hayward C. D., 1938]. Initial designs were conceptually similar to the conventional approach and used fundamental frequency and harmonic components of the differential currents. The ratio of the second harmonic of the differential currents to the fundamental frequency components of the differential currents was used to identify magnetizing inrush conditions.

Digital filtering and correlation techniques were used to compute the fundamental frequency and harmonic components of the differential currents [Skyles J. A. & Morrison I.F., 1977] [Schweitzer E.O. & Larson R.R.] [Sachdev M.S. & Shah D.V., 1981]. In fact, the main difference between the digital relays is the way the 50 Hz and 100 Hz current components are computed. Some of those techniques are: Discrete Fourier Transform, Least Squares Curve Fit, Finite-Impulse Response (FIR) filtering [Rahman M. A. & Jeyasurys B., 1988].

The use of high-quality, low-loss core materials in modern transformers has resulted in the reduction of harmonic contents in magnetizing inrush currents. Also, substantial harmonic components can be present in differential currents during winding faults within a transformer [Liu P. et al., 1989] [Pihler J. et al., 1996]. These may be due to current transformer saturation, parallel capacitance for adjusting the phase angle or the distributed capacitances of long EHV transmission lines to which the transformer may be connected. It is reported that for a power transformer connected to a source through a fairly long (40 km or more) underground 500KV lines and 1000KV overhead lines, the second harmonic component in fault current is increased together with the capacitance in power system [Akira Y. et al., 1979] [Yabe K., 1996]. As with classical static protection, new numeric protection can also lead to unnecessary operation or operation failures. This, in fact, is a consequence of the inability of protection algorithms to distinguish transient states from faults, or a consequence of distortions created by measurement sensors. This inability is due to conflicts which may arise in doubtful cases; for example, some criteria may recognize the inrush current, while other may support the internal fault hypothesis. Therefore, new approaches should be considered to improve the operation of a power transformer protection and remove these drawbacks.

1.2 Motivation and Objective

Today, *Fuzzy Logic* and *Artificial Neural Networks* represent a field of intensive research in various applications of system identification, control systems, pattern classification, load forecasting in power systems, and fault diagnosis. Fuzzy logic, which is a mathematical tool based on *fuzzy sets theory* [Zadeh L. A., 1965] [Zimmermann H. J., 1987], has rapidly become one of the most successful technologies for developing sophisticated control systems today. The reason for this is very simple. Fuzzy logic addresses such applications perfectly, as it resembles human decision making with an ability to generate precise solutions from certain or approximate information. It fills an important gap in engineering design methods left vacant by purely mathematical approaches (e.g. linear control design), and purely logic-based approaches (e.g. expert systems) in system design. While other approaches require accurate equations to model real-world behaviors, fuzzy design can accommodate the ambiguities of real-world human language and logic.

Artificial neural networks are applied in the case where the equations of a nonlinear system cannot be written, but there exist several numerical data files which can present the dynamic behavior of a system. The advantage of the neural networks [Haykin S., 1994] [Hertz J. et al., 1991] [Kohonen T., 1988] [Lippmann R. P., 1987] is that they are capable of learning dynamical behavior of a nonlinear system given an appropriate training data set.

Recently, the combination of fuzzy logic and neural networks has been studied for applying in real applications [Ikonen E. & Najim K., 1996] [Lin B. R., 1995] [Tani T. et al., 1996] [Vuorimaa P. et al., 1995]. With this combination, neuro-fuzzy systems use the advantages of both approaches, namely, fuzzy logic and neural networks. On the one hand, neuro-fuzzy systems can use uncertain and vague information available through expert knowledge or operator information. On the other hand, they can learn the dynamic behavior of a nonlinear system by observing sufficient training data. These advantages make neuro-fuzzy systems a powerful tool which can be applied in different disciplines as system identification, control systems, process control, pattern classification, load forecasting in power systems, and protection.

The principal objective of this thesis is to explore the capacity of neuro-fuzzy systems for identification of a power transformer. This research project comprises the following steps:

- Development of a neuro-fuzzy model for power transformers;
- Simulation of a three-phase power transformer including its non-linearity in MATLAB;
- Simulation of the neuro-fuzzy model during internal and external faults;
- Evaluation of the possibility of employing a neuro-fuzzy model as a differential protection approach.

1.3 Methodology

In this research, MATLAB and its toolboxes (Fuzzy Logic & Neural Networks toolboxes) have been used for developing the neuro-fuzzy models. Two models, one direct and one indirect, are developed. A hybrid learning algorithm is used for training of the models. This algorithm comprises two steps; First, in the forward pass, it fixes premise parameters and employs the *Least-Squares Estimator (LSE)* method to adjust consequent parameters. Then, in the backward pass, it fixes consequent parameters and utilizes the *Gradient Descent (GD)* method to adjust the premise parameters in order to minimize the error of the models.

Several training data files are used to train the models. These files include the rated condition, several over-load conditions, external faults and inrush current. However, they do not include internal fault conditions.

After completion of training, several new data files are used to validate the neuro-fuzzy models. These data files have not already been seen by the neuro-fuzzy models. Therefore, the generalization of the neuro-fuzzy systems can be verified and tested. Then, the possibility of using these neuro-fuzzy models as differential protection for a power transformer is discussed.

1.4 Survey of the Thesis

There are a total of six chapters in this thesis. In chapter 1, a synopsis of relevant problems, the objective and methodology of this work have already been presented and analyzed.

In chapter 2, a review of previous research in this field, is presented. Chapter 3 consists of three sections: In the first section, the concept of *Artificial Neural Networks (ANN)* and their learning abilities are explained. In the section that follows, the *Fuzzy Logic (FL)* concept is presented. Then, fuzzy sets, fuzzy relations, and approximate reasoning are introduced. Finally, in the last section, the synergism of fusing *fuzzy logic* and *artificial neural networks* techniques into an integrated system called *Neuro-Fuzzy System (NFS)* is introduced. Then, hybrid learning algorithm, in order to minimize the error of neuro-fuzzy systems, is explained.

In chapter 4, two models, one direct and one indirect, are developed for a three-phase power transformer. The structure and architecture of the models, and the learning procedure are explained in greater detail. The validation of the models and the possibility of using this approach as a protection method for three-phase power transformers are presented in chapter 5. Finally, in chapter 6, the impact of this work is summarized, improvements are suggested, and further research is recommended.

Chapter 2

Review of the Literature

2.1 Introduction

Identification theory is a vast subject of considerable interest to the power industry. Due to increasingly complex power systems, the need to quickly and accurately identify the important characteristics of power system components is a primary concern. The ability to adequately represent the important dynamics of a system, over a wide bandwidth, is of paramount importance for all identification schemes.

Any control action or protection design for a power system will only be as good as the model it is based on. The model may be obtained either analytically, where the model is derived from basic equations and the parameters are assumed, or experimentally, using direct measurements. In practice, however, it is very difficult, and sometimes, impossible to develop an analytic model for a nonlinear dynamic system.

A power transformer is an essential component of a power system. Power transformers may be subject to various types of faults. Proper design and setting of a differential relay for power transformers are recognized as challenging problems for protection engineers. In the case of a power transformer, detection of a differential current does not provide a clear distinction between internal faults and other conditions. Biased differential characteristics combined with 2nd and 5th harmonic restraints constitute a classical approach to the problem. Searching for better relay sensitivity, selectivity and speed of operation, initial designs conceptually similar to the conventional technique have

shifted to new recognition methods in the areas of both signal estimation and decision making.

More recently, advanced recognition and decision making techniques, including artificial neural networks and fuzzy set theory, have been used for the identification, control, and protection of power systems.

During this research, several papers and theses have been studied as bibliography. While it is not possible to review all of them in this chapter, some of the most important are reviewed. In the first two sections, different digital power transformer protection algorithms based on the harmonics restraint approach are reviewed. Then, in the next two sections, application of artificial neural networks for recognition of inrush current, and improvement of power transformer protection are discussed. The last paper presents a new approach for protection of power transformers based on fuzzy logic.

2.2 Harmonic Restraint Approach

Rahman M. A., Jeyasurya B., "A State-Of-Art Review of Transformer Protection Algorithms",
IEEE Transaction on Power Delivery, vol. 3, no. 2, April 1988.

This paper reviews different algorithms for digital differential protection power transformers. The following algorithms are briefly explained in their mathematical aspects:

- Fourier Analysis Approach;
- Rectangular Transform Approach;
- Algorithm based on Walsh Function;
- Haar Function Approach;
- Finite Impulse Response Approach (FIR);
- Least-Squares Curve Fitting Algorithm.

The ultimate purpose in all of the above mentioned algorithms is to determine the peak of the fundamental and harmonic content of the differential current as each new sample is taken. Since the inrush current has a higher percentage of harmonics than internal fault, this information is used to determine whether there is an inrush current condition or an internal fault. The authors use frequency response, which is a measure of the filtering characteristic of the algorithms. Each algorithm may be considered as four digital filtering computations, two for the fundamental frequency and two for the second harmonic. The frequency responses of the algorithms show that these algorithms are able to effectively extract components of the fundamental and second harmonic frequencies of the differential current from sample data. A three-phase transformer model is used to simulate the inrush current and internal faults. Since the restraining signal is well above the operating signal, the performance of all the algorithms for inrush current is good and there is not any possibility for malfunction. For internal faults, the restraining signal is higher immediately after inception of the internal fault. However, after about 15 ms, the operating signal is

higher than the restraining signal, and a trip signal is issued. The authors compare the computational requirements and time for all the algorithms. It shows that Least-Square Curve Fitting, Rectangular Transform, Fourier Analysis and Finite Impulse Response algorithms can do the computations in less than 40% of the sampling interval and excess time can be used for data acquisition, relay logic, and monitoring.

Grcar B., Dolinar D., "Integrated Digital Power Transformer Protection", *IEEE Proc. Gener.*

Transm. Distrib., 141(4), pp. 323-328, July 1994.

Dolinar D., Pihler J., Grcar B., "Dynamic Model of a Three-Phase Power Transformer", *IEEE/PES*

Winter Meeting, Columbus USA, February 1993.

The authors propose an integrated digital three-phase power transformer protection. It consists of a percentage differential relay with harmonic restraint at inrush and over-excitation conditions, an over-current relay with instantaneous and time-lag operation, a sensitive relay for selective operation at high impedance ground faults, and a fault recorder. The proposed integrated protection concept is developed on the basis of a nonlinear mathematical transformer model which includes nonlinear effects of saturation, hysteresis and eddy currents. In this paper, a complete hardware and software structure of an integrated transformer protection is given. The integrated protection algorithm is implemented on a high-performance digital processor DSP32C connected to a standard PC and a peripheral input-output unit. There are two program modules. The first program is

executed on PC to ensure an equidistant sampling interval and the transfer of sampled signals into the signal processor. The second program is executed on signal processor to execute the protection algorithm. The sampled currents are transformed on a common base by means of signal preprocessing. The transformation matrix T is used to obtain the differential and through currents. The transformation matrices T are predefined for different connection groups and stored in the memory as a configuration parameter. The differential and through currents for connection $Yd5$ are

$$i_d(k) = T i_p(k) - i_s(k)$$

$$i_{th}(k) = 0.5 [T i_p(k) - i_s(k)]$$

The determination of the fundamental, second and fifth harmonic components in differential, through and ground currents are done by the least-squares curve-fitting technique. The inrush and over-excitation conditions are detected on the basis of the percentage of the second and fifth harmonics in the differential current respectively. The slope of the percentage differential characteristic is changed based on the through current. Laboratory results and field testing indicate that the performance of the integrated digital relay is superior to that of existing static relays. Despite numerous laboratory and field tests, false operations or operation failures never occurred. The maximal operation time is approximately 25 ms. In addition, the algorithm has enough robustness in relation to the system frequency.

2.3 Artificial Neural Networks Approach

Perez L. G., Flechsig A. J., Meador J. L., Obradovic Z., "Training an Artificial Neural Network to Discriminate between Magnetizing and Internal Faults", *IEEE / PES Winter Meeting*, Columbus, OH, January 31 - February 5, 1993.

The authors devise a method for discriminating between inrush current and internal fault, based on a *Feed-Forward Neural Network (FFNN)*. To compromise between speed and accuracy, different architectures are selected. However, the network has one neuron in its output layer. There are 3 networks with 3 layers (12+2+1, 6+2+1 & 4+2+1) and 3 networks with only 2 layers (12+1, 6+1 & 4+1). The *sigmoid transfer function* is chosen for each neuron. The network is trained with the well-known *back-propagation algorithm*. The training data consists of two files. The first file represents the inrush currents, which are obtained by measuring on a small 50 VA, 120/240 V power transformer in the laboratory. The measured data represent an acceptable range of inrush current shapes. The desired output of *FFNN* for this group is considered as zero. The second training file consists of internal fault cases, which are produced by *EMTP*. The desired response of *FFNN* for this case is considered as one. After completing the training procedure, the neurons transfer functions are changed to *hard-limit*. This change increases the *FFNN* computation speed considerably, since it takes less computation time to implement a hard limit than a sigmoid transfer function. The results of simulation show that only four

architectures of the *NN* (12+2+1, 6+2+1, 12+1 & 6+1) show good performance and the others (4+2+1 & 4+1) show poor performance. While, the time necessary to detect inrush current is longer than by *Fourier analysis*, but the authors believe that this protection method is more secure as regards false trips. In this research, only the inrush current cases are considered and more work should be done in order to test the model with other non-internal fault hypotheses (as external faults mixed with saturation of the CTs).

Pihler J., Grear B., Dolinar D., "Improved Operation of Power Transformer Protection using Artificial Neural Network ", *IEEE / PES Summer Meeting*, Denver, Colorado, July 28 - August 1, 1996 .

The authors propose a way for using intelligent concepts to recognize the inrush current and restore the secondary current of CTs, which are partially or totally saturated, in order to improve the operation of a digital power transformer protection. They explain that digital relays with harmonic restraint are not reliable in all cases, and that in several cases the relays are caused to operate incorrectly. They propose to use an *artificial neural network* to recognize the inrush currents. It comprises 3 layers (6 + 4 + 1) and uses the *back-propagation algorithm* as learning rule. *The Sigmoid function* is considered as the transfer function for all the neurons. There are 137 training vectors which contain different inrush conditions, fault currents, and stationary transformer state currents. The desired output for the inrush conditions equals 1, and zero for the fault conditions. After

completion of the training, the network responds to all 137 training vectors correctly. The network incorrectly recognized only 2% of the unseen inrush patterns and 8% of other patterns. To restore the current of the saturated CT, another *artificial neural network* is used. It comprises 3 layers (20 + 3 + 1). Inputs are twenty samples of the secondary currents (one instantaneous and 19 previously). The target vector is the value of the primary current at the instant of observation. After training the network, it is tested with unseen patterns and the restored current differs from the target at amplitude values about 10%. They propose a criterium to select either the secondary currents obtained directly from the secondary side of the CTs or the restored currents from *ANN*. In protection algorithm, there are two branches for detecting inrush current. The first branch determines the inrush by computing the ratio of the second harmonic to fundamental. The second branch ascertains inrush by artificial neural network for all three differential currents simultaneously. In case of discrepancy, the *artificial neural network* has a higher priority. The proposed digital differential power transformer protection, including the *artificial neural network*, is tested on 30 KVA and 50 MVA transformers. The proposed protection algorithm has a reliable response and the following advantages:

- reliable establishment of inrush even in cases when inrush current contains less than 16% of the second harmonic component (inrush current detection is based on recognizing its wave shape);
- increasing the operating speed at inrush with a simultaneous or slightly delayed short circuit;

- improving the reliability in case of faults where a second harmonic component is present, even though the transformer has not been switched-on;
- reliable operation of protection at partially saturated current transformers.

2.4 Fuzzy Logic Approach

Kasztenny B., Rosolowski E., Saha M.M., Hillstrom B., “ A Self-Organizing Fuzzy Logic Based Protective Relay - An Application to Power Transformer Protection”, *IEEE paper 96 SM 386-3 PWRD*, presented at the 1996 IEEE/PES Summer Meeting, July 28 - August 1, Denver, Co.

This is a new approach for protection of the power transformer, based on *fuzzy logic*. When the differential current in one of the phases passes a threshold value (0.02 p.u.), the relay activates. In this case, the *fuzzy logic decision making engine* issues the tripping command if, based on information contained in the relaying signals, it is capable of rejecting the non-internal fault hypotheses. The non-internal fault hypotheses are as follows:

- inrush conditions;
- stationary over-excitation of a transformer core;
- external fault combined with saturation of CTs;
- external fault or high load current without saturation of CTs, but mixed with mismatched ratios of the transformer and CTs.

To recognize these non-internal fault hypotheses, the authors establish 12 criteria (3 for each hypothesis) in *linguistic forms* so that a *Fuzzy Inference System (FIS)* can be used to decide whether there is an internal fault hypothesis or a non-internal fault hypothesis. The 12 criteria are listed in Table 2.1, and a schematic diagram of the system is shown in Figure 2.1.

To obtain the membership function for each signal, 150 simulations are performed employing *ATP-EMPT*. These simulations are presented in the following cases:

- a) transformer energizing cases (16%);
- b) stationary over-excitation cases, including over-voltages and frequency reduction (7%);
- c) external faults with and without saturation of CTs (24%);
- d) internal faults including terminal, inter-winding, and turn-to-turn faults (53%).

A three-phase, two-winding, 5.86 MW, 140/10.52 kV, Yd-connected, five-leg core type power transformer is modeled by the digital ATP-based model. The sampling rate is assumed to be 20 samples per cycle (1 kHz). The differential and through currents are measured by measuring units which are based on *Finite impulse Response (FIR)* full-cycle orthogonal filters designed using the *least square method* with perfect separation between 1st, 2nd and 5th harmonics.

To determine the parameters of the *membership functions*, the probability density functions for internal and non-internal fault cases are determined. In the overlapping region, the decision making is vague and uncertain. Therefore, a linguistic variable is defined. For example, as is shown in Figure 2.2, the *membership function* has three distinct regions for the third criteria (C_3):

- $\Theta_3 \leq 0.10$: There is absolutely an internal fault, and there is no magnetizing inrush current;
- $\Theta_3 \geq 0.15$: There is certainly a magnetizing inrush current, and internal hypothesis is completely rejected;
- $0.10 \leq \Theta_3 \leq 0.15$: This is a fuzzy region and both cases can occur. The function for this region has been obtained by a self-adjusting algorithm.

Linguistic variables	Criteria
Case 1) Ruling out of the magnetizing inrush current	
$\Theta_1(n) = I_{\Delta 1}(n)$	C ₁ : The value of the differential current is higher than the highest expected inrush current level (instantaneous over-current principal)
$\Theta_2(n) = \text{Min} \{ \text{Max} i_{\Delta ph}(n-k-m) \}$ <small>k=0..N-1 m=0..[N/6], ph=R, S, T</small>	C ₂ : The wave shapes of the differential currents in all three phases do not show certain fragments (lasting no less than 1/6 of a cycle) where the levels of both the current and its derivative are close to zero (direct wave shape identification)
$\Theta_3(n) = I_{\Delta 2}(n) / I_{\Delta 1}(n)$	C ₃ : The second harmonic in the differential current is below some 10-15% of its fundamental (2nd harmonic restraint)
Case 2) Ruling out of the stationary over-excitation of a transformer core	
$\Theta_4(n) = I_{\Delta 1}(n)$	C ₄ : The level of the differential current is higher than in cases of transformer over-excitation (over-current principle)
$\Theta_5(n) = \sum_{k=0}^{[N/2]-1} V(n-k)$	C ₅ : The integral of the terminal voltage amplitude, V, for half a cycle, which reflects the flux in a transformer core, is below the saturation level (simplified flux based restraint)
$\Theta_6(n) = I_{\Delta 5}(n) / I_{\Delta 1}(n)$	C ₆ : The level of the 5th harmonic in the differential current is below some 30% of its fundamental (5th harmonic restraint)
Case 3) Ruling out of the external short-circuit mixed with saturation of CTs	
$\Theta_7(n) = \text{Max} \{ I_{R1}(k) \}, k = p-N+1 \dots p$	C ₇ : The large value of the through current did not exist during the cycle before the large value of the differential current was detected (sequence of events)
$\Theta_8(n) = I_{\Delta 2}(n) / I_{\Delta 1}(n)$	C ₈ : The level of the 2nd harmonic in the differential current is below some 20% of the fundamental component
$\Theta_9(n) = I_{\Delta 1}(n)$	C ₉ : The differential current is greater than the greatest current during external short-circuit under CTs saturation (over-current principle)
Case 4) Ruling out of the external short-circuit or high load current without CTs saturation	
$\Theta_{10}(n) = \frac{ I_{\Delta 1}(n) - I_{\Delta 1}(-[N/4]) }{ I_{R1}(n) - I_{R1}(-[N/4]) }$	C ₁₀ : The differential current is much greater than the through current (biased differential characteristic)
$\Theta_{11}(n) = \Theta_{10R}(n) - \Theta_{10S}(n) + \Theta_{10S}(n) - \Theta_{10T}(n) $ $+ \Theta_{10T}(n) - \Theta_{10R}(n) $	C ₁₁ : The relation between the differential and through currents are different in all three phases of the relay (asymmetry checking)
$\Theta_{12}(n) = I_{\Delta 1}(n)$	C ₁₂ : The differential current is greater than the greatest expected value of the current caused by a near heavy external fault and largest possible mismatch of the transformer and CTs ratios

Table 2-1 : Twelve criteria of the fuzzy logic decision making engine.

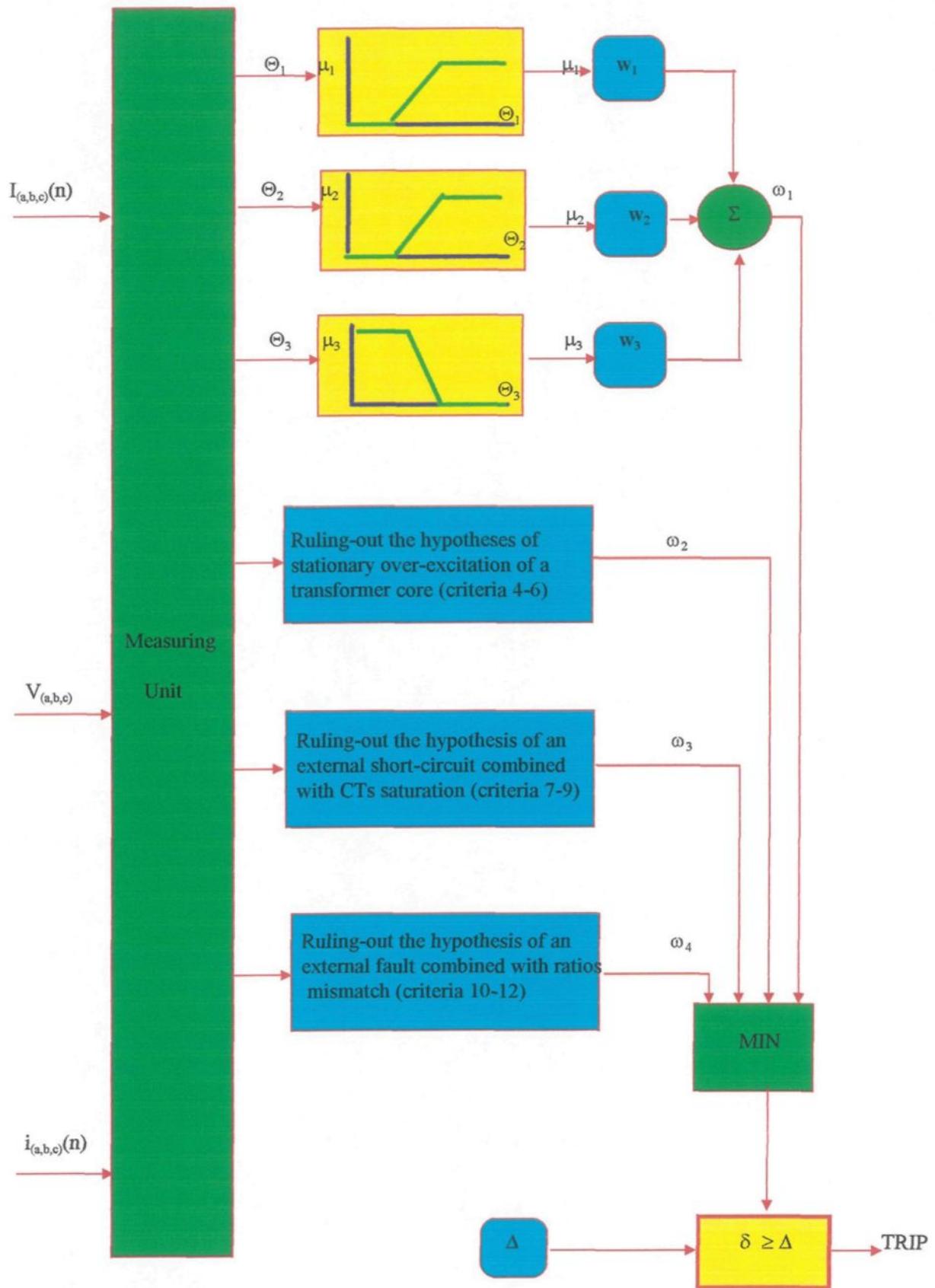


Figure 2.1 : A simplified block diagram of the Fuzzy Logic Relay (FLR) for power transformers.

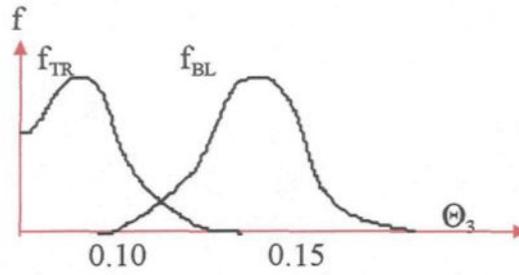


Figure 2.2 : Distribution of the second harmonic percentage in the differential current under internal faults and inrush conditions.

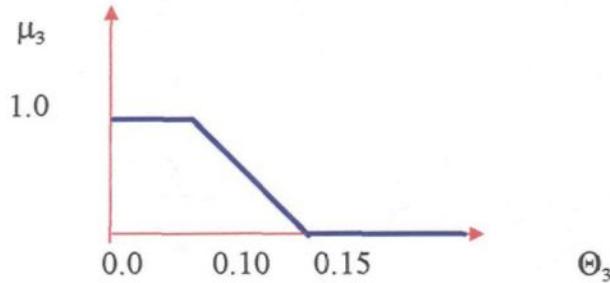


Figure 2.3 : The arbitrary fuzzy setting μ_3 for second harmonic restraint (C_3).

Figure 2.2 shows the probability density functions for both blocking and tripping signals. The membership function for Θ_3 is shown in Figure 2.3.

After determining the membership functions for all criteria, the weighting factors method is used to specify the criteria powers. For example, to rule out the inrush hypothesis, ω_1 , the criteria C_1 , C_2 and C_3 are aggregated.

$$\omega_1 = w_1 \mu_1 + w_2 \mu_2 + w_3 \mu_3,$$

$$w_1 + w_2 + w_3 = 1$$

In a similar manner, ω_2 , ω_3 and ω_4 are calculated. The relay should rule-out all the non-internal fault hypotheses prior to tripping. Consequently, the signal ω_1 , ω_2 , ω_3 and ω_4 are aggregated into the overall tipping support, δ .

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

If δ overreaches a threshold value, Δ , the tripping command is issued.

$$\text{TRIP} = (\delta \geq \Delta)$$

Kasztenny *et al.* Introduced the algorithms based on statistical information obtained by mass-simulation using *ATP-EMPT*, for self-adjusting the following parameters:

- fuzzy setting, μ_1, \dots, μ_{12} ;
- criteria weighting factors, w_1, \dots, w_{12} ;
- tripping threshold, Δ .

The *Fuzzy Logic protective Relay (FLR)* shows no error over the training data, whether all three elements of the *FLR* are set arbitrary or self-organized with average tripping time less than half a cycle, or 2.7ms respectively. The research shows, however,

that the *FLR* is not robust enough against unseen cases and it trips falsely in 4% of non-internal cases.

To Improve the *FLR* and stabilize the relay, Kasztenny et al. Suggested the following approaches:

- re-learn the tripping threshold using the entire data-base;
- artificially increase the tripping threshold so that the relay is stable;
- apply an extra delay in tripping.

The provided examples show a good stability and selectivity and the robustness of the relay is approved.

Chapter 3

Fundamental Theories

3.1 Introduction

Over the last 10 years, several advanced techniques for modeling and controlling processes have entered electrical, chemical, petroleum, and manufacturing plants. These techniques include *Artificial Neural Networks (ANN)* and *Fuzzy Logic*.

Artificial neural networks are based on a novel approach to modeling. While other modeling techniques, such as linear regression, may suffice for simple problems, neural networks are good at solving complex problems. The key strength of neural networks is that they are excellent at modeling extremely difficult, complex problems, offering a powerful predictive capability to engineering. The key drawback is that they require large amounts of data. The three major neural network applications are :

1. Prediction;
2. Control;
3. Fault diagnosis.

Fuzzy logic is attracting a great deal of attention in the industrial world, and among scientists and researchers. It has emerged as a profitable tool in control systems and complex industrial processes, as well as for diagnosis systems and other expert systems. It is important to realize that fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth (truth values between “completely

truth” and “completely false”). As its name suggests, it is the logic underlying modes of reasoning which are approximate rather than exact. The importance of fuzzy logic derives from the fact that most modes of human reasoning, and especially common sense reasoning, are approximate in nature.

This chapter consists of three sections. In the first section, the concept of artificial neural networks and their learning abilities are explained. Then, their architectures and *back-propagation learning algorithm* are briefly introduced. Fuzzy logic is presented in the second section, and its structure and approximate reasoning are introduced. The synergism of fusing fuzzy logic and neural networks techniques into an integrated system called *neuro-fuzzy system* is discussed in the last section. Then, parameters adjustment algorithm, in order to minimize the error of the system, is explained. Finally, *ANFIS*, Adaptive Neuro-Fuzzy Inference System [Jang J.-S. R., Gulley N., 1995],[Jang J.-S. R., 1993], is introduced.

SECTION ONE

3.1.1 What are Artificial Neural Networks?

It has been a goal of science and engineering to develop intelligent machines for many decades. Scientists want to know what is the difference between a computer and a human brain, and how they can mimic the brain. To answer these questions, many people in different disciplines, including psychology, mathematics, neuroscience, physics, engineering, computer science, philosophy, biology, and linguistics, have been working for many years, and the research will continue for several years to come.

Anyone knows that the brain is more powerful and faster than a digital computer in some aspects. Consider, for example, human vision, which is an information-processing task. It is the function of the visual system to provide a representation of the environment around us and, more importantly, to supply the information we need to interact with the environment. To be specific, the brain routinely accomplishes perceptual recognition tasks (e.g., recognizing a familiar face embedded in an unfamiliar scene) is something of the order of 100-200 *ms*, whereas tasks of much lesser complexity will take days on a huge conventional computer.

The brain has many other features that would be desirable in artificial neural networks:

- It is robust and fault tolerant. Nerve cells in the brain die every day without significantly affecting its performance.
- It is flexible. It can easily adjust to a new environment by *learning*. It does not have to be programmed in Pascal, Fortran or C.
- It can deal with information that is fuzzy, probabilistic, noisy, or inconsistent.
- It is highly parallel. It is worth remarking that the typical cycle time of neurons is a few milliseconds, which is about a million times slower than their silicon counterparts, semiconductor gates. Nevertheless, the brain can do very fast processing for tasks like vision, motor-control, and decision on the basis of incomplete and noisy data, tasks that are far beyond the capacity of a supercomputer. This is obviously possible only because billions of neurons operate simultaneously.
- It is small, compact, and dissipates very little power.
- It has an enormous efficient structure. Specifically, the energetic efficiency of the brain is approximately 10^{-16} joules (J) per operation per second, whereas the corresponding value for the best computers in use today is about 10^{-6} joules per operation per second.

Artificial neural networks (ANN) are mathematical models of the human brain with the hope that the model can learn by itself through what we usually refer to as *experience*.

3.1.2 Model of an Artificial Neuron

The first model of an artificial neuron was proposed in 1943 by McCulloch and Pitts [McCulloch W. & Pitts W., 1943]. Although it is a very simple computation unit, it is the basic element of artificial neural networks. Figure 3.1.1 shows the model of a neuron. Each neuron may have several inputs. There is a set of *synapses*, or *connecting links*, between inputs and neuron. The input signals are multiplied by their *weights* or *strengths* before summing them. Specifically, a signal x_j connected to neuron k is multiplied by the synaptic weight w_{kj} . The first subscript refers to the neuron in question, and the second, to the input end of the synapse to which the weight refers. The weight w_{kj} is positive if the associated synapse is *excitatory*; it is negative if the synapse is *inhibitory*.

An adder is used for summing the input signals, weighted by the respective synapses of the neuron. The adder output n , often referred as the *net input*, goes into a *transfer function* f , which produces the scalar neuron output a . This transfer function is usually referred to as an *activation function* or a *squashing function*. The activation function limits the amplitude of the output of a neuron to some finite value. Typically, the normalized amplitude range of the output of a neuron is written as the closed unit interval $[0,1]$ or alternatively $[-1,1]$.

In mathematical form, we may describe the k th neuron by writing the following pair of equations:

$$n_k = \sum_{j=1}^p (w_{kj}x_j + b_k)$$

and

$$a_k = f(n_k)$$

where x_1, x_2, \dots, x_p are the input signals; $w_{k1}, w_{k2}, \dots, w_{kp}$ are the weights of neuron k ; n_k is the output of the summer; b_k is the bias; and a_k is the output signal of the neuron.

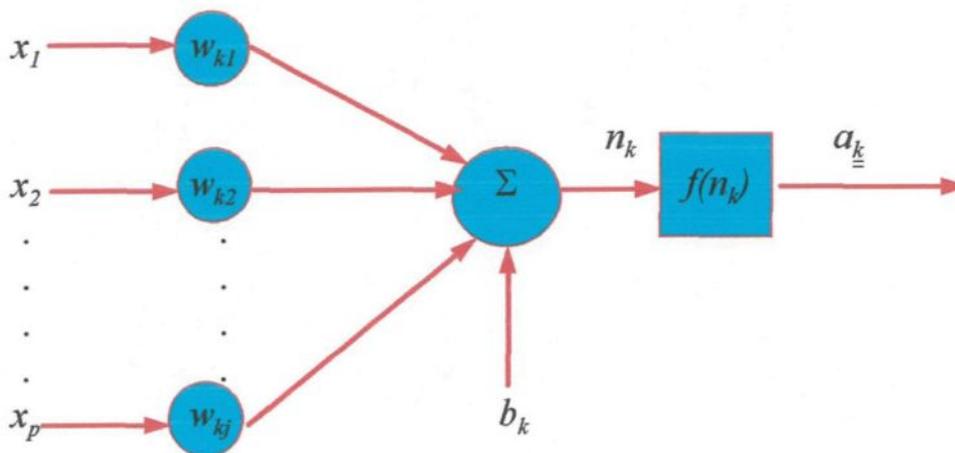


Figure 3.1 : Multiple-Input Neuron.

The bias b_k is an external parameter of artificial neuron k . It is usually considered as a new synapse, whose input is,

$$x_0 = -1$$

and whose weight is,

$$w_{k0} = b_k$$

Note that w and b are both *adjustable* scalar parameters of the neurons. Typically, the transfer function is chosen by the designer and then the parameters w and b will be adjusted by some learning rule so that the neuron input/output relationship meets some specific goal.

3.1.3 Types of Activation Functions

The activation function which defines the output of a neuron in terms of its net input n , may be a linear or a nonlinear function of n . A particular transfer function is chosen to satisfy some specification of the problem that the neuron is attempting to solve. Most of the activation functions which are commonly used in artificial neural networks are illustrated in Table 3.1.1.

Name	Input/Output Relation	Icon	MATLAB Function
Hard Limit	$a = 0 \quad n < 0$ $a = 1 \quad n \geq 0$		hardlim
Symmetrical Hard Limit	$a = -1 \quad n < 0$ $a = 1 \quad n \geq 0$		hardlims
Linear	$a = n$		purelin
Saturating Linear	$a = 0 \quad n < 0$ $a = n \quad 0 \leq n \leq 1$ $a = 1 \quad n > 1$		satlin
Symmetric Saturating Linear	$a = -1 \quad n < -1$ $a = n \quad -1 \leq n \leq 1$ $a = 1 \quad n > 1$		satlins
Log-Sigmoid	$a = \frac{1}{1 + e^{-n}}$		logsig
Hyperbolic Tangent Sigmoid	$a = \frac{e^n - e^{-n}}{e^n + e^{-n}}$		tansig
Positive Linear	$a = 0 \quad n < 0$ $a = n \quad 0 \geq n$		poslin
Competitive	$a = 1$ neuron with max n $a = 0$ all other neurons		compet

Table 3-1 : Activation functions

3.1.4 Learning

When an architecture is selected for a neural network, one may ask;“ How do we choose the connection weights and biases so that the network can do a specific task? ”

We can *teach* the network to perform the desired task by iterative adjustments of the weights and biases. This is one of the most interesting features of artificial neural networks; it is the ability to learn from a set of inputs/outputs, or sometimes only a set of inputs, that represents the behavior of a system or process in question. Learning is an adaptive process that adjusts the weights and biases of neural networks in order to minimize a cost function.

Learning in the context of neural networks is defined as follows [Haykin S., 1994]:

Learning is a process by which the free parameters of a neural network are adapted through a continuing process of stimulation by the environment in which the network is embedded. The type of learning is determined by the manner in which the parameter changes take place.

The neural networks have this advantage that it is not necessary to specify every detail of a calculation and find the equations which can express the behavior of the system or process. Instead, one simply has to compile a training set of representative examples. This means that we can hope to treat problems where appropriate rules are very hard to know it in advance. It may also save a lot of tedious and expensive software design and

programming even when we do have explicit rules. If there are no (or they are too difficult to find) explicit rules, or the optimum algorithm for a particular problem, neural networks are a powerful tool for the task.

There are many interesting methods for *training* a neural network to do a specific task. In all of them, the main purpose is to adjust parameters of neural networks in order to minimize a cost function. They fall into two broad categories: *supervised learning* and *unsupervised learning*.

1. ***Supervised Learning*** : In *supervised learning*, the learning rule is provided with a set of examples (the *training set*) of proper network behavior:

$$\{\mathbf{x}_1, \mathbf{d}_1\}, \{\mathbf{x}_2, \mathbf{d}_2\}, \dots, \{\mathbf{x}_q, \mathbf{d}_q\},$$

where \mathbf{x}_q is an input to the network and \mathbf{d}_q is the corresponding *target output*. As the inputs are applied to the network, the network outputs are compared to the target outputs. The learning rule is then used to adjust the weights and biases of the network in order to move the network outputs closer to the target outputs.

2. ***Unsupervised Learning*** : In *unsupervised learning*, the weights and biases are modified in response to network inputs only. There are no target outputs available. Most of these algorithms perform some kind of clustering operation. They learn to categorize the input patterns into a finite number of classes. This is especially useful in such applications as vector quantization.

One of the powerful *supervised learning* techniques is *the back-propagation algorithm*.

3.1.4.1 Back-Propagation Learning

With introduction of *back-propagation algorithm*, many researchers and scientists have become interested in this algorithm and have used it for training *multi-layer feed-forward neural networks*. A multi-layer feed-forward neural network consists of several layers.

The first layer is called *input layer* and receives inputs from environment and feeds forward through layers. The last layer is the output layer, since its outputs are interesting for us and they are the final outputs of neural network. There are often one or more layers in between, which are *called hidden* layers since they do not have any communication with the environment.

The basic idea is that if the network gives the wrong answer, the weights are corrected so that the error is lessened and, as a result, future responses of the network are more likely to be correct.

Back-propagation networks are composed of a number of interconnected layers; It means that each layer is fully connected to the layers below and above. It typically starts out with random weights and biases. When the network is given an input, the updating of activation values propagates forward from the input layer through each hidden layer, to the

output layer. The output layer then provides the response of the network. After completion of the feed forward pass, the learning mechanism starts with the output layer and propagates backward through each internal unit to the input layer. That is why it is called back-propagation algorithm. It overcomes the limitations of the perceptron, (perceptrons can only classify patterns that are linearly separable), because it can adopt two or more layers of weights, and each hidden layer acts as a layer of feature detectors. The power of back-propagation lies in its ability to train hidden layers and thereby escape the restricted capabilities of single layer networks.

The back-propagation learning rule can be used to adjust the weights and biases of a network in order to minimize the sum-squared error of the network. This is done by continually changing the values of the network weights and biases in the direction of steepest descent with respect to error. Suppose that in a multi-layer feed-forward neural network, neuron j lies in a layer to the right of neuron i , and neuron k lies in a layer to the right of neuron j when neuron j is in a hidden layer. Then the back-propagation algorithm can be expressed in mathematical form as follows:

$$a_j(t) = f_j(n_j(t))$$

$$e_j(t) = d_j(t) - a_j(t)$$

$$E(t) = \frac{1}{2} \sum e_j^2(t)$$

$$\Delta w_{ji}(t) = -\eta \frac{\partial E(t)}{\partial w_{ji}(t)}$$

By using the chain rule, the partial derivative can be expressed in terms of two factors, one expressing the rate of change of error with respect to the output a_j , and the other expressing the rate of change of the output of the neuron j with respect to the input to the same neuron. Finally, the correction $\Delta w_{ji}(t)$ applied to $w_{ji}(t)$ is expressed by:

$$\Delta w_{ji} = \eta * \delta_j(t) * a_i(t)$$

where

Δw_{ji} = weight correction;

η = learning rate parameter;

$\delta_j(t)$ = local gradient;

$a_i(t)$ = input signal of neuron j .

For calculating of $\delta_j(t)$, two cases are distinguished:

- If neuron j is an output node, $\delta_j(t)$ equals the product of the derivative of $f(n_j(t))$ and the error signal $e_j(t)$, both of which are associated with neuron j .

$$\delta_j(t) = f'(n_j(t)) * e_j(t)$$

- If neuron j is a hidden node, $\delta_j(t)$ equals the product of the associated derivative of $f'(n_j(t))$ and the weighted sum of the δ 's computed for the neurons in the next hidden or output layer that are connected to neuron j .

$$\delta_j(t) = f'(n_j(t)) * \sum \delta_k(t) w_{kj}(t)$$

SECTION TWO

3.2.1 What is Fuzzy Logic ?

Humans, when making decisions, tend to work with vague or imprecise concepts which can often be expressed linguistically. Prof. Lotfi A. Zadeh proposed an approach for modeling of this decision making process [Zadeh, 1965], and is based on the theory of *approximate reasoning* which enables certain classes of linguistic statement to be treated mathematically. First, investigations by Prof. Zadeh concerned how to use mathematical tools to represent human language and knowledge [Zadeh, 1973]. He was the first who introduced the terms of *fuzzy rules* and *linguistic variables* in control theory. In a paper [Zadeh, 1972], he claims that fuzzy algorithms underlie much of human thinking. We use them both consciously and unconsciously when we talk, park a car, recognize patterns. This use is more intuitive and qualitative than systematic and quantitative. Moreover, Zadeh believes that the modern control theory must become less preoccupied with mathematical rigor and precision, and more concerned with the development of qualitative or approximate solutions to pressing real world problems. In short, he proposed that all problems in which the data, the objectives and the constraints are too complex, or too ill-defined to admit a precise mathematical analysis, have to be treated by approximate (fuzzy) solutions. This new approach is receiving more and more attention, not only in research, but also in industrial applications.

Fuzzy controllers were developed to imitate the performance of human expert operators by encoding their knowledge in the form of linguistic rules [Mamdani, 1975]. They provide a complementary alternative to the conventional analytical control methodology. Some authors argue that fuzzy controllers are suitable where a precise mathematical model of the process being controlled is not available [Kickert W. J. M. & Mamdani E. H., 1978] [Li Y. F. & Lau C. C., 1988].

3.2.2 Basic Notions of Fuzzy Logic

In this part, fundamental terms and concepts of fuzzy logic are briefly defined.

3.2.2.1 Fuzzy Set

A general definition of a set can be stated as follows [Kaufmann, 1988]:

“A set is a collection of objects distinct and perfectly specified.”

A subset is a subgroup of a set. For example, let A to be a finite referential set:

$$A = \{a, b, c, d, e, f\}$$

We can form a crisp subset of A , for example:

$$B = \{b, d, f\}$$

In the classical set theory, one element can either belong to a set, or not. This property can be represented by a *degree of membership*. This concept is basic in the classical set theory. However, the main concept of fuzzy theory is a notion of *fuzzy set*. Fuzzy set is an extension of crisp set. Zadeh gave the following definition [Zadeh, 1965]:

A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership (characteristic) function which assigns to each object a grade of membership ranging between zero and one.

After him, many authors found different ways of denoting fuzzy sets. Zimmermann [Zimmerman, 1990] writes:

A fuzzy set is denoted by an ordered set of pairs, the first element of which denotes the element (x) and the second ($\mu_B(x)$) the degree of membership:

$$B = \{(x, \mu_B(x)) \mid x \in X\}$$

where μ_B takes values in the interval $[0,1]$.

Fuzzy sets can be regarded as a generalization of the concept of the classical (crisp) sets whose membership function only requires two values $\{0,1\}$. However, it should be mentioned that a classical set always has a unique membership function, whereas every fuzzy set has an infinite number of membership functions that can represent it [Bezdek, 1993].

3.2.2.2 Linguistic Variable

Fuzzy sets can be used to represent *linguistic variables*. Linguistic variables are the process states and control variables in a fuzzy controller. Their values are defined in linguistic terms. They can be words or sentences in a natural language. For example, for the linguistic variable “*height*”, a set of terms can be defined:

$$H(\textit{height}) = \{\textit{tall}, \textit{medium}, \textit{short}\}.$$

3.2.2.3 Membership Function

Every fuzzy set can be represented by its *membership function*. If the referential set is an infinite set, these values can be represented as a continuous membership function. In general, the shape of a membership function depends of the application, and can be monotonic, triangular, trapezoidal or bell-shaped as shown in Figure 3.2.1.

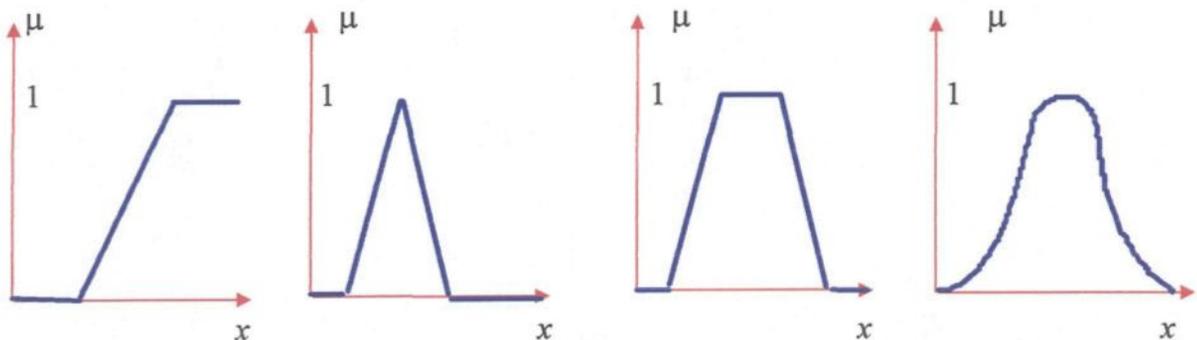


Figure 3.2 : Different shapes of membership functions: monotonic, triangular, trapezoidal and bell-shaped.

3.2.3 Operations on Fuzzy Sets

As operations are defined on classical sets, similar operations are defined on fuzzy sets. However, due to the fact that membership values are no longer restricted to $\{0,1\}$, and can have any value in the interval $[0,1]$, these operators cannot be uniquely defined. Fuzzy set theory offers a vast range of operations that do not exist in the classical theory [Zadeh, 1965].

3.2.3.1 Complement

Complementation in fuzzy set theory corresponds to the complementation in classical set theory. Thus, the membership values in a complement subset are:

$$\mu_{\bar{B}}(x) = \text{not}(\mu_B(x)) = 1 - \mu_B(x)$$

which corresponds to the same operation in the classical theory. The algebra of fuzzy sets is similar to the algebra with ordinary sets except:

$$B \cap \bar{B} \neq \emptyset \quad \text{and} \quad B \cup \bar{B} \neq S$$

This means that the Aristotelian “*non contradiction*” is not acceptable with fuzzy sets.

3.2.3.2 Intersection or Triangular Norms

The extension of the intersection of two classical sets to the intersection of two fuzzy sets is not uniquely defined. It is clear that intersection operation for fuzzy sets should be subject to the intersection of classical sets, because a classical set can be seen as a special case of a fuzzy set. For the intersection of fuzzy sets Zadeh suggested the *min* operator and the *algebraic product* [Zadeh, 1965]. Following Zadeh's idea many researchers proposed various operators for this operation [Zimmermann, 1990].

min operator	$\mu_A(x) \text{ and } \mu_B(x) = \min \{ \mu_A(x), \mu_B(x) \}$
algebraic product	$\mu_A(x) \text{ and } \mu_B(x) = \mu_A(x) * \mu_B(x)$
bounded product	$\mu_A(x) \text{ and } \mu_B(x) = \max \{ 0, \mu_A(x) + \mu_B(x) - 1 \}$
drastic product	$\mu_A(x) \text{ and } \mu_B(x) = \begin{cases} \mu_A(x) & \text{if } \mu_B(x) = 1 \\ \mu_B(x) & \text{if } \mu_A(x) = 1 \\ 0 & \text{if } \mu_A(x), \mu_B(x) < 1 \end{cases}$
Einstein product	$\mu_A(x) \text{ and } \mu_B(x) = \frac{\mu_A(x)\mu_B(x)}{2 - [\mu_A(x) + \mu_B(x) - \mu_A(x)\mu_B(x)]}$
Hamacher product	$\mu_A(x) \text{ and } \mu_B(x) = \frac{\mu_A(x)\mu_B(x)}{\mu_A(x) + \mu_B(x) - \mu_A(x)\mu_B(x)}$

Table 3-2 : Intersection or Triangular Norms of two Fuzzy Sets

Let A and B be two fuzzy sets in U , the universe of discourse, with membership functions μ_A and μ_B respectively. The most important intersection operators are listed in Table 3.2.1.

All these operators belong to the so-called *triangular norms* (T-norms). Functions T define a general class of intersection operators for fuzzy sets and can be parametric or non-parametric.

3.2.3.3 Union Triangular Co-Norms

For the union of two fuzzy sets, there is a class of operators named *triangular co-norms* (T-conorms or S-norms). The most used union operators in the literature are listed in Table 3.2.2.

Suppose that we define two fuzzy sets by their membership functions μ_A and μ_B which have triangular membership functions (dotted lines on Figure 3.2.2.a). The application of *T-norm* (in this example, the operator is *min*) gives the fuzzy set “ A and B ” which is represented by its membership function $\mu_{A \text{ and } B}(x)$ (solid line on Figure 3.2.2.a). The application of *T-conorm* (here *max* operator) on these fuzzy sets gives the fuzzy set represented with solid line as shown in Figure 3.2.2.b.

max operator	$\mu_A(x) \text{ or } \mu_B(x) = \max \{ \mu_A(x), \mu_B(x) \}$
algebraic sum	$\mu_A(x) \text{ or } \mu_B(x) = \mu_A(x) + \mu_B(x) - \mu_A(x) * \mu_B(x)$
bounded sum	$\mu_A(x) \text{ or } \mu_B(x) = \min \{ 1, \mu_A(x) + \mu_B(x) \}$
drastic sum	$\mu_A(x) \text{ or } \mu_B(x) = \begin{cases} \mu_A(x) & \text{if } \mu_B(x) = 0 \\ \mu_B(x) & \text{if } \mu_A(x) = 0 \\ 1 & \text{if } \mu_A(x), \mu_B(x) > 0 \end{cases}$
Einstein sum	$\mu_A(x) \text{ or } \mu_B(x) = \frac{\mu_A(x) + \mu_B(x)}{1 + \mu_A(x)\mu_B(x)}$
Hamacher sum	$\mu_A(x) \text{ or } \mu_B(x) = \frac{\mu_A(x) + \mu_B(x) - 2\mu_A(x)\mu_B(x)}{1 - \mu_A(x)\mu_B(x)}$

Table 3-3 : Union Triangular Co-Norms of two Fuzzy Sets

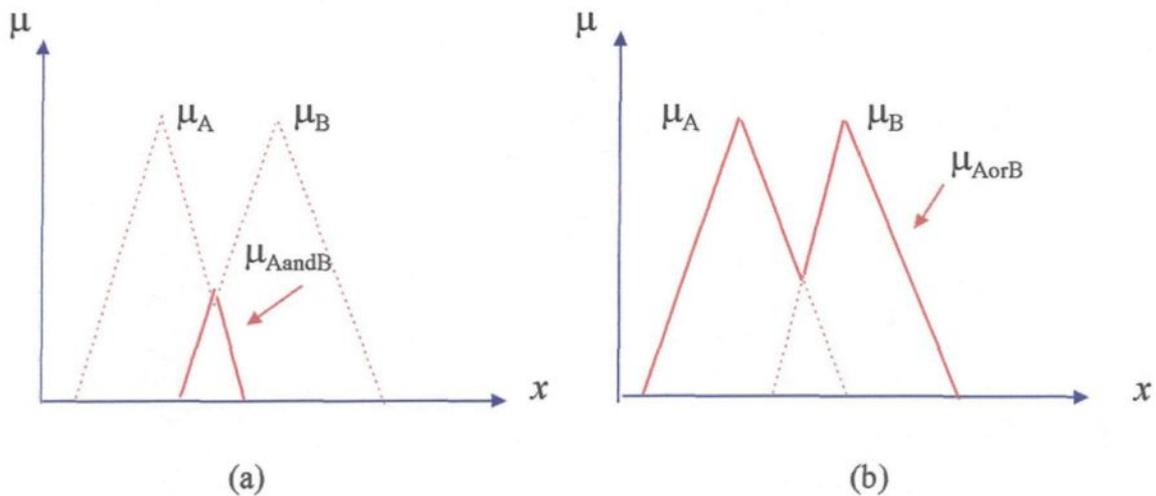


Figure 3.3 : Graphical representation of operations with fuzzy set; (a) Triangular norm (min operator); (b) Triangular co-norm (max operator).

3.2.4 Notion of Linguistic Rule

The principal idea of fuzzy logic systems is to express human knowledge in the form of linguistic *if-then* rules. Every rule has two parts:

- *antecedent* or *premise* part, expressed by *If ...and ...*
- *consequent* part, expressed by *then ...*

The antecedent part is the description of *the state* of the system, and the consequent is *the action* that the operator who controls the system must take. There are several forms of *if-then* rules. Zadeh was the first who introduced the notion of fuzzy rule [Zadeh, 1973].

The general form of this rule is:

Rule: *If x is A, then y is B.*

Example: *If the temperature is High, then the pressure is Low*

3.2.5 General Structure of Fuzzy Systems

Fuzzy Inference Systems (FIS) are also known as *fuzzy models*, *Fuzzy Associative Memories (FAM)*, *fuzzy-rule-based systems*, and *fuzzy controller*, when used as controllers.

Basically *FIS* are composed of five functional blocks (Figure 3.2.3.):

1. **Rule base:** containing a number of fuzzy *if-then* rules;
2. **Database:** defines the membership functions of the fuzzy sets and their parameters used in the fuzzy rules. Usually, the *rule base* and the *database* are jointly referred to as the *knowledge base*;
3. **Decision-making unit:** performs the inference operations on the rules;
4. **Fuzzification interface:** transforms the crisp inputs into a degree of match with linguistic variables
5. **Defuzzification interface:** transforms the fuzzy results into a crisp output

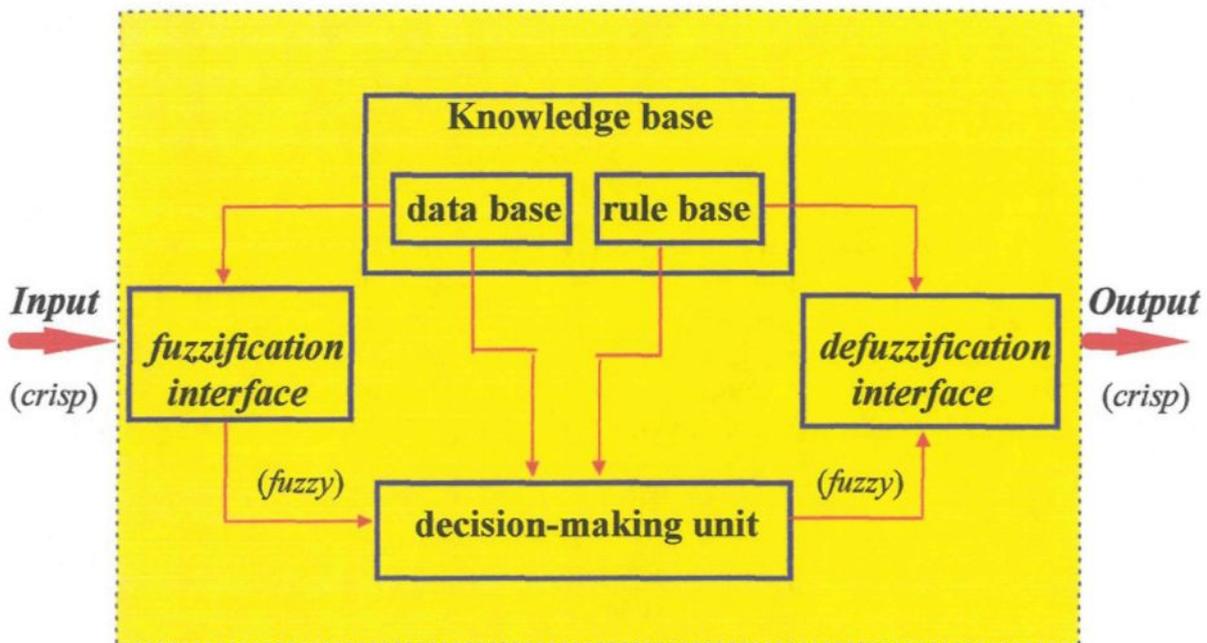


Figure 3.4 : *Fuzzy Inference System*

3.2.5.1 Procedure of Fuzzy Reasoning

The following steps are performed by fuzzy inference systems to obtain *fuzzy reasoning* (inference operations upon fuzzy if-then rules).

1. This step which is often called *fuzzification*, compares the input variables with the membership functions on the antecedent to obtain the membership values of each linguistic label.
2. Application of the T-norm (usually *min* or *product*) on the membership values of the antecedent part of the rules to get *firing strength* or the *weight* for each rule.
3. Generation of the *consequent value* of each rule. It can be fuzzy or crisp.
4. This step which is called *defuzzification*, aggregates the qualified consequents to produce a crisp output.

The first step in the application of fuzzy reasoning is a *fuzzification* of inputs in the controller. It means that to every crisp value of input we attribute a set of degrees of membership ($\mu_j, j=1, \dots, n$) to fuzzy sets defined in the universe of discourse for that input. The next step is the application of the linguistic rules. A fuzzy controller consists of a set of control rules which are combined using the sentence connectives. Suppose that a fuzzy system has two inputs x, y and one output z , and that n linguistic rules have been defined as follows:

If x is A_1 and y is B_1 then z is C_1

If x is A_2 and y is B_2 then z is C_2

...

If x is A_n and y is B_n then z is C_n

where x , y and z are linguistic variables representing the process state variables and the control variable; A_i , B_i and C_i ($i = 1, \dots, n$) are fuzzy sets defined in the universe of discourse for x , y and z respectively.

In mathematical sense, activation of the rules is the application of *T-norm* [Lee, 1990], in order to get a firing strength for every rule. Usually, it means that the operator *min* or *product* is applied on membership values. It is denoted here by w_i :

$$w_i = \min(\mu_A(x), \mu_B(y))$$

Consequently, the firing strengths are combined using the compositional operator, which expresses the sentence connective, and the consequent value (fuzzy or crisp) is generated.

Finally, defuzzification is performed in order to get crisp output. Figure 3.2.4. shows the fuzzy system.

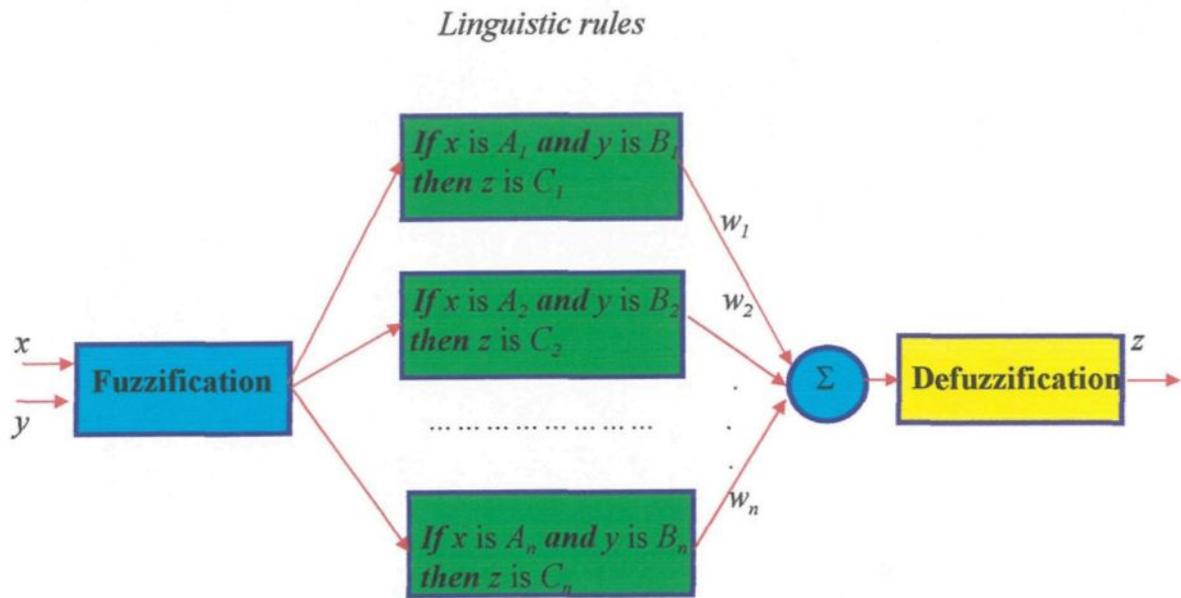


Figure 3.5 : General structure of the fuzzy system.

3.2.5.2 Type of Fuzzy Reasoning

There are several types of fuzzy reasoning. The most important, in the literature, are:

Type 1: Max dot method. The final output membership function for each output is the union of the fuzzy sets assigned to that output in a conclusion, after scaling their degree of membership values to peak at the degree of membership for the corresponding premise [Zimmermann, 1990].

Type 2: Min max method. The final output membership function is the union of the fuzzy sets assigned to that output in a conclusion, after cutting their degree of membership values at the degree of membership for the corresponding

premise. The crisp value of output is the center of gravity of the resulting fuzzy set [Lee, 1990].

Type 3: Tsukamoto's method. The output membership function has to be monotonically non-decreasing. Then, the overall output is the weighted average of the crisp output of each rule induced by the rule strength and the output membership functions [Tsukamoto, 1979].

Type 4: Takagi and Sugeno method. The output of each rule is a linear combination of input variables. The crisp output is the weighted average of the output of each rule [Jang, 1993].

To illustrate these four types of fuzzy reasoning, we will consider a system with only two rules, as follows;

R₁: *If x is A₁ and y is B₁ then z is C₁*

R₂: *If x is A₂ and y is B₂ then z is C₂*

The decision procedure for the four types of fuzzy inference systems is shown on Figure 3.2.5. Fuzzy operator *and* is *min*.

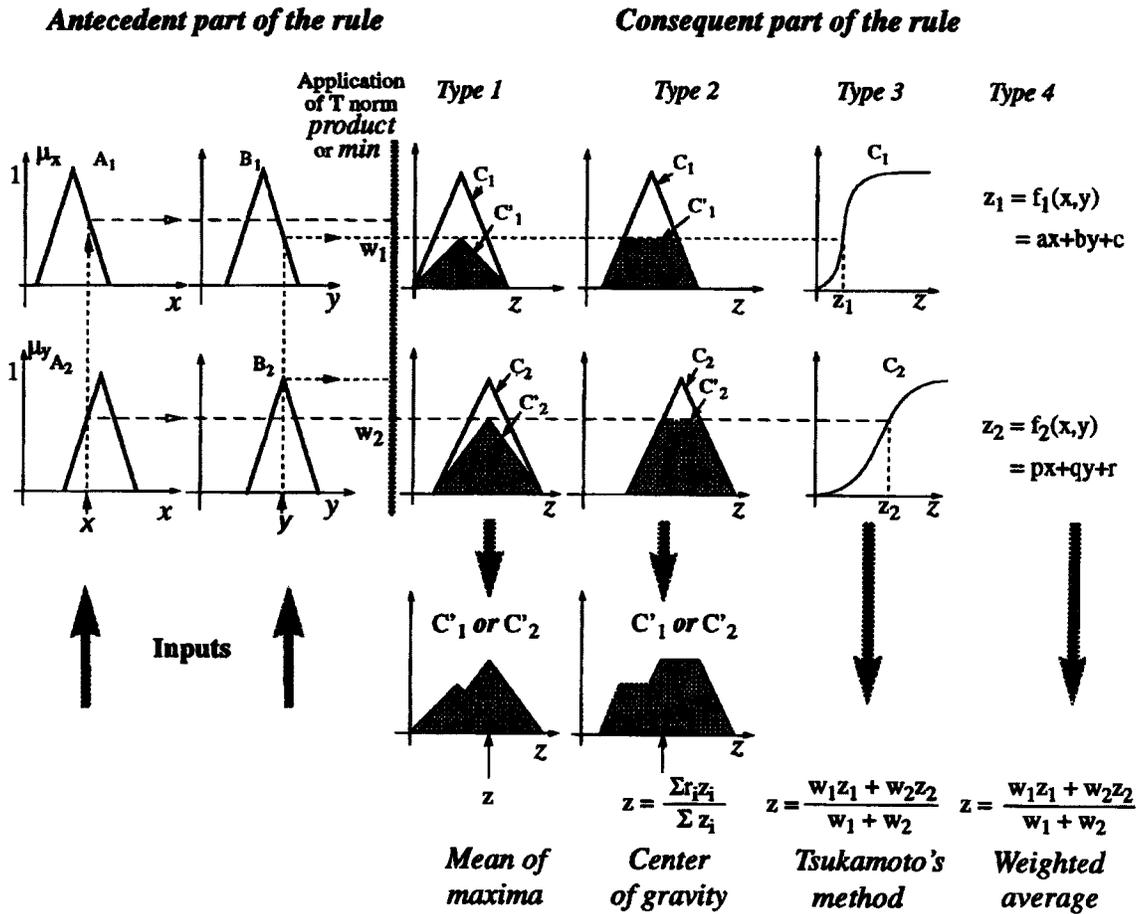


Figure 3.6 : Four types of reasoning in fuzzy inference systems.

3.2.5.3 Defuzzification Strategies

Defuzzification is an operation aiming to produce a non-fuzzy control action. It transforms a union of fuzzy sets into a crisp value. Several methods for defuzzification are proposed in the literature. The most important methods are mentioned below.

- ***The center of gravity method*** : This widely used method generates a center of gravity (or center of area) of the resulting fuzzy set of a control action. If we discretize the universe it is:

$$z = \frac{\sum_{i=1}^n r_i z_i}{\sum_{i=1}^n z_i}$$

where n is the number of quantisation levels, r_i is the amount of control output at the quantisation level i and z_i represents its membership value [Berenji, 1992].

- ***The mean of maximum method*** : The mean of maximum method generates a crisp control action by averaging the support values which their membership values reach the maximum. In the case of discrete universe:

$$z = \sum_{i=1}^l \frac{r_i}{l}$$

where l is the number of the quantized r values which reach their maximum membership [Lee, 1990].

- ***Tsukamoto's method*** : If monotonic membership functions are used, then the crisp control action can be calculated as follows:

$$z = \frac{\sum_{i=1}^n w_i z_i}{\sum_{i=1}^n w_i}$$

- **The weighted average method** : This method is used when the fuzzy control rules are the functions of their inputs [Takagi, 1983] as shown in the Figure 3.2.5 for type 4. In general, the consequent part of the rule is:

$$z = f(x, y)$$

If w_i is the firing strength of the i th rule, then the crisp value is given by:

$$z = \frac{\sum_{i=1}^n w_i f(x_i, y_i)}{\sum_{i=1}^n w_i}$$

where n is the number of firing rules.

SECTION THREE

3.3.1 What are Neuro-Fuzzy Systems ?

In the design of a conventional *fuzzy system*, the user must tune by trial-and-error the membership functions of fuzzy sets defined in the input and output universes of discourse. This drawback is eliminated with *neuro-fuzzy systems* [Jang J.-S. R. & Sun C. T.,1995] [Wang L. X., 1994] which combine the advantages of neural networks and fuzzy systems. By employing supervised learning methods, it is now possible to optimize both the antecedent and consequent parts of a linguistic *rule-base* fuzzy system.

This section introduces *neuro-fuzzy systems* which combine the properties of neural networks and fuzzy systems. First, the background and the taxonomy of neuro-fuzzy systems are presented. After, the interest is focused on knowledge structure, network architecture and learning algorithm.

3.3.2 Background of Neuro-Fuzzy Systems

In the previous sections, neural networks and fuzzy logic systems were presented. It was noted that neural networks have two main benefits. First, they are capable of learning non-linear mapping of numerical data. Second, they perform parallel computation. However, the operation of neural networks have also many weaknesses. For example, in

the popular *multi-layer perceptron network*, the knowledge of the system is distributed into the whole network as synaptic weights. Therefore, it is very hard to understand the meaning of weights, and the incorporation of prior knowledge into the system is usually impossible. Although the knowledge of *Radial Basis Function (RBF)* and *self-organizing map neural networks* is in a more comfortable form, it cannot be easily extracted into linguistic rules. Fuzzy logic uses linguistic terminology to express the knowledge of the system. This makes possible a close interaction between the system and a human operator, which is a very desirable property of fuzzy logic system. But since, in general, knowledge acquisition is difficult and the universe of discourse of each input variable needs to be divided into several intervals, applications of fuzzy systems are restricted to the fields where expert knowledge is available and where the number of input variables is small.

The aim of neuro-fuzzy systems, as is shown in Figure 3.3.1, is to combine collectively the benefits of both approaches. Simply, the operation of the system is expressed as linguistic fuzzy expression and learning schemes of neural networks are used

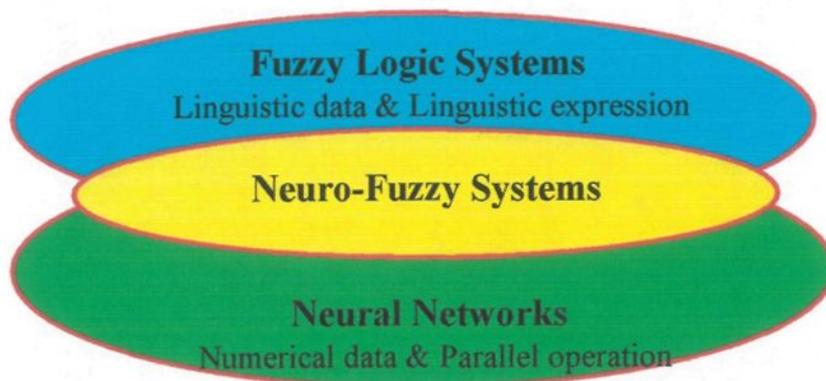


Figure 3.7 : Neuro-fuzzy systems integrate fuzzy logic and neural networks.

to train the system. In addition, neuro-fuzzy systems allow incorporation of both numerical and linguistic data into the system. The neuro-fuzzy system is also capable of extracting fuzzy knowledge from numerical data, which is an important property [Abe & Lan, 1995].

The neuro-fuzzy systems can be divided into two main groups:

1. Neural fuzzy inference systems
2. Fuzzy neural networks

The origin idea of neural fuzzy inference systems is to incorporate neural concepts, such as learning and parallelism, into fuzzy logic inference systems (fuzzy controllers, in the context of control applications). Neural fuzzy inference systems realize fuzzy inference [Berenji, 1992] [Halgamuga & Glenser, 1994] [Jang, 1993]. The architecture of the systems are parallel, and they exploit the same learning algorithms, as used with neural networks.

In fuzzy neural networks [Gupta & Rao, 1994] [Pal & Mitra, 1992] [Pedrycz, 1992], the fuzzy ideas are incorporated into neural networks. Lee and Lee [Lee & Lee, 1975] are the first who worked on neuro-fuzzy systems, especially on fuzzy neural networks. Their approach replaced the weighted sum of the *McCulloch-Pitts* neuron by a corresponding fuzzy operation. The operation of their neuro-fuzzy system was exactly the same as the *McCulloch-Pitts* neural network. Unfortunately, they did not provide any training rule for the network.

In this research, we are interested in neural fuzzy inference systems, which will be described in greater detail below. Then, a specific type of neuro-fuzzy systems called *ANFIS*, will be introduced.

3.3.3 Neural Fuzzy Inference Systems

The basic idea in neural fuzzy inference systems is to incorporate parallel architecture and learning capability to fuzzy inference systems. These systems are implemented as multi-layer networks [Jang, 1993], and they were trained using a hybrid learning algorithm which consists of the *gradient descent* and *least squares estimate methods*. Moreover, close functional similarities between fuzzy inference systems and *RBF* networks were also noticed [Jang, 1993] [Nie & Linkens, 1993] [Wang & Mendel, 1992]. In the following sections, knowledge structures and learning schemes of neural fuzzy inference systems are presented.

3.3.3.1 Knowledge Structure and Linguistic Variables

Fuzzy rules are the fundamental part of the knowledge base in a fuzzy inference system. These rules define behavior of a system or process. In practice, there are three typical forms of fuzzy rules used in neuro-fuzzy systems.

The fuzzy reasoning rules can be divided into three main types [Jang, 1993]. For simplicity, only the two-input, single-output model of the neuro-fuzzy system is presented.

As Figure 3.3.2 illustrates, three types of the fuzzy rules can be described as follows:

Type 1: The output membership functions used in this scheme must be monotonically non-decreasing [Tsukamoto, 1979]. The overall output is the weighted average of the crisp output of each rule induced by the firing strength of the rule (usually is the *product* or *minimum* of the degrees of match with the premise part) and output membership functions.

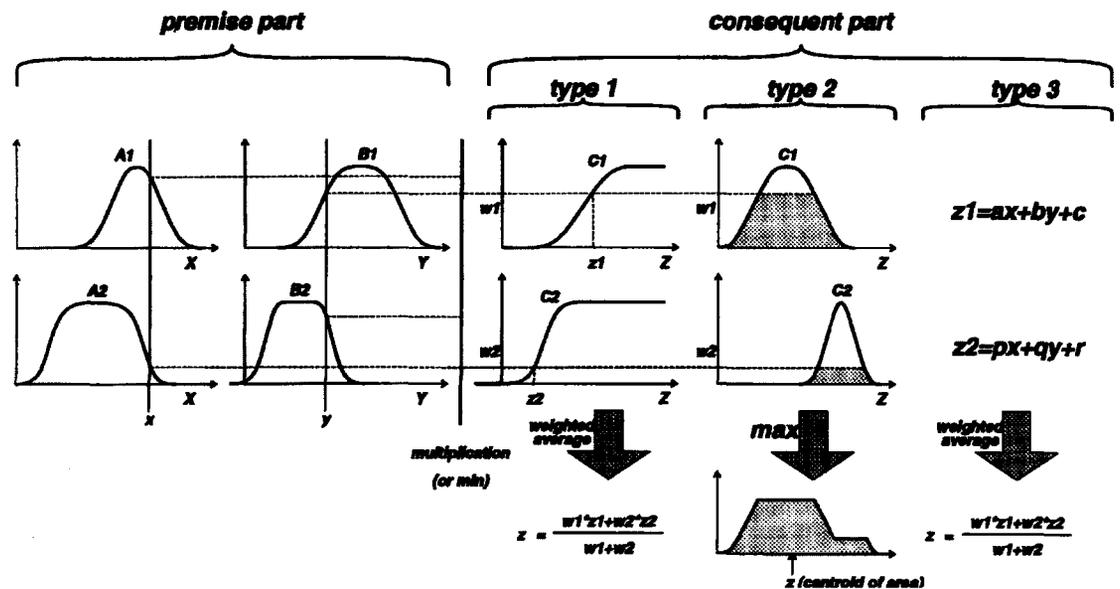


Figure 3.8 : Fuzzy if-then rules and fuzzy reasoning mechanisms.

Type 2: The overall fuzzy output is derived by applying “*max*” operation to the qualified fuzzy outputs (each of which is equal to the minimum of firing strength and the output membership function of each rule). Various schemes have been proposed to choose the final crisp output based on the overall fuzzy output; some of them are *center of area*, *bisector of area*, *mean of maxima*, *maximum criterion*, etc. [Lee (1), 1990] [Lee (2), 1990].

Type 3: Takagi and Sugeno’s fuzzy if-then rules are used [Takagi & Sugeno, 1983, 1985]. The output of each rule is a linear combination of input variables plus a constant term, and the final output is the weighted average of the output of each rule.

3.3.3.2 Network Architecture

The fuzzy logic inference system can be considered as a five-layer artificial neural network, as shown in Figure 3.3.3. This type of architecture is the most popular among neural fuzzy inference systems. Since we have used *ANFIS*, which stands for *Adaptive- Network-based Fuzzy Inference System*, in this research, the architecture of *ANFIS* is explained. For simplicity, the fuzzy inference system which has only two inputs x and y and one output z is considered. It should be noted that the third type of fuzzy rule is used. In addition, suppose that the rule base comprises only two fuzzy rules of Takagi and Sugeno’s type:

Rule 1: If x is A_1 and y is B_1 , then $f_1 = p_1x + q_1y + r_1$

Rule 2: If x is A_2 and y is B_2 , then $f_2 = p_2x + q_2y + r_2$

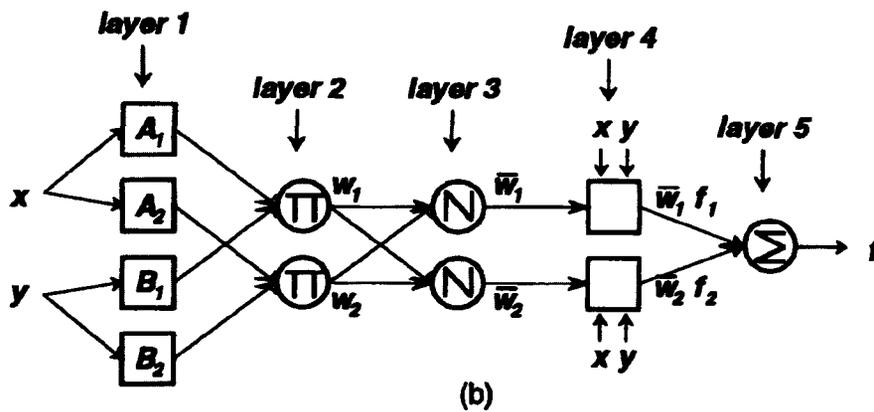
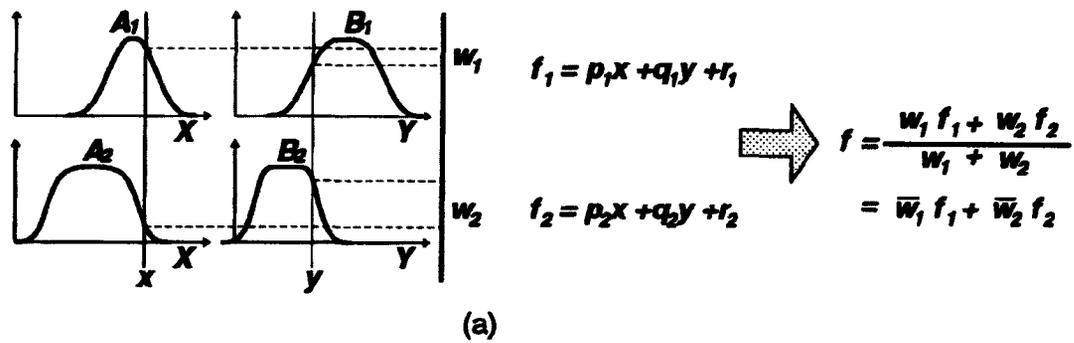


Figure 3.9 : (a) type-3 fuzzy reasoning; (b) equivalent ANFIS (type-3 ANFIS).

The operation ANFIS can be described layer by layer as follows:

Layer 1) Fuzzification

This layer consists of linguistic labels such as *small, large, cold, warm*, etc. The crisp inputs x and y are fuzzified by using membership functions of the linguistic variables A_i and B_i . Usually, the membership functions are chosen to be bell-shaped with maximum equal to 1 and minimum equal to 0, such as the *generalized bell function*

$$\mu_{A_i}(x) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i} \right)^2 \right]^{b_i}}$$

or the *Gaussian function*

$$\mu_{A_i}(x) = \exp \left[- \left(\frac{x - c_i}{a_i} \right)^2 \right]$$

where $\{a_i, b_i, c_i\}$ or $\{a_i, c_i\}$ in the latter case, is the parameter set. As the values of these parameters change, the membership function is modified and various forms of membership functions on the linguistic label A_i are obtained. In fact, any continuous and piecewise differentiable function, such as commonly used *trapezoidal* or *triangular-shaped* membership functions, are qualified candidates. Parameters in this layer are referred to as *premise parameters*.

LAYER 2) Rule nodes

The second layer contains one node for each fuzzy *if-then* rule. Each rule node performs connective operation, between the rule antecedent (*if-part*). Usually, the *minimum* or the *product* is used as intersection **AND**. For instance,

$$w_i = \mu_{A_i}(x) * \mu_{B_i}(y), \quad i = 1,2.$$

Each node output represents the firing strength of a rule.

Layer 3) Normalization

In this layer, the firing strengths of the fuzzy rules are normalized according to

$$\bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1,2.$$

Layer 4) Consequence layer

Every node in this layer is related to rule consequent (*then-part*) with a node function:

$$\bar{w}_i f_i = \bar{w}_i (p_i x + q_i y + r_i),$$

where \bar{w}_i is the output of the previous layer, and $\{p_i, q_i, r_i\}$ is the parameter set. These parameters are referred to as *consequent parameters*.

Layer 5) Summation

This layer computes the overall output as the summation of the incoming signals:

$$\text{overall output} = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i}$$

Thus, an adaptive network, which is functionally equivalent to a type-3 fuzzy inference system, has been constructed.

3.3.3.3 Learning Algorithm

The learning of the neuro-fuzzy system can be divided into two main parts:

- structure identification
- parameter identification

The former is related to finding a suitable number of fuzzy rules and a proper partitioning of input and output space. The latter deals with the adjustment of system parameters, such as membership function parameters.

There are several learning algorithms for neuro-fuzzy systems. Jang [Jang, 1993] proposed a learning scheme, called *hybrid learning algorithm*, which is a combination of the *least-squares estimate (LSE)* and the *gradient descent* for tuning the *ANFIS* architecture. The system is initialized with a number of membership functions and a fixed rule base. The learning scheme consists of two separate passes. In the forward pass, input signals go forward until they reach to the output layer, and the consequent parameters are identified by the *LSE*. In the backward pass, the error rates propagate backward and the premise parameters are updated by the *gradient descent*.

Chapter 4

Neuro-Fuzzy Models

4.1 Introduction

In this chapter, two neuro-fuzzy models for a non-linear three-phase power transformer are developed. First, their structures and architectures are explained. After determination of the architecture, the models should be trained by a set of inputs/outputs. To acquire the dynamic behavior of a system, a set of inputs/outputs which includes sufficient dynamic behavior of a system should be presented to the neuro-fuzzy models. This set of inputs/outputs data is called *training data*. The generalization of the dynamic behavior of a system depends on the training data. This means that by increasing the amount of information in the training data files, a neuro-fuzzy system learns more about a process, or system under consideration, and it can better generalize the dynamic behavior of a system.

As shown by Narendra and Parthasarathy [Narendra & parthasarathy, 1990], there are two schemes for identification of a system:

- Parallel model
- Series-parallel model

Since the series-parallel model converges faster and it is more accurate, in practice, this model is employed.

After determining the architecture of the models, a training algorithm should be selected to train the neuro-fuzzy models. An epoch number, which is the number of passes through all of the training input and target vectors, and an error goal should be chosen. The training process stops if the designated epoch number is reached or the error goal is achieved, whichever comes first.

4.2 Identification

Identification consists of setting up a suitably parameterized identification model and adjusting the parameters of the model to minimize a cost function based on the error between the plant and the identification model outputs. However, as shown in what follows, suitable precautions have to be taken to ensure that the procedure results in convergence of the identified model parameters to their desired values. In general, there are two identification models as follows:

1. *Parallel Identification Model*

Suppose that we want to identify the discrete nonlinear system

$$y(k+1) = f(y(k), \dots, y(k-n+1); x(k), \dots, x(k-m+1)) \quad (4-1)$$

where x and y are the input and output, respectively, n and m are positive integers, and f is an unknown function. In parallel identification model, the output of the identification

model is fed back to the model to predict the value of the output in $k+1$, and it can be written:

$$\tilde{y}(k+1) = \tilde{f}(\tilde{y}(k), \dots, \tilde{y}(k-n+1); x(k), \dots, x(k-m+1)) \quad (4-2)$$

where \tilde{f} is a neuro-fuzzy system, and \tilde{y} is the output of the identification model. Figure 4.1 shows the parallel model.

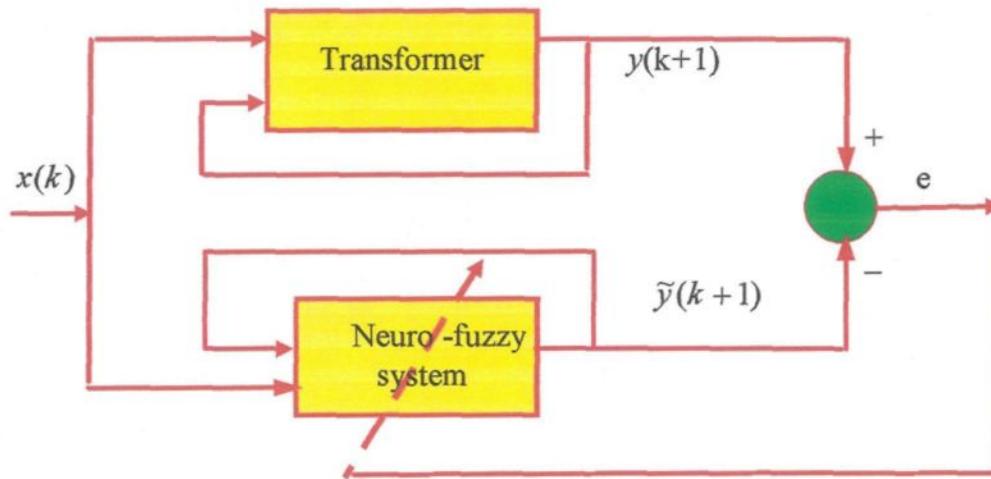


Figure 4.1 : Basic scheme of the parallel identification model using neuro-fuzzy systems.

When a parallel model is used, there is no guarantee that the parameters will converge or that the output error will tend to zero. Conditions under which the parallel model parameters will converge even in the linear case are not known, therefore, another identification is preferred which is known as *series-parallel model*.

2. Series-Parallel Identification Model

In contrast to the parallel model which was described above, in the series-parallel model the output of the plant (rather than the identification model) is fed back into the identification model as shown in Figure 4.2. This implies that in this case, the identification model has the form

$$\tilde{y}(k+1) = \tilde{f}(y(k), \dots, y(k-n+1); x(k), \dots, x(k-m+1)) \quad (4-3)$$

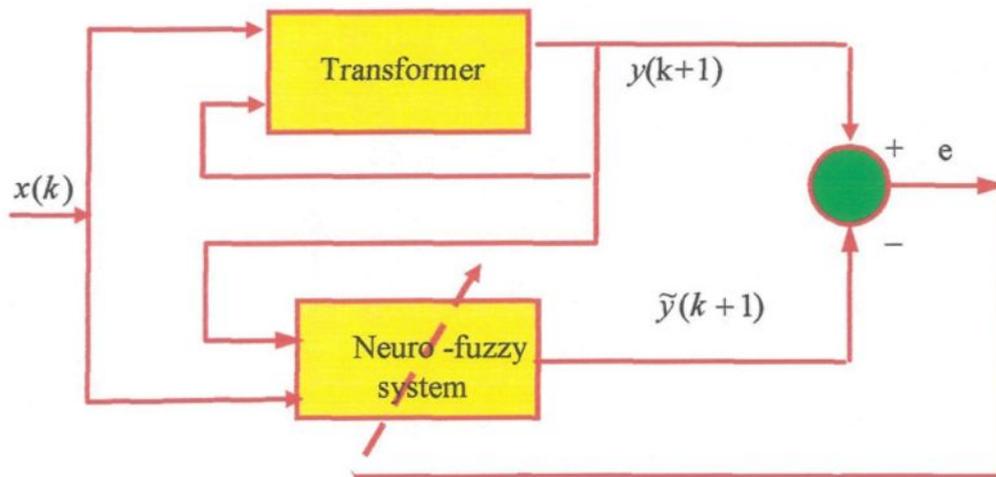


Figure 4.2 : Basic scheme of the series-parallel identification model using neuro-fuzzy systems

As shown by Narendra and Parthasarathy [Narendra and Parthasarathy, 1990], the series-parallel model is better than the parallel model, and it has several advantages. Since the plant is assumed to be BIBO stable, all the signals used in the identification procedure

are bounded. Further, since no feedback loop exists in the model, static back propagation can be used to adjust the parameters reducing the computational overhead substantially. Finally, assuming that the output error tends to a small value asymptotically, so that $y(k) \approx \tilde{y}(k)$, the series-parallel model may be replaced by a parallel model without serious consequences. This has practical implications if the identification model is to be used off-line. Therefore, considering the above mentioned advantages, the series-parallel model is selected.

4.3 Structure of the Neuro-Fuzzy System

First, the input and output variables should be identified. In general, the output variable is usually easy to identify since it is the variable that is challenged to predict it. The inputs, however, are not as easy to determine, because it is not always obvious which input variables affect the output. Due to the difficulty in determining which variables affect the output, it is typical in modeling to over-collect data. One may collect as many variables as one believes contribute to the output. Later in the analysis, some type of statistical or correlation technique is used to identify the input variables that actually contribute to the output.

To use the redundancy of information, two models are developed. In the first model, which is called *direct model*, the primary and secondary currents at instance t are used as input in order to predict the value of the secondary current at instance $t+1$. The second

model, which is called *indirect model*, uses the same inputs to predict the value of the primary current at instance $t+1$. Figures 4.3 and 4.4 show the schematic diagrams of each model.

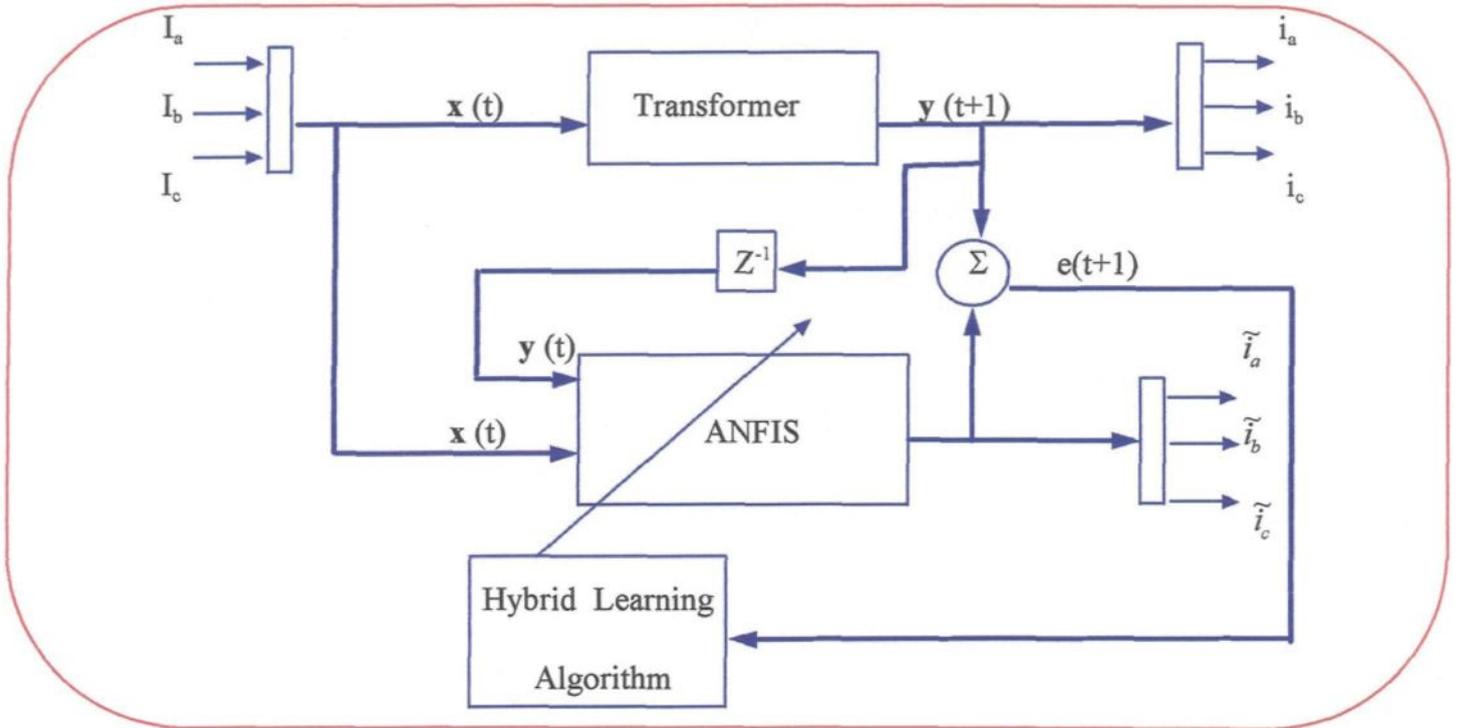


Figure 4.3 : Direct Model

An important aspect of the structure of the model is the use of the currents of the other phases instead of using *unit-delay elements* (denoted by z^{-1}). Since the inputs are the primary and secondary currents of the transformer, we can assume that the current in phase b and c are similar to the current in phase a with a delay (120 degree electrically).

Therefore, the currents of the other phases are used as the feedback and *unit-delay elements*.

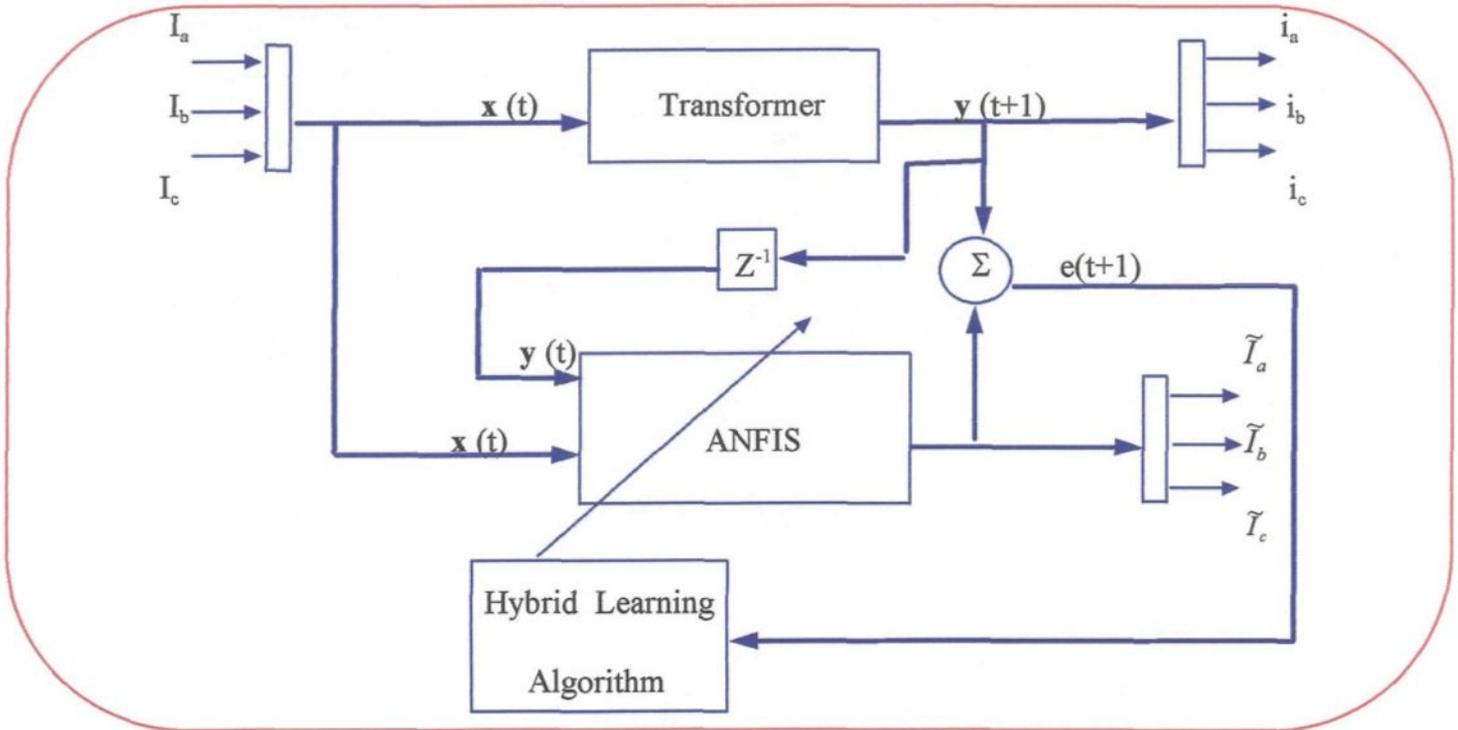


Figure 4.4 : Indirect Model

In neuro-fuzzy system, basically there are three types of input space partition:

- grid partition
- tree partition
- scatter partition

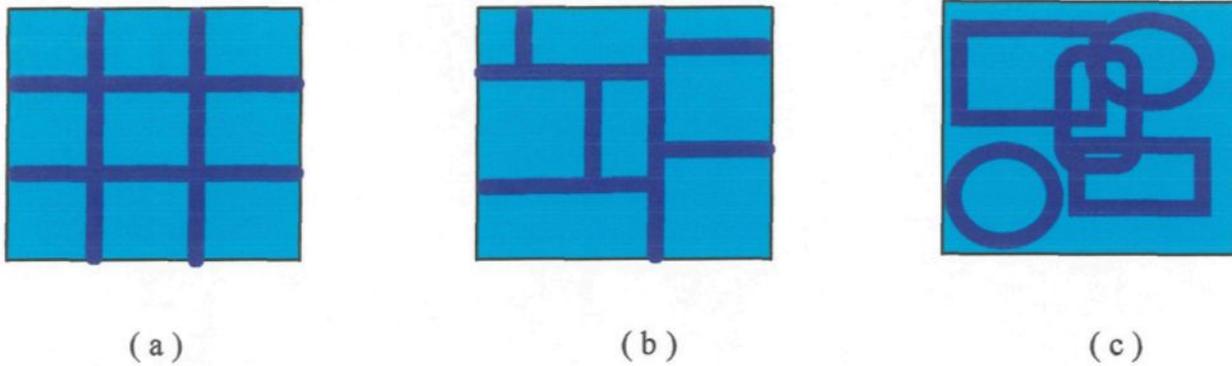


Figure 4.5 : *Various methods of partition the input space : (a) grid partition; (b) tree partition, (c) scatter partition.*

As it is shown in Figure 4.5 (a), grid partition consists of all possible combinations of membership functions of all inputs. This leads to an exponential explosion even when the number of inputs is moderately large. For instance, for a system with 10 inputs, each with two membership functions, the grid partition leads to 1024 (2^{10}) rules, which is prohibitively large for any practical learning methods. This situation, where the number of fuzzy rules in a grid partition increases exponentially with the number of input variables, is called *curse of dimensionality*.

Figure 4.5 (b) shows a typical tree partition, in which each region can be uniquely specified along a corresponding decision tree. The tree partition relieves the problem of an exponential increase in the number of rules. However, more membership functions for each input are needed to define these fuzzy regions, and these membership functions do not usually bear clear linguistic meanings such as *small*, *big* and so on.

Scatter partition uses a clustering algorithm to determine different clusters in the whole input space which determine regions of possible occurrence of the input vectors. This method which is shown in Figure 4.5 (c), can limit the number of rules to a reasonable amount.

Grid partition is supported in MATLAB. Therefore, this method is used for partitioning of the whole input space. To avoid the *curse of dimensionality* problem, only 2 membership functions for each input are considered.

There are several types of membership functions. In MATLAB, eleven types of membership functions are provided. The only condition a membership function must really satisfy is that it must vary between 0 and 1. A *triangular* membership function is selected because it is a simple membership function and the calculation is done faster. On the other hand, in contrast to a *generalized Bell-shape* membership function, which is saturated near its center, a *triangular* membership function does not suffer this pitfall. This is an important consideration because when the currents increase, and there is a short-circuit or over-load, the *generalized Bell-shape* membership function does not let the model follow the variation of currents in saturation regions. However, there is not any saturation region for the *Triangular* membership function.

It should be noted that *grid partition* and the *triangular* membership function are used only for the premise of the *if-then rules*, while the *Sugeno fuzzy model* (also called *TSK fuzzy model*) is used for the consequences of the *if-then rules*. The *Sugeno fuzzy model* has several advantages and it can be more expressive than the *Mamdani fuzzy model*.

Because it is a more compact and computationally efficient representation than the *Mamdani fuzzy model*, the *Sugeno fuzzy model* lends itself to adaptive techniques. The advantages of the *Sugeno fuzzy model* are as follows [Jang & Gulley, 1995]:

- Computational efficiency
- Works well with linear techniques
- Works well with optimization and adaptive techniques
- Guaranteed continuity of the output surface
- Better suited to mathematical analysis

A typical fuzzy rule in a *Sugeno fuzzy model* has the form

$$\text{if } x \text{ is } A \text{ and } y \text{ is } B \text{ then } z = f(x, y)$$

where A and B are fuzzy sets in the antecedent, while $z = f(x, y)$ is a crisp function in the consequent. A first-order polynomial is used instead of $f(x, y)$, which is called a *first-order Sugeno fuzzy model*. Therefore, the parameters of the consequent are linear parameters which can be adjusted by the *Least Square Method* (LSM), which will be explained in the next section.

4.4 Learning Algorithm

According to ANFIS architecture, the output of the model can be expressed as a linear combination of the consequent parameters, if the values of premise parameters are given. For example consider a neuro-fuzzy system with two inputs and one output, and with only two *if-then* rules, as in Figure 4.6.

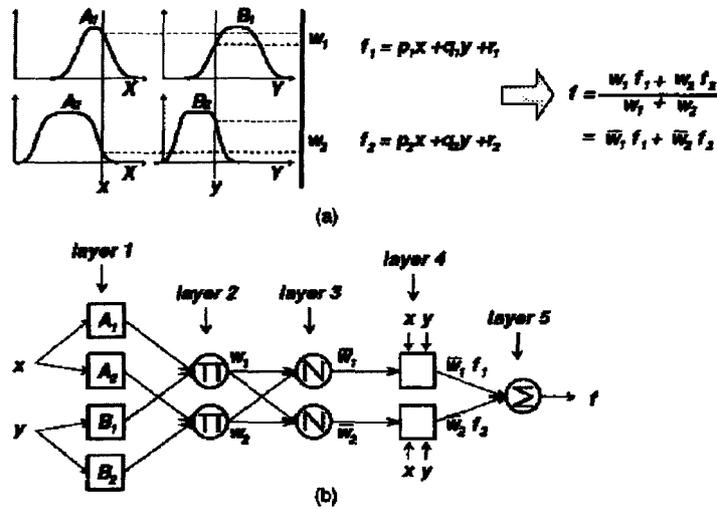


Figure 4.6 : (a) fuzzy reasoning; (b) Equivalent ANFIS

The output f can be written as

$$f = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2$$

$$f = \bar{w}_1 f_1 + \bar{w}_2 f_2 \quad (4 - 4)$$

$$f = (\bar{w}_1 x) p_1 + (\bar{w}_1 y) q_1 + (\bar{w}_1) r_1 + (\bar{w}_2 x) p_2 + (\bar{w}_2 y) q_2 + (\bar{w}_2) r_2$$

which is linear in the consequent parameters $\{p_1, q_1, r_1, p_2, q_2, r_2\}$. Now, given the values of premise parameters, we can apply P training data to the system and obtain a matrix equation:

$$A\Theta = B \quad (4 - 5)$$

where Θ is an unknown vector whose elements are consequent parameters. This equation represents the standard linear least-squares problem and the best solution for Θ , which minimize $\|A\Theta - B\|^2$, is the *least-squares estimator* (LSE) Θ^* :

$$\Theta^* = (A^T A)^{-1} A^T B, \quad (4 - 6)$$

where A^T is the transpose of A and $(A^T A)^{-1} A^T$ is the pseudo-inverse of A if $A^T A$ is non-singular.

After the values of consequent parameters are identified, the gradient descent method can be used to adjust the values of premise parameters in order to minimize the error of the model. The error signal for each training data entry is defined by,

$$e(n) = d(n) - y(n) \quad (4 - 7)$$

where n represents the n th training data entry. The overall error measure is,

$$E = \sum_1^P e(n) \quad (4 - 8)$$

and with using of the chain rule, the correction value for each premise parameters can be calculated:

$$\Delta p_i = -\eta \frac{\partial E}{\partial p_i} \quad (4 - 9)$$

$$p_{i,new} = p_{i,old} + \Delta p_i$$

Therefore, the hybrid learning algorithm is used for identification of the three-phase power transformer. In short, to apply the hybrid learning algorithm in a batch mode, each epoch is composed of a forward and a backward pass. In the forward pass, after an input vector is applied, the outputs of the nodes in the network are calculated layer by layer until the final output is obtained. In this way, the matrices A and B are constructed, and by using equation (4 - 6), the parameters of consequent are identified. In the backward pass, the consequent parameters are fixed and the error signals propagate from the output end toward the input end. Then, the gradient vector is accumulated for each training data entry. Finally, the premise parameters are updated by the gradient descent method in equation 4 - 9. Table 4.1. summarizes the hybrid learning algorithm.

	FORWARD PASS	BACKWARD PASS
premise parameters	fixed	gradient descent
consequent parameters	least squares estimate	fixed
signals	node outputs	error rated

Table 4-1 : Hybrid learning procedure for ANFIS

4.5 Training Data

As mentioned above, training data should include rated conditions of a three-phase power transformer in addition to dynamic transients of the transformer. Since neuro-fuzzy systems are self-learning systems, that is they learn the behavior of systems by observing different values of inputs/outputs, a well-prepared training data plays a significant role in the validation and generalization of a model. In other words, the key point to remember is to have enough data that are well-distributed in the process operating range. A neuro-fuzzy system is only as good as the data with which it was trained.

After determining the structure of the neuro-fuzzy system, the training data should be applied to train the system. There are four training data files. Each file contains 3840 sampling data of primary and secondary currents, applied voltages and load voltages. They also include the sampling times. Figures 4.7, 4.8, 4.9, and 4.10 show the training data files. It should be noted that a resistive load is connected to the secondary side of the transformer. Therefore, the secondary currents and secondary voltages have similar waveforms.

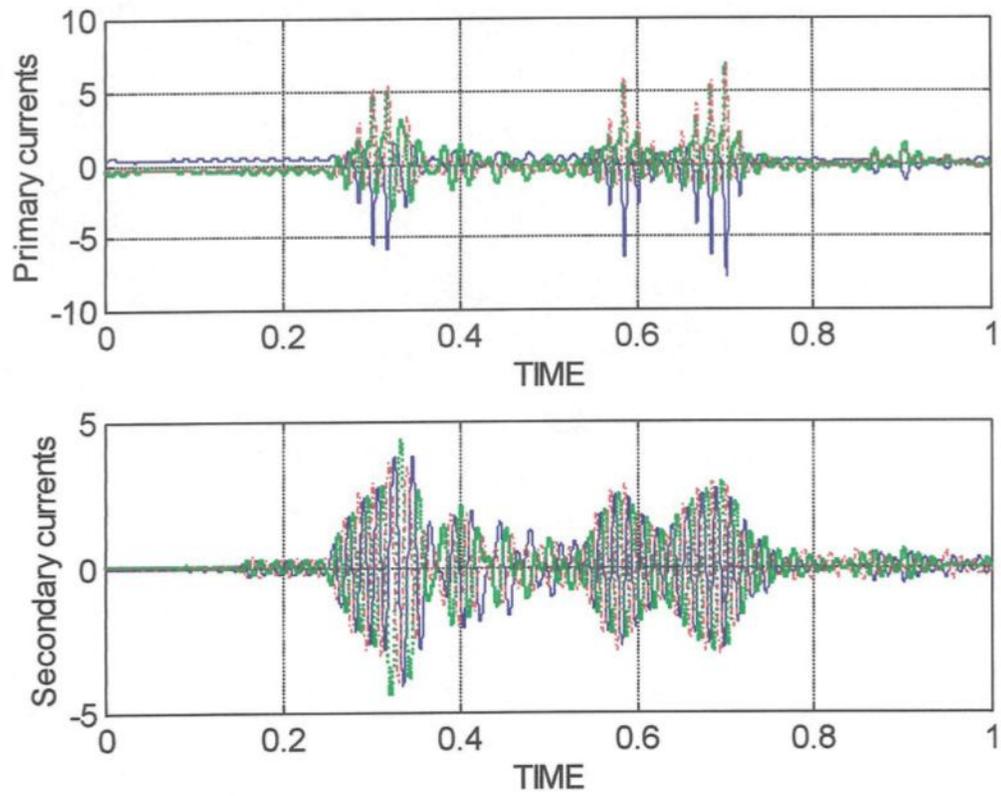


Figure 4.7 : *Train1* , an example of training data.

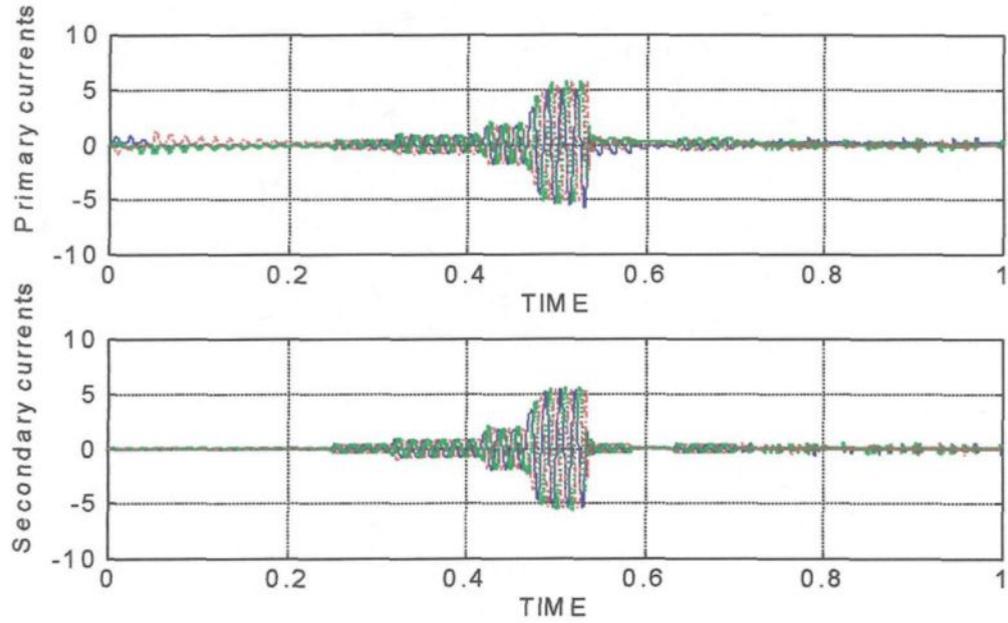


Figure 4.8 : *Train2* , an example of training data.

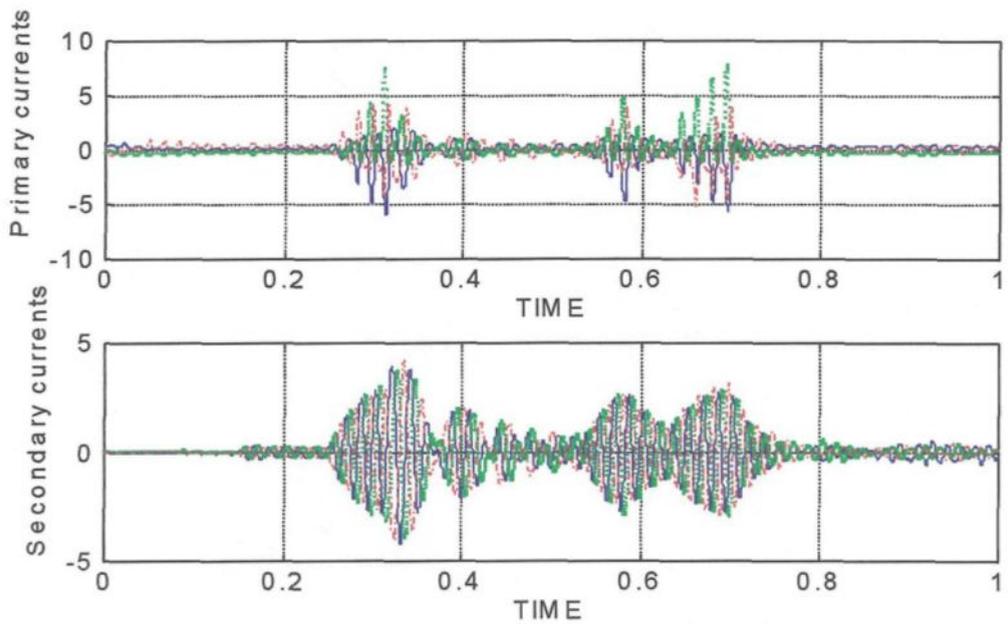


Figure 4.9 : *Train3* , an example of training data.

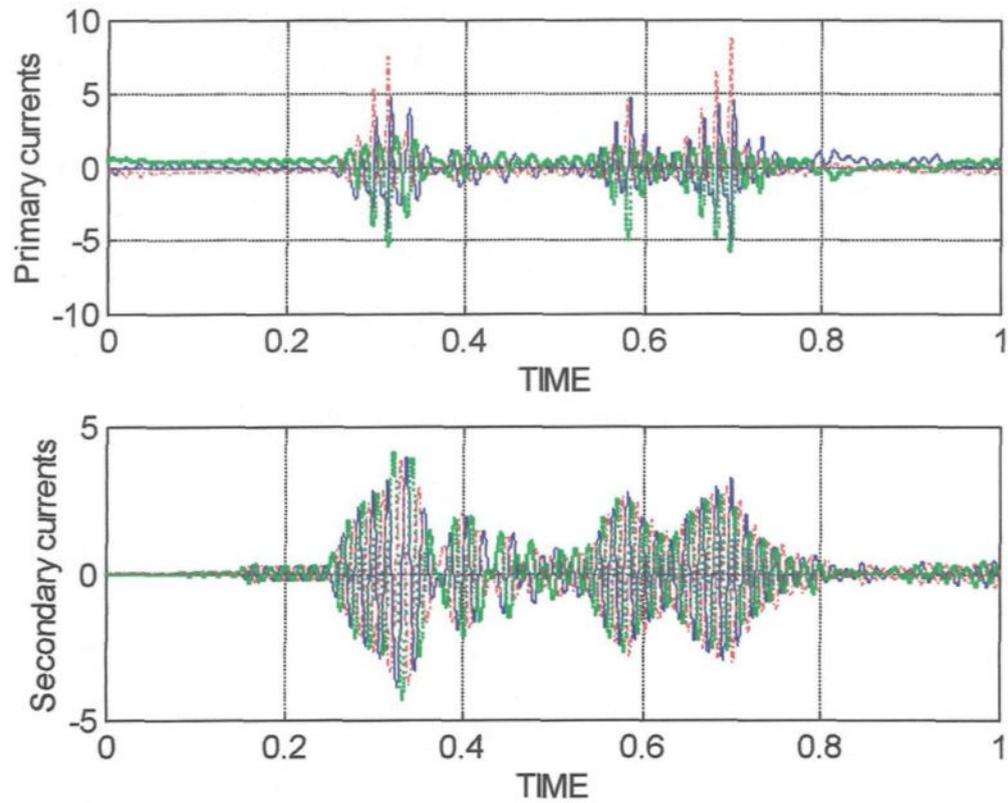


Figure 4.10 : *Train4 , an example of training data.*

Identification theory shows that the most appropriate signals for the modeling of a system are those that include information in all frequency bands. In general, an identification model should be excited by a summation of n sinusoidal signals. In this research, an empirical method is considered which respects the following conditions:

- Good response when an abrupt change occurs in the primary or secondary sides of the transformer.

- Have a valid response when the frequency of the applied voltage varies from 10% to 300% of the fundamental frequency.

Therefore, the frequency of applied voltage is modulated as follows:

$$v_a(t) = V_n \sin(2\pi(f_c + f_m(t)) + \phi) \quad (4 - 10)$$

where $f_m(t)$ is a modulation signal. Figure 4.11 shows an example of a modulated voltage signal which is applied to the primary side of the transformer, and the corresponding load voltage on the secondary side.

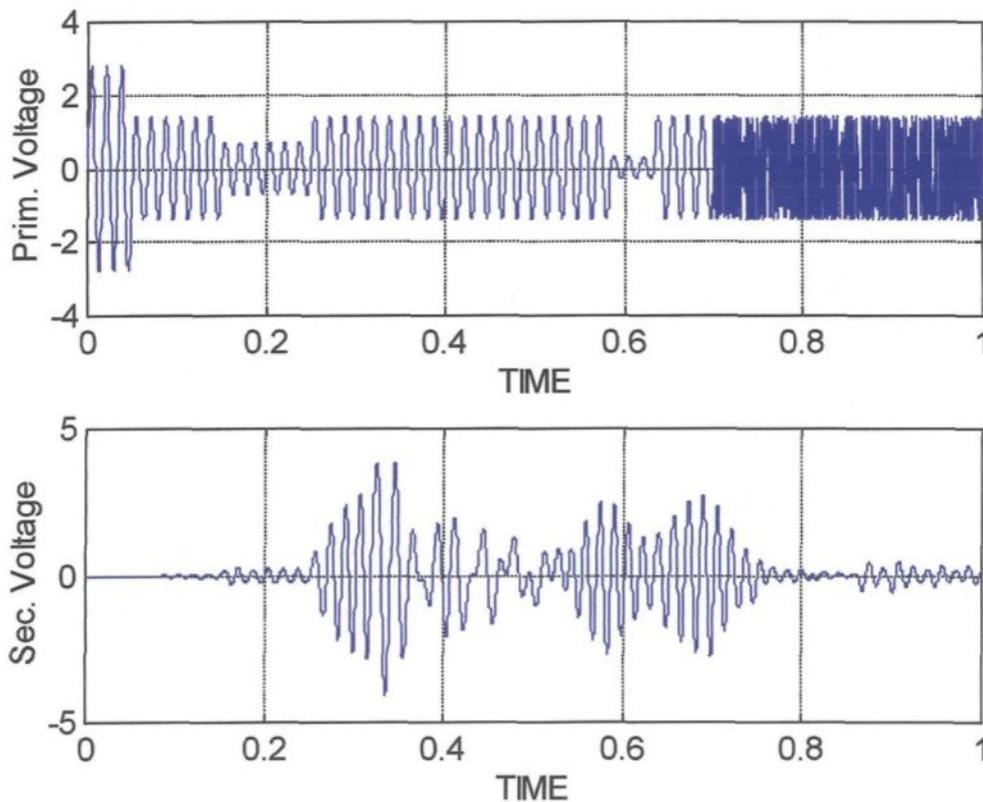


Figure 4.11 : *Primary and secondary voltages.*

In order to have a proper excitation of the neuro-fuzzy system, different values of modulation frequencies randomly distributed between 6 Hz to 200 Hz, several values of applied voltage, and different load conditions are considered. The amplitude of the applied voltage varies from 0.5 p.u. to 2.8 p.u., and the load conditions are varied in the range of 0.01 p.u. to 10 p.u. (from open circuit to short circuit). Figures 4.7, 4.8, 4.9, and 4.10 show the training data files. It can be noted that the transformer is excited in different modes, from completely saturated and extreme short circuit conditions to its rated conditions.

4.6 Pre-processing

Pre-processing, which may take the form of a linear transformation of the input data, or sometimes a more complicated method, has a significant role in determining the performance of the final system. Although neural networks and neuro-fuzzy systems can perform essentially arbitrary non-linear mapping from the raw input data directly onto the required final output values, in practice, such an approach will generally give poor results for several reasons. For instance, in a chemical plant, two of the inputs might represent a temperature and a pressure respectively. Depending on the units in which each of these is measured, and their typical values, they may have values which differ by several orders of magnitude. Furthermore, the typical sizes of the inputs may not reflect their relative importance in determining the required outputs. On the other hand, we may have very large and very small values for data. Therefore, in the gradient descent method, the gradient

value may vary in a large range, and the learning value may also be large at some points and small at the other points. Thus, the network may choke completely or learn very slowly if the magnitudes of the inputs are too large. Pre-processing of input data can solve these problems, make it easy to fit the model, yield a more consistent model, increase the convergence speed, and reduce the training time.

First, the training data are transformed to the per unit quantities. The nominal values of the three-phase power transformer is given in Table 4 - 2.

Electrical parameters of the three-phase power transformer	
S_n (KVA)	100
V_{pn} (KV)	15
V_{sn} (V)	400
I_{pn} (A)	3.58
I_{sn} (A)	144
N_p (Turns)	2025
N_s (Turns)	54
K (Ratio)	37.5

Table 4-2 : *Electrical parameters of the three-phase power transformer.*

In practice, a given value of base voltage in a three-phase system is a line-to-line voltage, and a given value of base kilovoltamperes is the total three-phase base, thus the following formulas are used to obtain the base quantities.

$$V_{\text{pbase}} = \sqrt{\frac{2}{3}} V_{\text{pn}}(\text{L-L})$$

$$Z_{\text{pbase}} = \frac{V_{\text{pn}}(\text{L-L}) \times V_{\text{pn}}(\text{L-L})}{S_{\text{n}}(3\Phi)}$$

$$I_{\text{pbase}} = \frac{V_{\text{pbase}}}{Z_{\text{pbase}}} \quad (4 - 11)$$

$$V_{\text{sbase}} = \frac{N_{\text{s}}}{N_{\text{p}}} V_{\text{pbase}}$$

$$I_{\text{sbase}} = \frac{N_{\text{p}}}{N_{\text{s}}} I_{\text{pbase}}$$

By applying a linear transformation all of inputs can be arranged to have similar values. In practice, however, input normalization ensures that all of the input and target variables are of order unity, in which case it is expected that the network parameters should also be of order unity. To do this, each of the input variables is treated independently, and for each variable x_i , we calculate its mean \bar{x}_i , and variance σ_i^2 , with respect to the training set, are calculated using the following formula:

$$\bar{x}_i = \frac{1}{N} \sum_{n=1}^N x_i^n$$

$$s_i^2 = \frac{1}{N-1} \sum (x_i^n - \bar{x}_i)^2$$
(4 - 12)

where $n = 1, \dots, N$ labels the patterns. We then define a set of re-scaled variables given by

$$\tilde{x}_i^n = \frac{x_i^n - \bar{x}_i}{\sigma_i}$$
(4 - 13)

It is easy to see that the transformed variables given by the \tilde{x}_i^n have zero mean and unit standard deviation over the transformed training set. This transformation gives inputs symmetric about zero. Learning is normally much faster when a symmetric training data is used, for example, if a network is trained to map the non-linear function $\sin(x)$ with inputs from 0 to $2 * \pi$ and from $-\pi$ to $+\pi$, the network with the symmetric data will learn much faster.

Since the training of the model may involve an iterative algorithm, it will generally be convenient to process the whole training set using the pre-processing transformation, and then use this transformed data set to train the model. Table 4 - 3 shows the program in MATLAB language, which is used for pre-processing of the training data sets.


```

end
for j=8:10
    trndat1(i,j)=trndat(i,j)/vsb;    % Per-unit values of the secondary voltages
end
for j=11:13
    trndat1(i,j)=trndat(i,j)/isb;    % Per-unit values of the secondary currents
end
end

%*****%
%                               Normalization of the data                               %
%*****%

% In this step, the data is normalized so that a zero mean and a standard deviation equal to
% one are achieved.

[m,n]=size(trndat1);
datmean=mean(trndat1);    % Mean calculation for all variables
datstd=std(trndat1);    % Standard deviation calculation for all variables
for i=1:m
    trndat2(i,1)=trndat1(i,1);
    for j=2:n
        trndat2(i,j)=(trndat1(i,j)-datmean(j))/datstd(j);    % Normalized data
    end
end
end

```

4.7 Training of the Model

After determination of the structure of the neuro-fuzzy model and preprocessing of training data, a learning scheme should be developed. In practice, there are two schemes of learning:

- off-line learning or batch learning
- on-line learning or pattern learning

In *off-line learning* the update action takes place only after each *epoch* or *sweep*. On the other hand, in *on-line learning* the parameters are updated immediately after each input/output pair has been presented. However, it is possible to combine these two learning modes and update the parameters after k training data entries have been presented, where k is between 1 and maximum number of input-output pairs in training data file.

Kamwa and Grondin [Kamwa & Grondin, Nov. 1996] proposed an interesting scheme. Although they used the scheme for training an artificial neural network, it is very effective and useful for training a neuro-fuzzy system. Using this scheme for training a neuro-fuzzy system decreases the amount of the required calculations. Therefore, it makes the process of training faster and it converges rapidly. For example, as it has been explained, to update the consequent parameters (see section 4.4. *LEARNING ALGORITHM*), by presenting each input-output pair to the model, a row of the matrices A and B are constructed. Then A^{-1}

should be calculated. If the number of input-output pairs is small, it can be calculated rapidly, however, for a large matrix, calculating A^{-1} takes a long time.

Figure 4.12 shows a learning scheme employed for training the neuro-fuzzy system. First, the structure of the neuro-fuzzy model with initial values of the parameters should be determined. In MATLAB, *genfis1* determines the initial values of the parameters. Then the first training file is presented, and the parameters of the model are adjusted so that to minimize the total error of the system. These parameters values are considered as the initial values for the second training data file, and the second training file is presented to train the system and adjust the parameters to have a better and more precise model. This process is continued for all the training files in the first loop, and then the loop is repeated N times. Finally, the validation of the model should be checked with a training file which has not been presented to the model. If the model is not very precise or not acceptable, the final model should be considered as the initial model and all the steps should be repeated with the new initial values. If the model is still not accurate, the structure of the neuro-fuzzy model should be modified, its complexity increased, and the process restarted from zero.

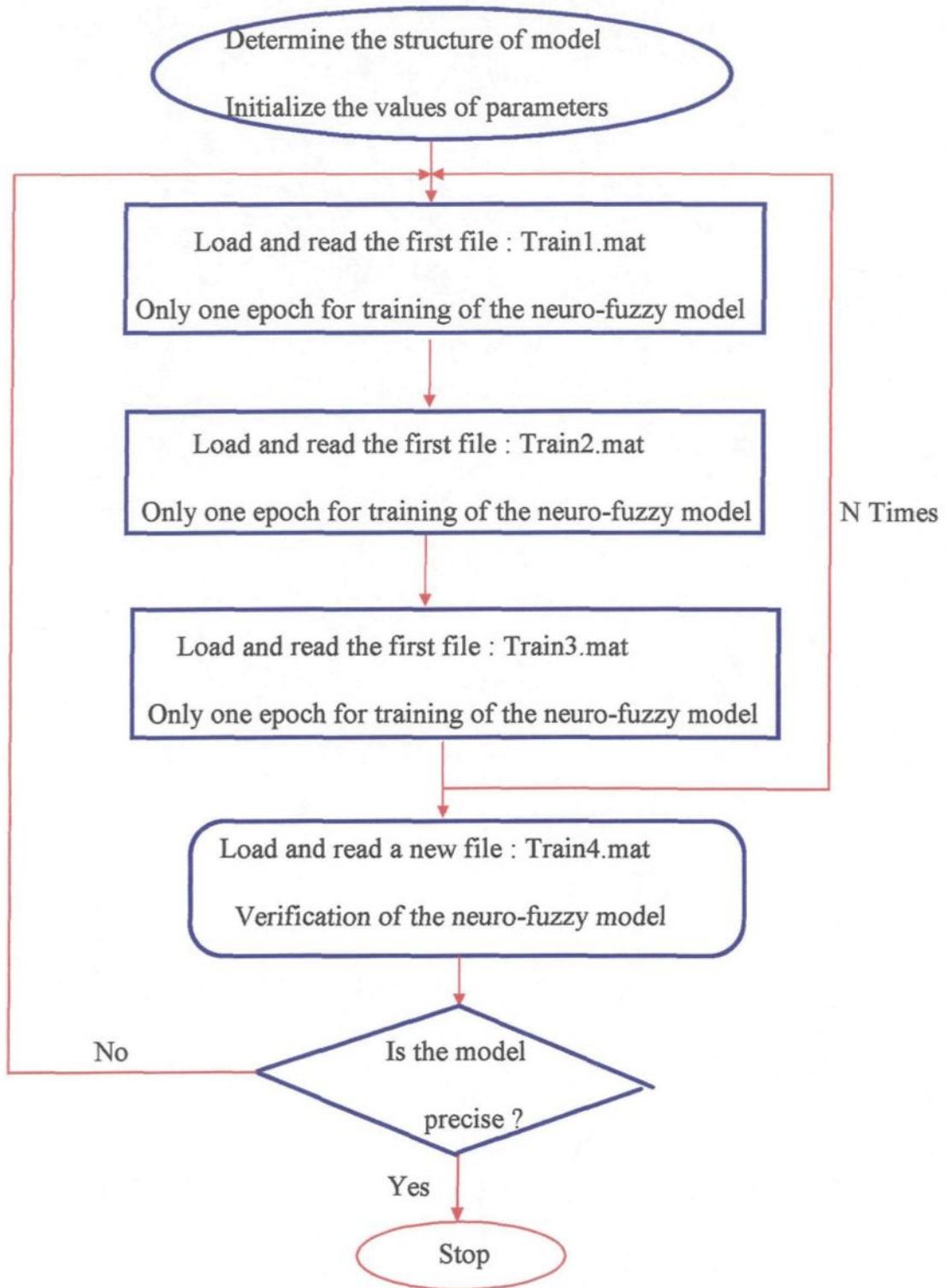


Figure 4.12 : Training Algorithm.

Chapter 5

Validation

5.1 Introduction

When the training of the direct and indirect models have been completed, the accuracy and rigidity of the system should be examined to determine how well it works.

These tests should be done in two steps:

- Verification;
- Validation.

In the verification process, the direct and indirect models encounter the training data that have been used during the training procedure. The models response to the data which have already seen. Therefore, if the parameters have been adjusted properly, the direct and indirect models should predict the actual outputs precisely, and the errors are few and of small amplitude. In this case, the models contain the dynamic characteristics of the transformer.

Validation plays an important role since it can determine the generalization of a model. In other words, we want to investigate the behavior of the neuro-fuzzy system when it encounters input data that has not been seen before. If the direct and indirect models can predict the behavior of the transformer with few errors , it means that they can generalize the behavior of the power transformer very well. On the other hand, if they encounters input data which contain information about abnormal conditions (like internal faults), the

direct and indirect models should show large errors in amplitude since they have not encountered any internal fault during the training procedure. It should be mentioned that to achieve good generalization toward unseen data, the size of the training data set should be larger than the number of modifiable parameters in a neuro-fuzzy system.

5.2 Verification of the Direct and Indirect Models

Verification of the direct and indirect models simply require that the training data be applied as inputs to the models, while all parameters of the models are kept at fixed values. In this manner, it can be determined how well the models have learned the dynamic characteristics of the transformer.

As mentioned above, the training data files comprise rated conditions of the three-phase power transformer, several overloads, and external faults. They do not comprise any internal faults. Therefore, the amplitude of the errors of the direct and indirect models, in all the above mentioned conditions, must be small and the intelligent relay should not issue any trip signal. As shown in Figures 5.1 to 5.4, the models predict their actual output precisely whenever a rated condition or even an overload occurs. However, the amplitude of the errors of models increase whenever there is an external fault with large fault currents. This means that the value of the instantaneous errors is proportional to the amplitude of the output signals. In other words, the performance of the models are good

while there is not a large fault current. In the case of a large fault current, the value of errors increase and there is a risk of issuing a false trip signal.

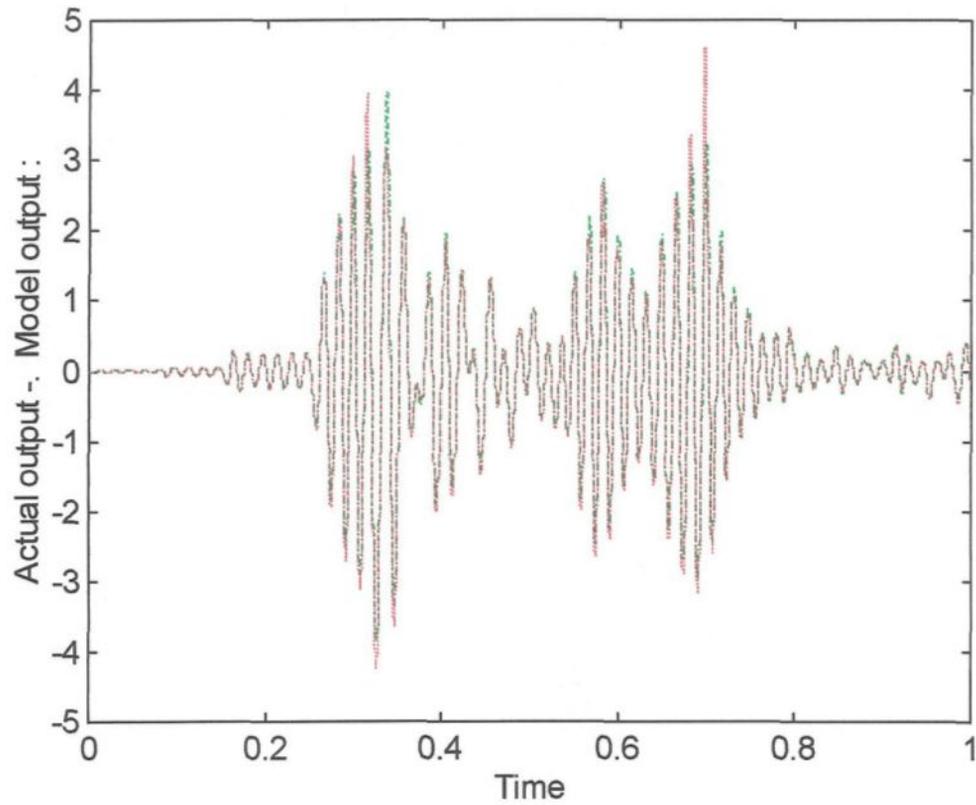


Figure 5.1 : Prediction of the secondary current by the direct model.

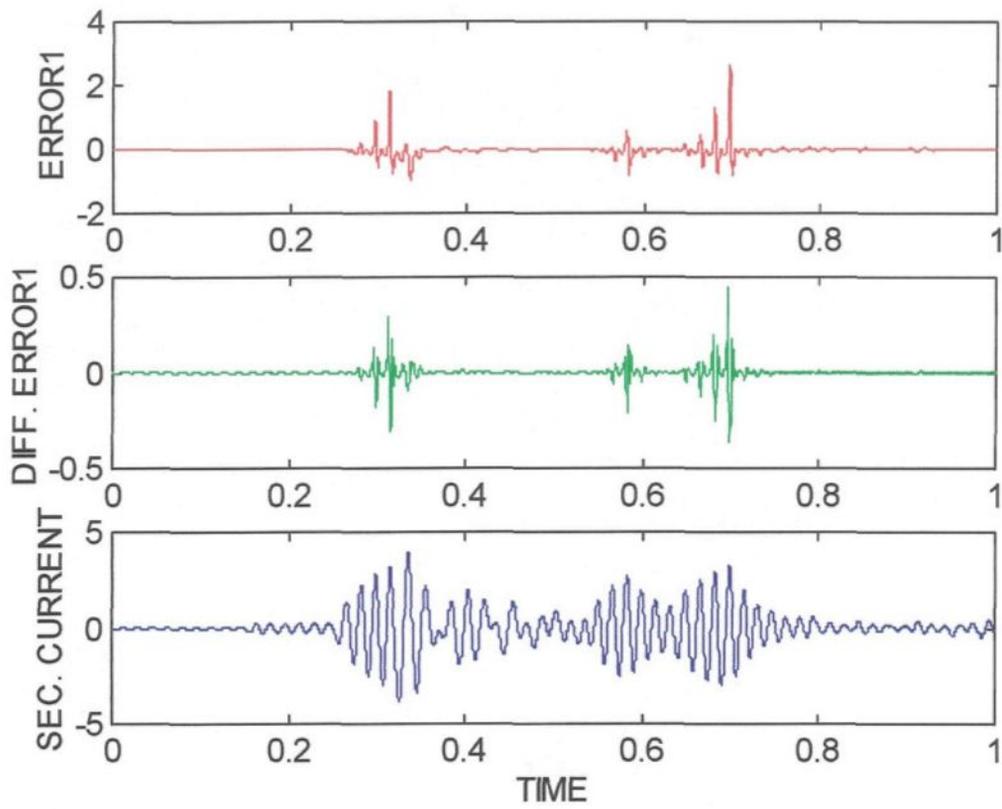


Figure 5.2 : *This figure consists of three subplots; Top : Error of the direct model; Middle : Difference error of the direct model; Bottom : Secondary current of the transformer*

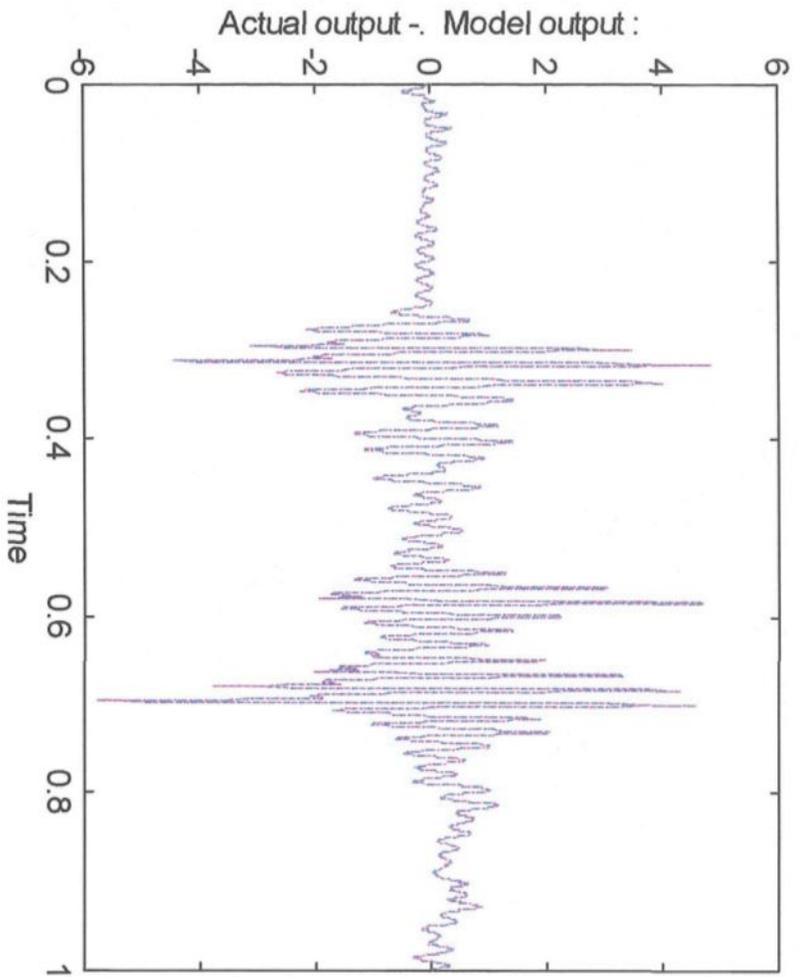


Figure 5.3 : Prediction of the primary current by the indirect model.

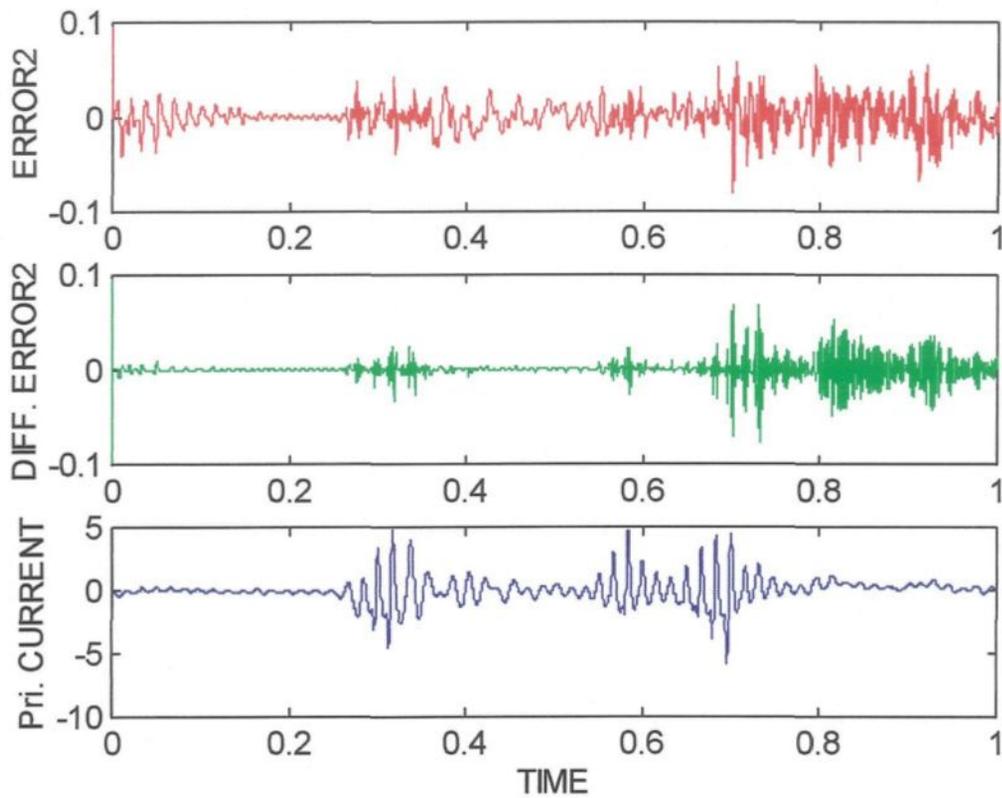


Figure 5.4 : *This figure consists of three subplots; Top: Error of the indirect model; Middle : Difference error of the indirect model; Bottom : Primary current of the transformer*

To diminish the risk of malfunction of the intelligent relay, a *hybrid method* is defined. Figure 5.5 shows the *hybrid method*, which combines the signals of the intelligent relay with an over current relay in a *decision-making unit*.

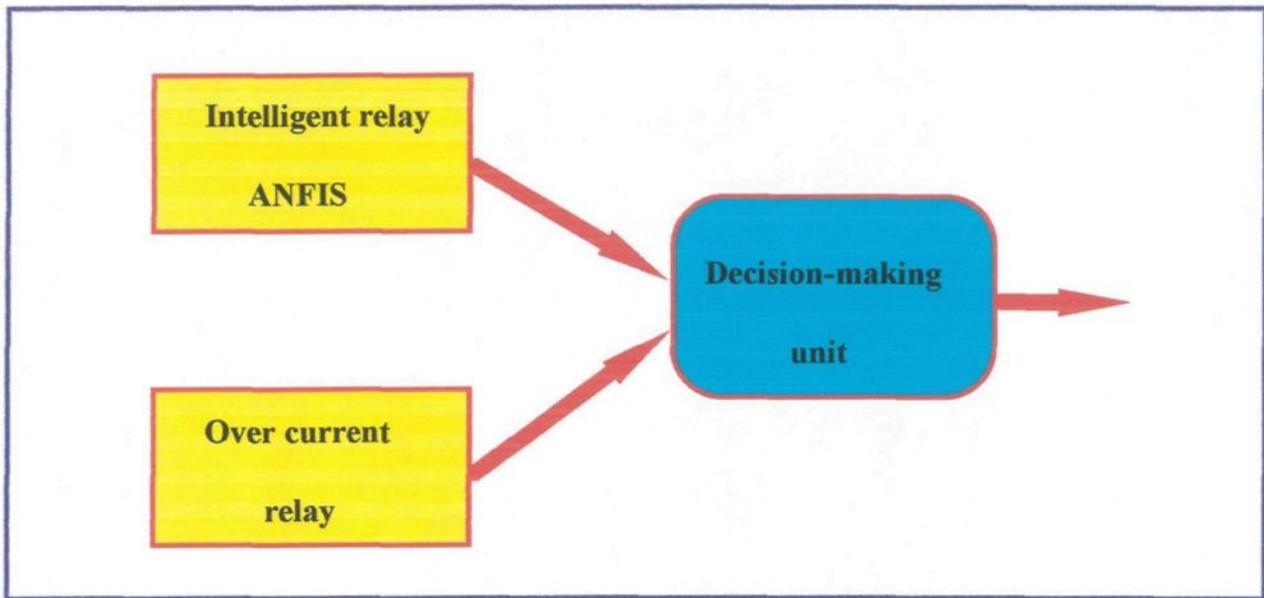


Figure 5.5 : *Hybrid method, which is the combination of intelligent relay and over current relay signals.*

For decision-making unit, there are 4 possible cases.

- The intelligent relay and the over current relay indicate that there is no fault.
- The intelligent relay output is zero but the over current relay declares that there is an external fault.
- An internal fault is detected by the intelligent relay, however, the over current relay indicates that there is no external fault.
- Finally, the intelligent relay detects an internal fault and an external fault is also declared by the over current relay.

Only in the third case, the decision-making unit issues a signal indicating an internal fault. This means that the output signal of the over current relay has higher priority than the

intelligent relay. Therefore, when both relays are activated, the decision-making unit does not issue any signal indicating an internal fault. It is clear that in the first two cases, the intelligent relay does not detect any internal fault. Therefore, the decision-making unit does not declare an internal fault.

Table 5.1 shows the truth table of the decision-making unit. The *hybrid method* configuration shows that when the training data files are applied to verify the direct and indirect models, an internal fault is not detected, and the amplitude of the errors of the models are generally small.

Intelligent relay	Over current relay	Decision-making unit
0	0	0
0	1	0
1	0	1
1	1	0

Table 5-1 : Truth table of the decision-making unit

5.3 Validation of the Direct and Indirect Models

In the validation procedure, new data files, which are called *validation files*, are used to verify the generalization of a neural network or a neuro-fuzzy system. The validation files consist of data and information that have not been seen by the neural networks or the neuro-fuzzy systems. Therefore, they are completely new information for them. By applying the validation files, the behavior and the errors of the direct and indirect models are observed. If they can predict the behavior of the transformer under rated conditions, and their output errors remain small, the models can be accepted as a good predictor of the behavior of the transformer under rated condition. When an internal fault occurs, the amplitude of the errors should increase. Since the direct and indirect models have not been trained with data files, which consist of any internal fault, and they cannot predict the behavior of the power transformer under internal fault conditions, the predicted values are not very precise and the amplitude of the errors increase considerably. The trip signal is issued when the errors increase above a threshold value.

5.3.1 Description of the Validation Data Files

According to practical standards in protection engineering, a complete and exhaustive simulation should be carried out to determine the limitation of the performance of the neuro-fuzzy system, which is considered as an intelligent relay.

In the validation data files, several parameters are varied to have an exhaustive set of simulations. These parameters are explained as follows:

- *Initial phase angle*: changing the initial phase of the applied voltage to the primary side of the transformer. Four different values are selected for the initial phase of the applied voltage, which can change the shape of inrush currents and the amount of the second harmonic. Therefore, we can investigate the behavior of the system for different values of inrush currents. These four values are zero, $\pi/4$, $\pi/2$ and π .
- *winding* : internal fault is simulated on the primary or secondary windings.
- *Phase* : internal fault is simulated on different phases. Therefore, three possible cases exist.
- *Load* : different loads are selected before and after internal faults. The load variations consist in open and short-circuits. These load values are
 - I. open-circuit;
 - II. 10% of the nominal load;
 - III. 50% of the nominal load;
 - IV. nominal load;
 - V. 200% of the nominal load;
 - VI. 400% of the nominal load;
 - VII. 800% of the nominal load (short-circuit).

- *Fault amplitude* : different percentages of windings are short-circuited to simulate different levels of internal fault. These values are as follows:
 - i. 0% of the winding is short-circuited (healthy winding).
 - ii. 3% of the winding is short-circuited.
 - iii. 10% of the winding is short-circuited.
 - iv. 15% of the winding is short-circuited.
 - v. 40% of the winding is short-circuited.
 - vi. 75% of the winding is short-circuited.
 - vii. 95% of the winding is short-circuited.

5.3.2 Internal Fault at the Secondary Side of the Power Transformer

The validation files that include internal faults in the secondary of the transformer have the following configuration:

- internal fault of 15% in the secondary side which occurs at 400ms, including the following perturbations in the network:
 - a) temporary short-circuit and over-voltage in the primary side
 - b) variable load
 - c) different initial phase angle for the applied voltage

The validation files are T3121211, T3121214, T3121244 and T3121264. Figures 5.6 to 5.11 show the result of the validation only for the first two validation files. However, the *RMSE (Root Mean Squared Error)* values are calculated for all of them. As mentioned earlier, these files contain an internal fault with 15% of the secondary winding short-circuited in phase α . The internal faults occur at 400ms and they have different initial phase angles and load values.

As it is shown in these figures, the errors of the direct and indirect models increase in amplitude, after occurrence of an internal fault. Tables 5.2 and 5.3 show the values of *RMSE* of the *direct* and *indirect models* respectively, when these validation files are applied. They illustrate that *RMSE* before the occurrence of an internal fault is very small, while it increases after the occurrence of an internal fault in the secondary side.

Validation File	Before internal fault	After internal fault
T3121211	0.0448	0.5351
T3121214	0.0408	0.4194
T3121244	0.0369	0.0894
T3121264	0.0243	0.0932

Table 5-2 : The RMSE of the direct model before and after an internal fault.

Validation File	Before internal fault	After internal fault
T3121211	0.3727	6.1648
T3121214	0.6887	1.3037
T3121244	0.2519	1.2752
T3121264	0.2181	1.2863

Table 5-3 : The RMSE of the indirect model before and after an internal fault

Figure 5.6 consists of four subplots. From the bottom, the first subplot shows the *secondary current* of phase *a*. The second illustrates the difference error of the *direct model*, while the third plot shows the error of the *direct model*. Finally, the last plot represents the *trip signal*. It is clear that the amplitude of the error of the direct model is very small before the occurrence of the internal fault, while it rises after the occurrence of the internal fault and causes a trip signal to be issued.

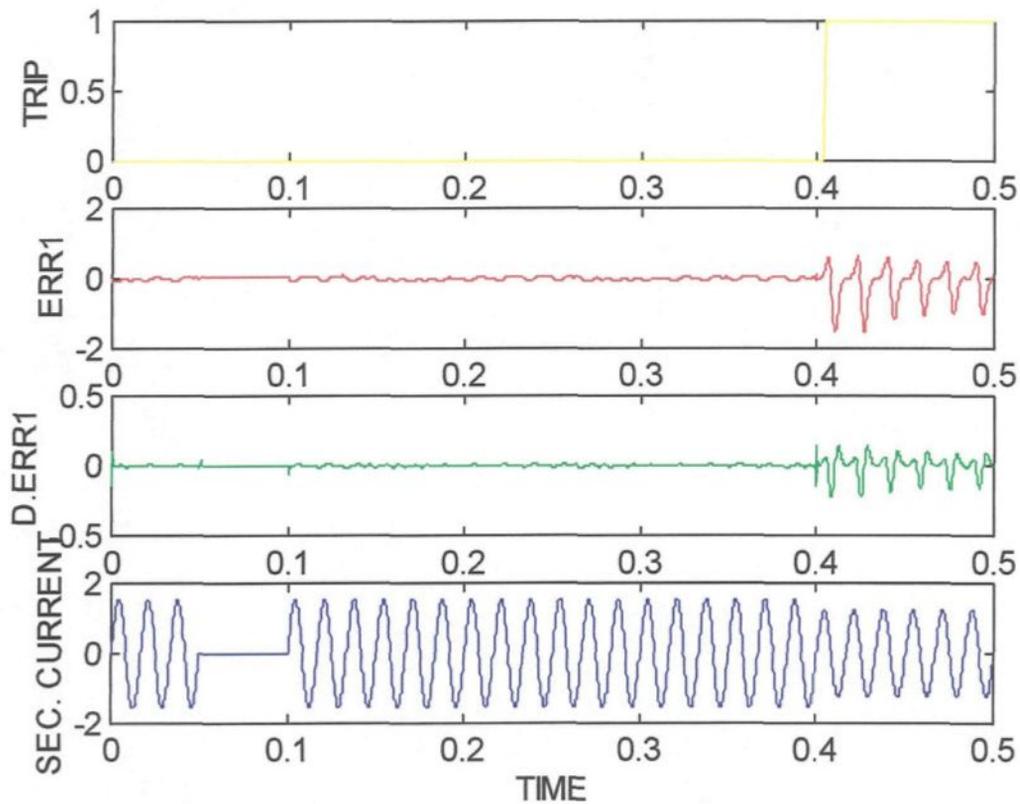


Figure 5.6 : Direct model, validation file T3121211.

Figure 5.7 consists of four subplots. From the bottom, the first subplot shows the *primary current* of phase *a*. The second illustrates the difference error of the *indirect*

model, while the third plot shows the error of the *indirect model*. Finally, the last plot represents the *trip signal*. Like the direct model, the error of the indirect model is small in amplitude before the occurrence of the internal faults. However, it increases at 400 msec when an internal fault occurs and the intelligent relay detects the internal fault rapidly.

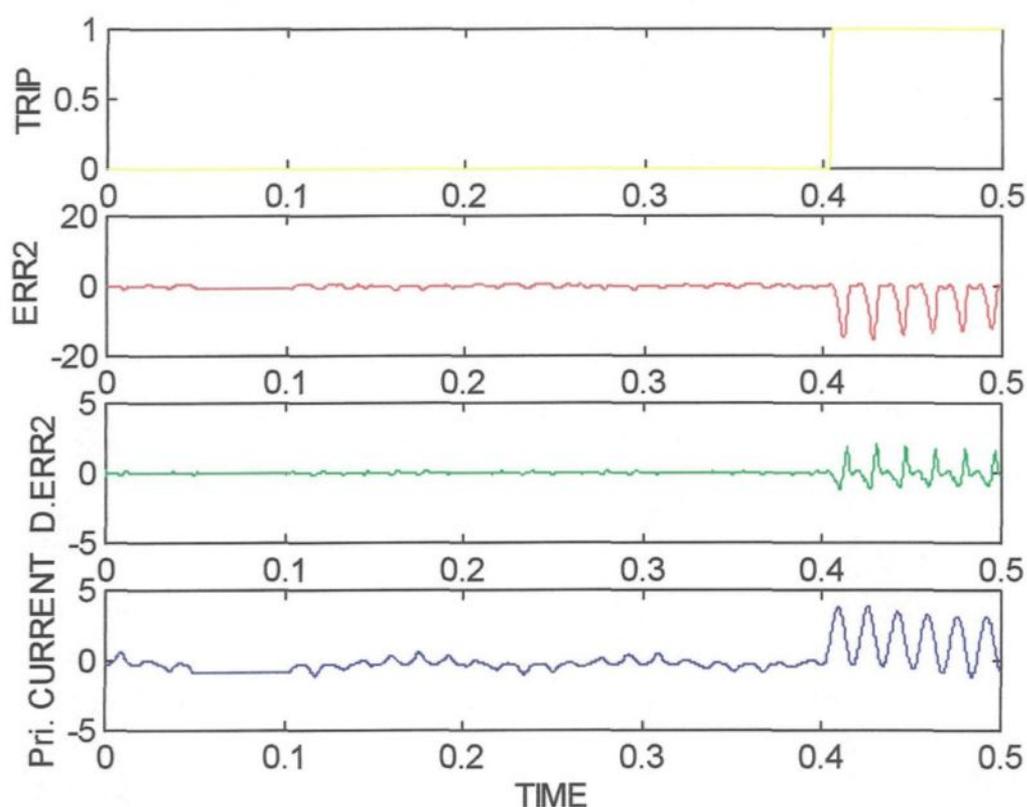


Figure 5.7 : Indirect model, validation file T3121211.

According to these figures, it is obvious that the direct and indirect models can detect the internal fault successfully. The direct and indirect models can predict the secondary and primary currents of the power transformer precisely while there is not any internal fault.

However, they cannot determine the behavior of the transformer during an internal fault. Therefore the amplitude of the errors of the models increase after an internal fault. Figure 5.8 presents the secondary current of the power transformer and the output of the direct model.

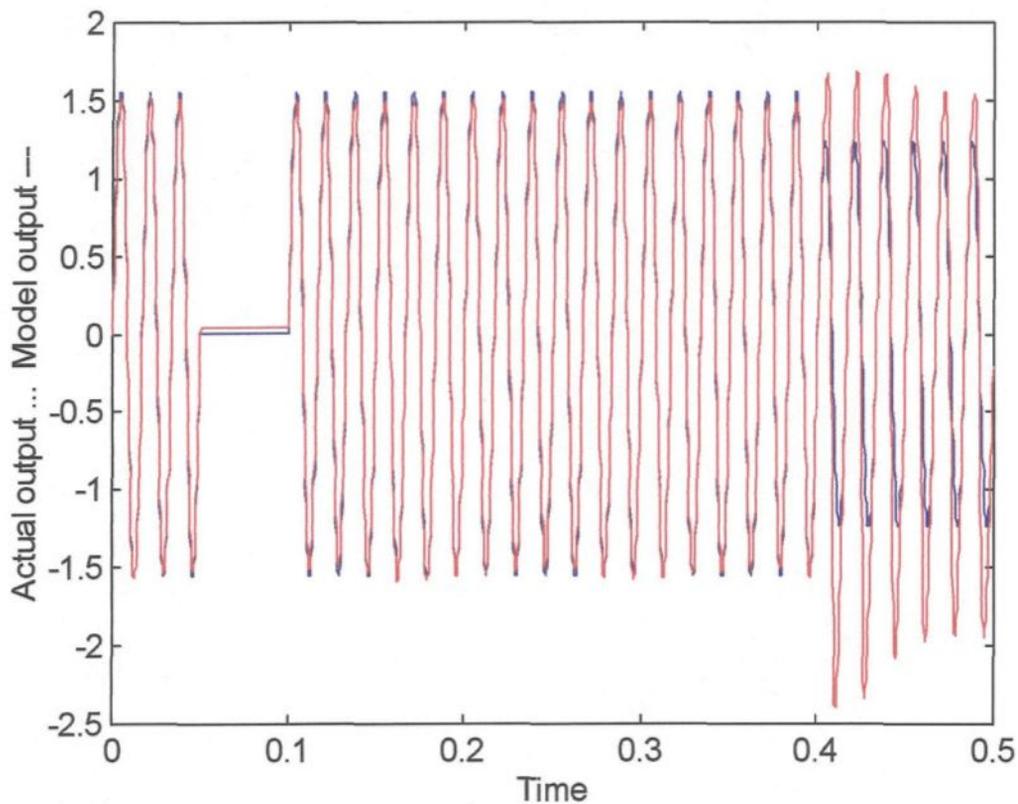


Figure 5.8 : Comparison of the direct model output with the secondary current of the power transformer, validation file T3121211.

Figure 5.9 consists of four subplots. From the bottom, the first subplot shows the secondary current of phase a . The second illustrates the difference error of the *direct*

model, while the third plot shows the error of the *direct model*. Finally, the last plot represents the *trip signal*. It is clear that the amplitude of the error of the direct model is very small before the occurrence of the internal fault, while it rises after the occurrence of the internal fault. The intelligent relay recognizes the internal faults in a cycle after the occurrence of the internal fault.

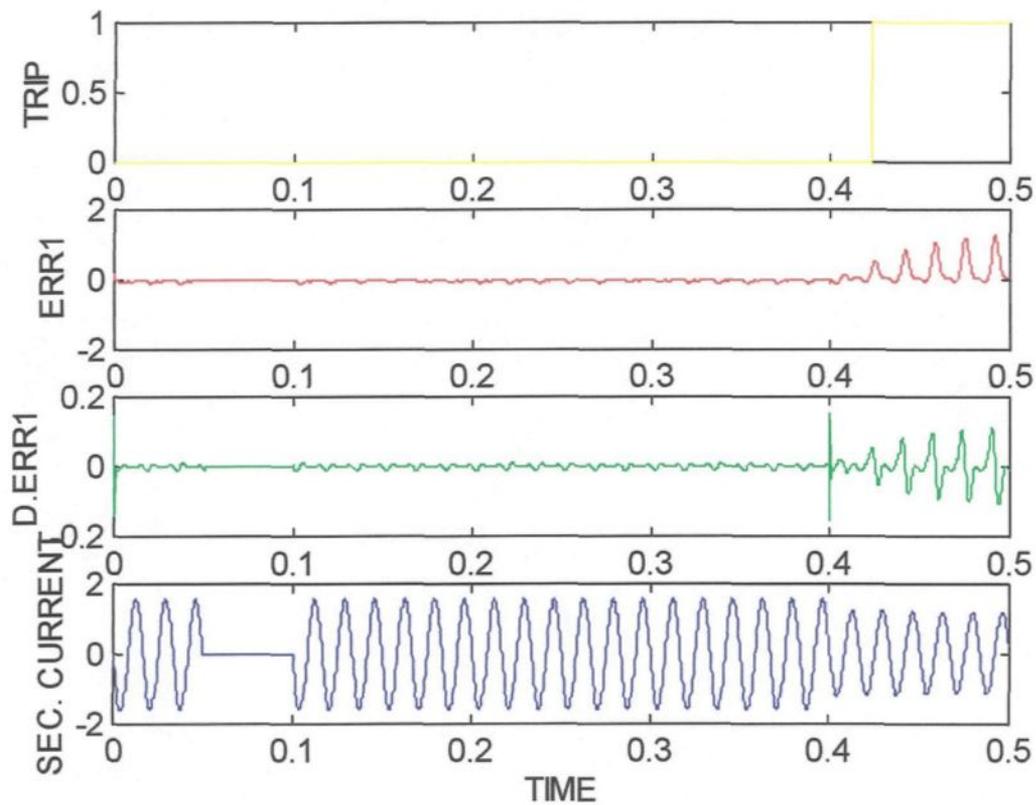


Figure 5.9 : Direct model, validation file T3121214.

Figure 5.10 consists of four subplots. From the bottom, the first subplot shows the *primary current* of phase *a*. The second illustrates the difference error of the *indirect model*, while the third plot shows the error of the *indirect model*. Finally, the last plot represents the *trip signal*. Like direct model, the amplitude of the error of the indirect model is small before the occurrence of the internal faults. However, it increases when an internal fault occurs and the intelligent relay detects the internal fault in less than a cycle.

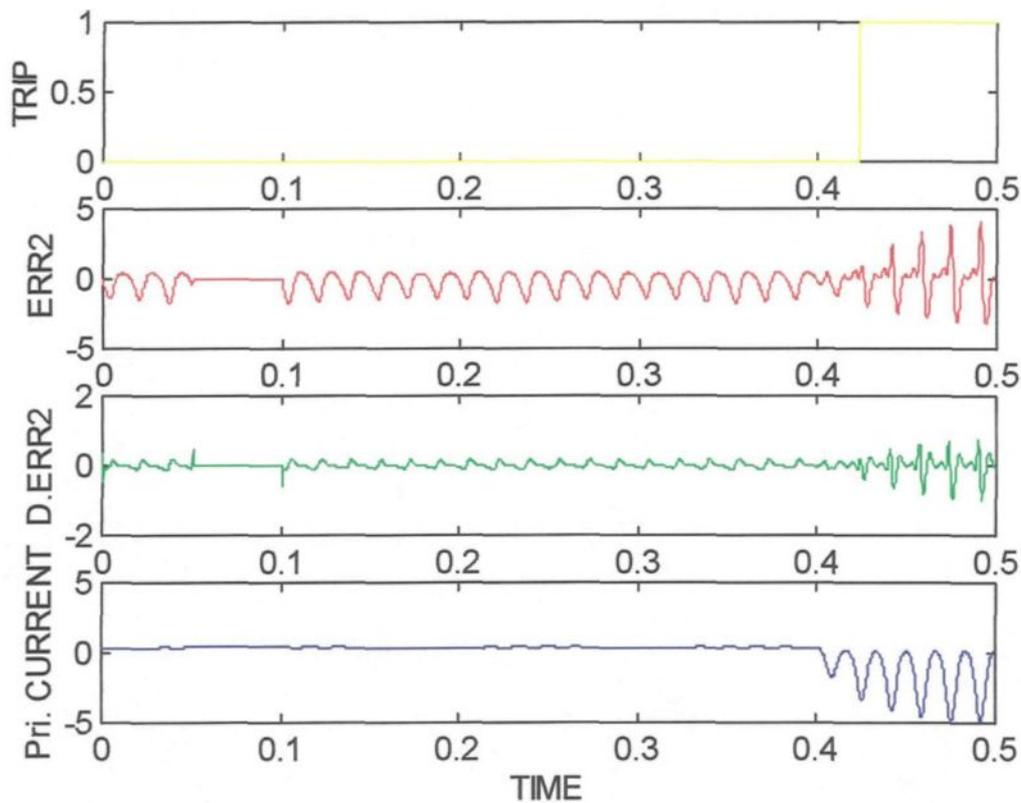


Figure 5.10 : Indirect model, validation file T3121214.

According to Figures 5.9 and 5.10, it is obvious that the direct and indirect models can detect the internal fault successfully. The models can predict the primary and secondary currents of the power transformer precisely while there is not an internal fault. However, they cannot determine the behavior of the transformer during an internal fault. Therefore the amplitude of the error of the models increases after an internal fault. Figure 5.11 presents the primary current of the power transformer and the output of the indirect model.

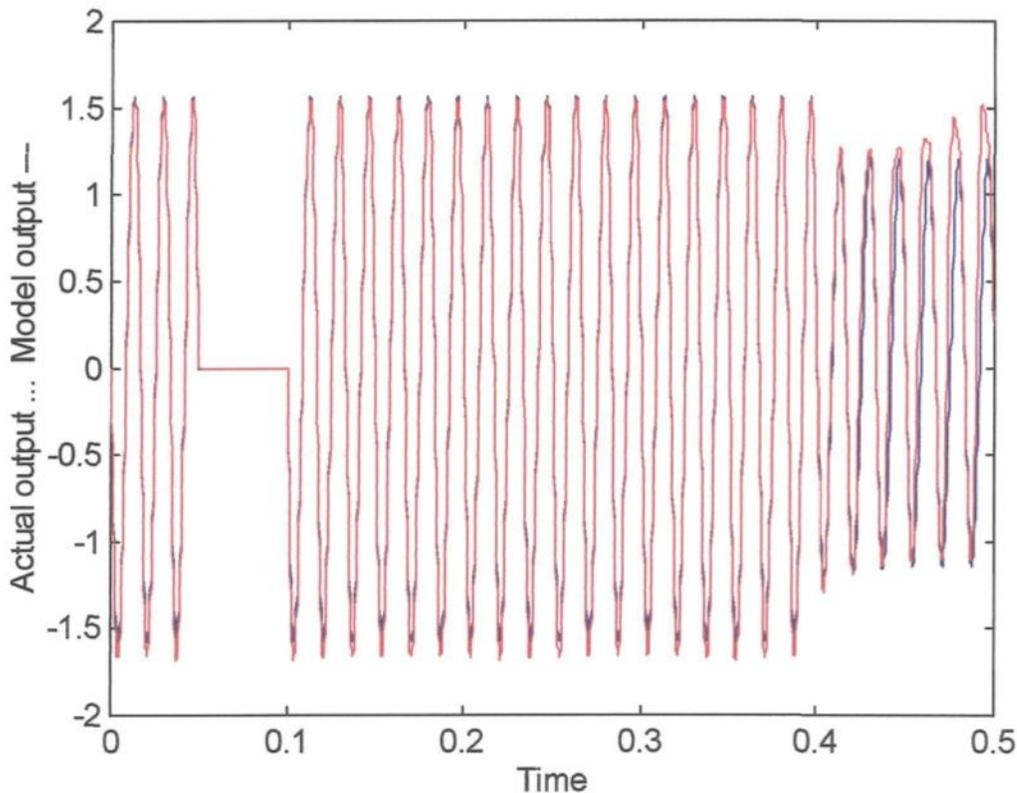


Figure 5.11 : Comparison of the indirect model output with the primary current of the power transformer, validation file T3121214.

5.3.3 Internal Fault at the Primary Side of the Power Transformer

There are several validation files which contain internal faults in the primary side of the transformer. These validation files have the following configurations:

- different values of internal faults in the primary side of the transformer exist. These values are 15%, 10% and 3% of the primary winding in phase a are short-circuit.
- different load values, from open-circuit to short circuit, are considered.
- different initial phase angles for the applied voltage to the transformer are selected. These values are zero, $\pi/4$, $\pi/2$, and π degree.

The validation files are T3111211, T3111233, T3111243 and T3111244. Figure 5.12 to 5.16 show the results of the validation only for the first two validation files. However, the *RMSE (Root Mean Squared Error)* values are calculated for all of them. These files contain internal faults with 15% of the primary winding short-circuited in phase a . The internal fault occurs at 200 *msec* and they have different initial phase angles and load values.

As it is shown in these figures, the errors of the direct and indirect mode

illustrate that *RMSE* before the occurrence of an internal fault is very small while it increases after the occurrence of an internal fault in the primary side of the transformer.

Validation File	Before internal fault	After internal fault
T3111211	0.0882	0.3672
T3111233	0.0833	0.2919
T3111243	0.0907	0.3438
T3111244	0.0764	0.1741

Table 5-4 : The *RMSE* of the direct model before and after an internal fault.

Validation File	Before internal fault	After internal fault
T3111211	0.4221	2.3274
T3111233	0.4398	1.4262
T3111243	0.5871	1.0720
T3111244	0.2944	1.4596

Table 5-5 : The *RMSE* of the indirect model before and after an internal fault.

Figure 5.12 consists of four subplots. From the bottom, the first subplot shows the *secondary current* of phase *a*. The second illustrates the difference error of the *direct*

model, while the third plot shows the error of the *direct model*. Finally, the last plot represents the *trip signal*. This figure presents that the *direct model* could predict the secondary current precisely before the occurrence of an internal fault (0.2 sec), while the amplitude of the error increases after the internal fault.

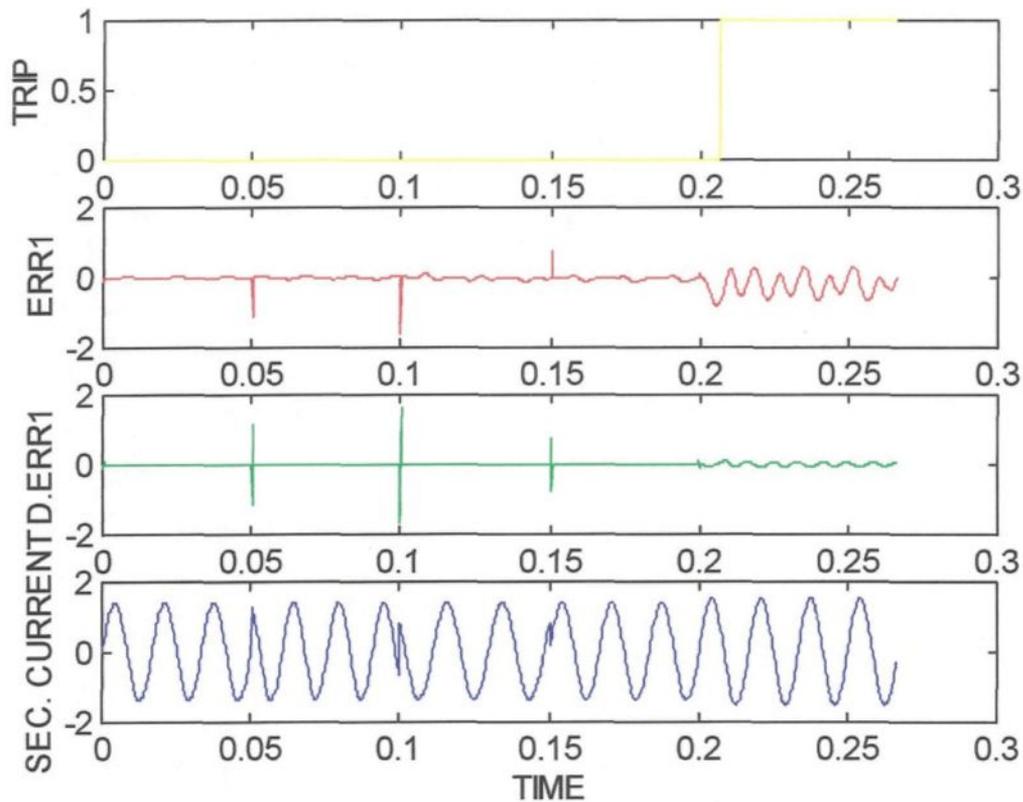


Figure 5.12 : Direct model, validation file T3111211.

Three spikes at time 0.05 sec, 0.1 sec, and 0.15 sec are observed in the second and third subplots. They are due to abrupt changes in the secondary current, which can be seen in the first subplot (bottom). Since these kinds of variations have not been included in the training data files, the *direct model* cannot predict these variations and the amplitude of the

error increases at this points. However, since the trip signal is issued based on both the amplitude of the errors of the *direct* and *indirect models*, the intelligent relay neglects these spikes and issues a trip signal after observing the internal fault.

Figure 5.13 consists of four subplots. From the bottom, the first subplot shows the *primary current* of phase *a*. The second illustrates the difference error of the *indirect model*,

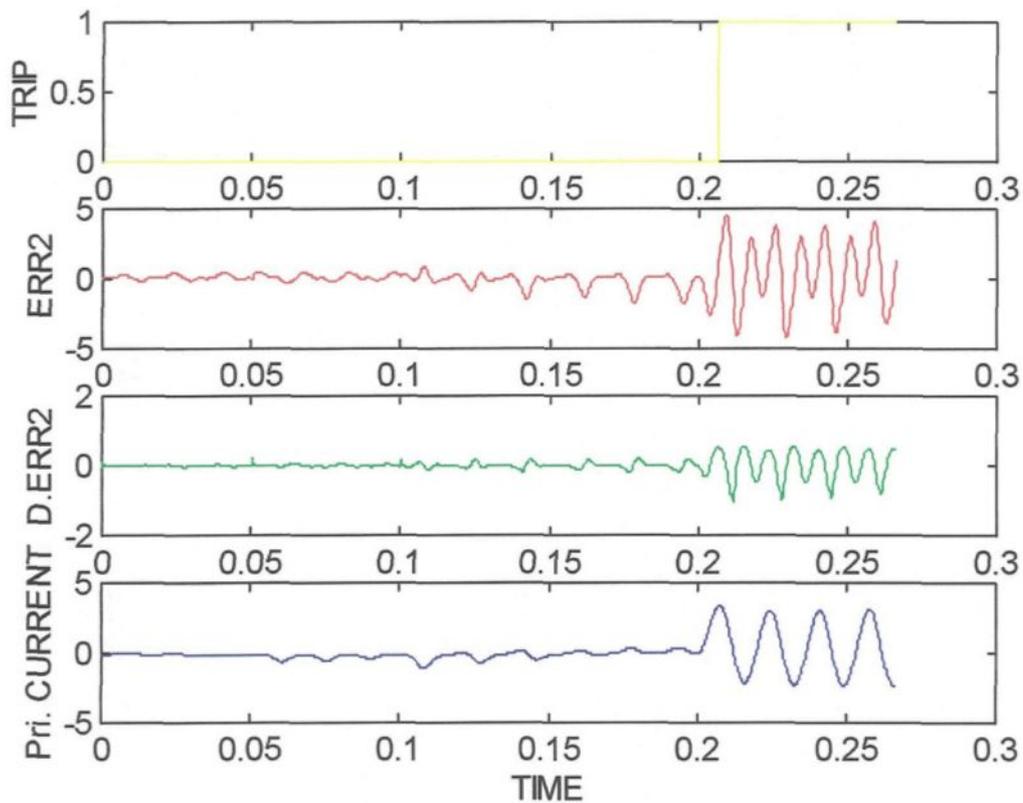


Figure 5.13 : Indirect model, validation file T3111211.

while the third plot shows the error of the *indirect model*. Finally, the last plot represents the *trip signal*.

According to Figures 5.12 and 5.13, it is obvious that the direct and indirect models can detect the internal fault successfully. The models can predict the primary and the secondary currents of the power transformer precisely while there is not an internal fault. However, they cannot determine the behavior of the transformer during an internal fault. Therefore, the amplitude of the errors of the models increase after an internal fault. Figure 5.14 presents the secondary

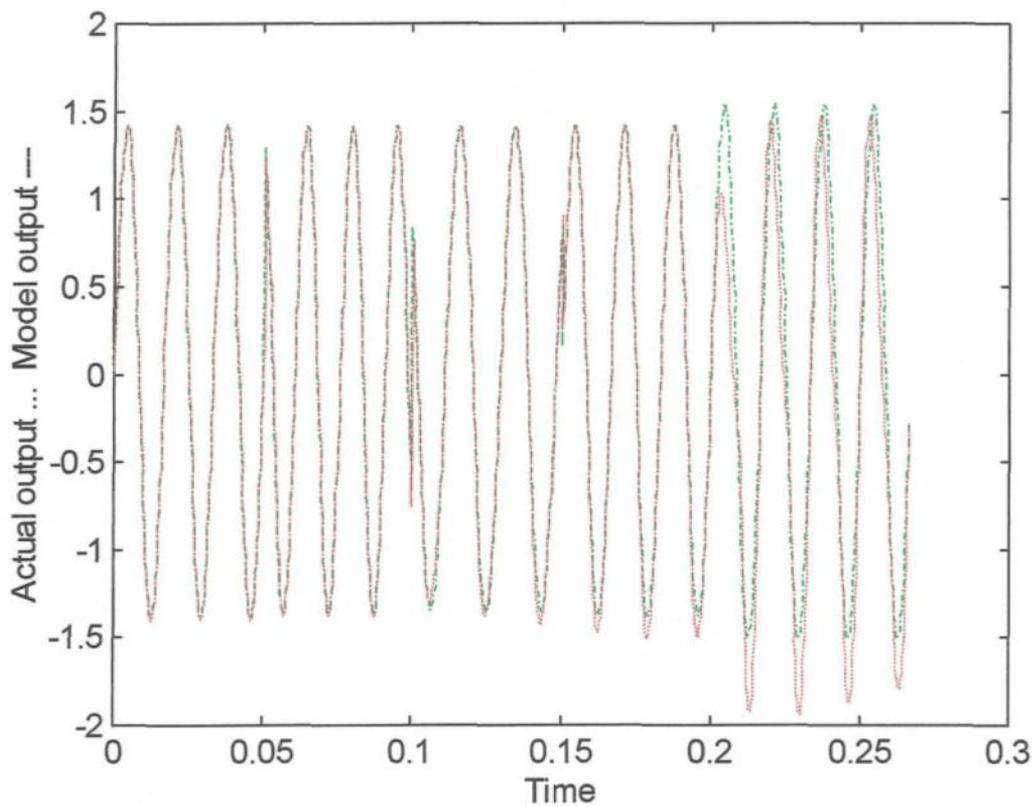


Figure 5.14 : *Comparison of the direct model output with the secondary current of the power transformer, validation file T3111211.*

current of the power transformer and the output of the direct model. As mentioned before, at time 0.05 sec, 0.1 sec, and 0.15 sec, there are some abrupt changes and the direct

model cannot predict the secondary current exactly. However, except for these points, the model predicts it correctly.

Figure 5.15 consists of four subplots. From the bottom, the first subplot shows the secondary current of phase *a*. The second illustrates the difference error of the direct model, while the third plot shows the error of the direct model. Finally, the last plot represents the *trip signal*. This figure presents that the direct model could predict the secondary current

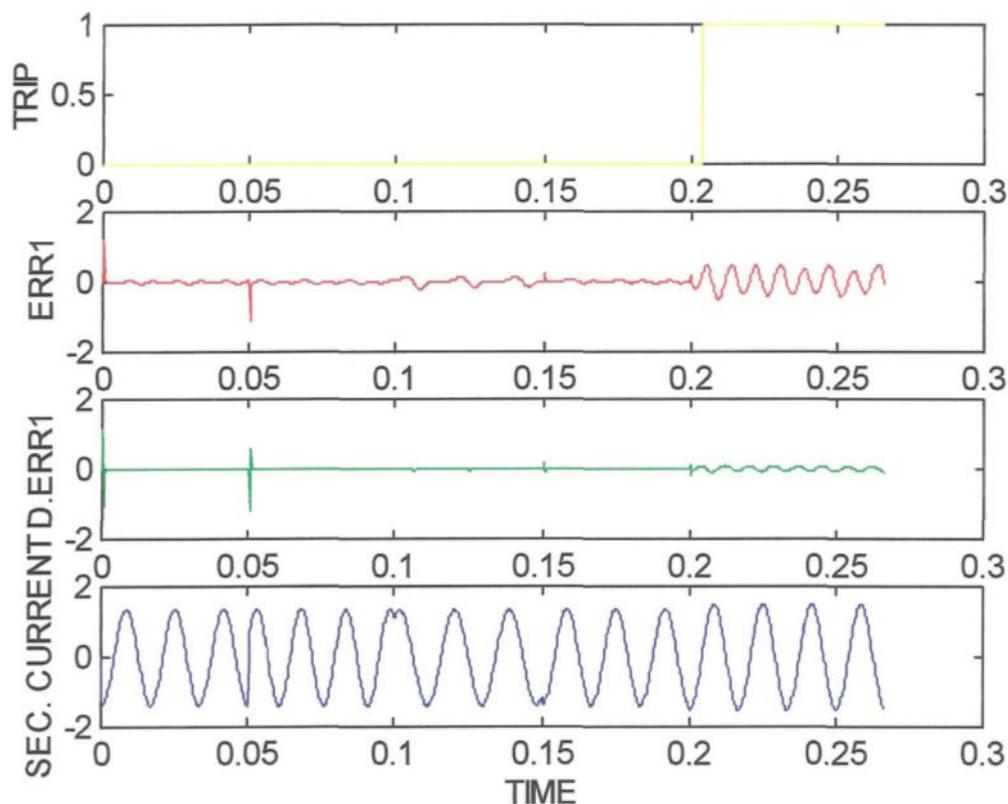


Figure 5.15 : Direct model, validation file T3111233.

precisely before the occurrence of an internal fault (0.2 sec), while the amplitude of the error increases after the internal fault. Two spikes at time 0.0 sec, and 0.05 sec are observed in the second and third subplots. They are due to abrupt changes in the secondary current which can be seen in the first subplot (from bottom). Since these kinds of variations have not been included in the training data files, the direct model cannot predict these variations and the error increases in amplitude at these points. However, since the trip signal is issued based on the amplitude of the errors of the *direct* and indirect models, the intelligent relay neglects these spikes and issues a trip signal after observing the internal fault.

Figures 5.16 consists of four subplots. From the bottom, the first subplot shows the primary current of phase *a*. The second illustrates the difference error of the indirect model, while the third plot shows the error of the indirect model. Finally, the last plot represents the *trip signal*.

Finally, there are some validation files which include internal faults in the primary side of the transformer with 10% or 3% of the primary winding short-circuited in phase *a*.

The validation files are T2111214, T2111233, T5111214 and T5111262. Figure 5.17 to 5.20 show the results of applying the second and the third validation files. However, the *RMSE (Root Mean Squared Error)* values are calculated for all of them. The internal fault occurs at 50 msec and they have different initial phase angles and load values.

As is shown in these Figures, the error of the direct and indirect models increase in amplitude after occurrence of an internal fault for the first two validation files which 10%

of the primary winding short-circuited in phase a (see Figures 5.17 and 5.18). However, the error for the

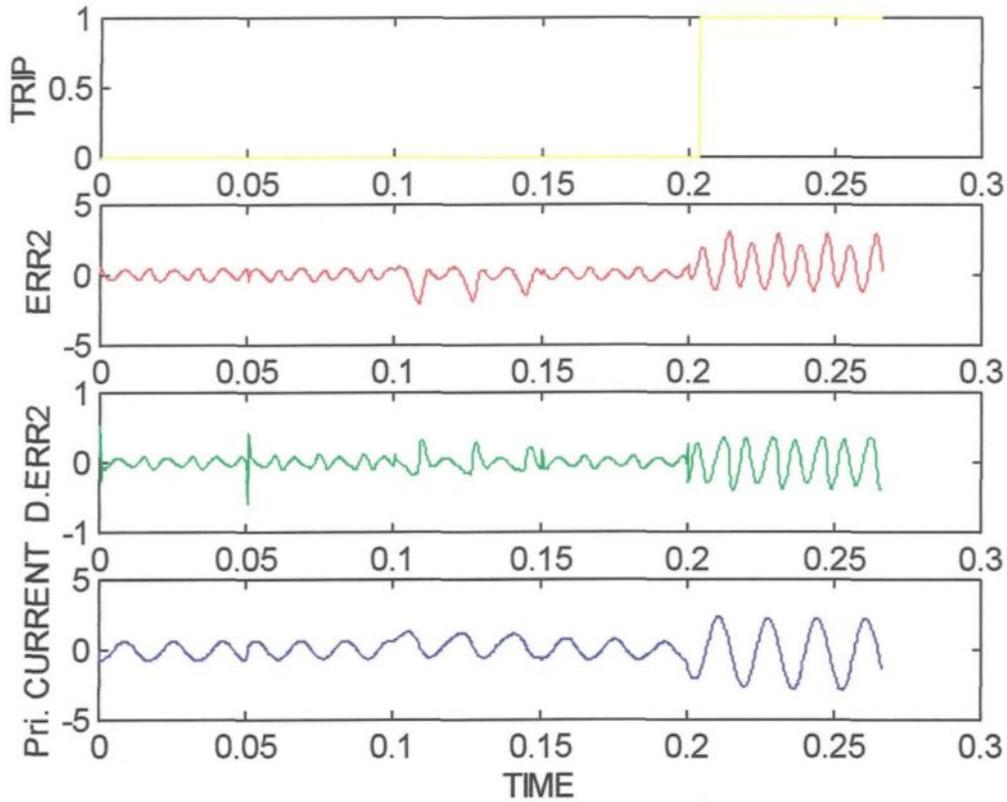


Figure 5.16 : Indirect model, validation file T3111233.

last two validation files does not increase in amplitude very much after occurrence of an internal fault (see Figures 5.19 and 5.20). Since only 3% of the primary winding of the transformer is short-circuited for the last two validation files, the direct and indirect models are not as sensitive as the previous cases. Tables 5.6 and 5.7 show the values of **RMSE** of the direct and indirect models when these validation files are applied. They illustrate that for the first two validation files, the **RMSE** before the occurrence of an internal fault is

very small while it increases after the occurrence of an internal fault in the primary side of the transformer. In contrast, for the last two validation files, the amplitude of the errors do not change very much after the occurrence of an internal fault. This indicates that the models are not sensitive enough for a small internal fault and they cannot recognize and detect them precisely.

Validation File	Before internal fault	After internal fault
T2111214	0.0290	0.2130
T2111233	0.0997	0.2880
T5111242	0.0758	0.0821
T5111262	0.0419	0.0286

Table 5-6 : The RMSE of the direct model before and after an internal fault.

Validation File	Before internal fault	After internal fault
T2111214	0.1398	1.7103
T2111233	0.2283	1.3546
T5111242	0.3077	0.2893
T5111262	0.2483	0.2347

Table 5-7 : The RMSE of the indirect model before and after an internal fault.

Figure 5.17 consists of four subplots. From the bottom, the first subplot shows the secondary current of phase α . The second illustrates the difference error of the direct model, while the third plot shows the error of the direct model. Finally, the last plot represents the trip signal. This Figure shows that the direct model could predict the secondary current precisely before the occurrence of an internal fault (0.05 sec), while the error increases in amplitude after the internal fault.

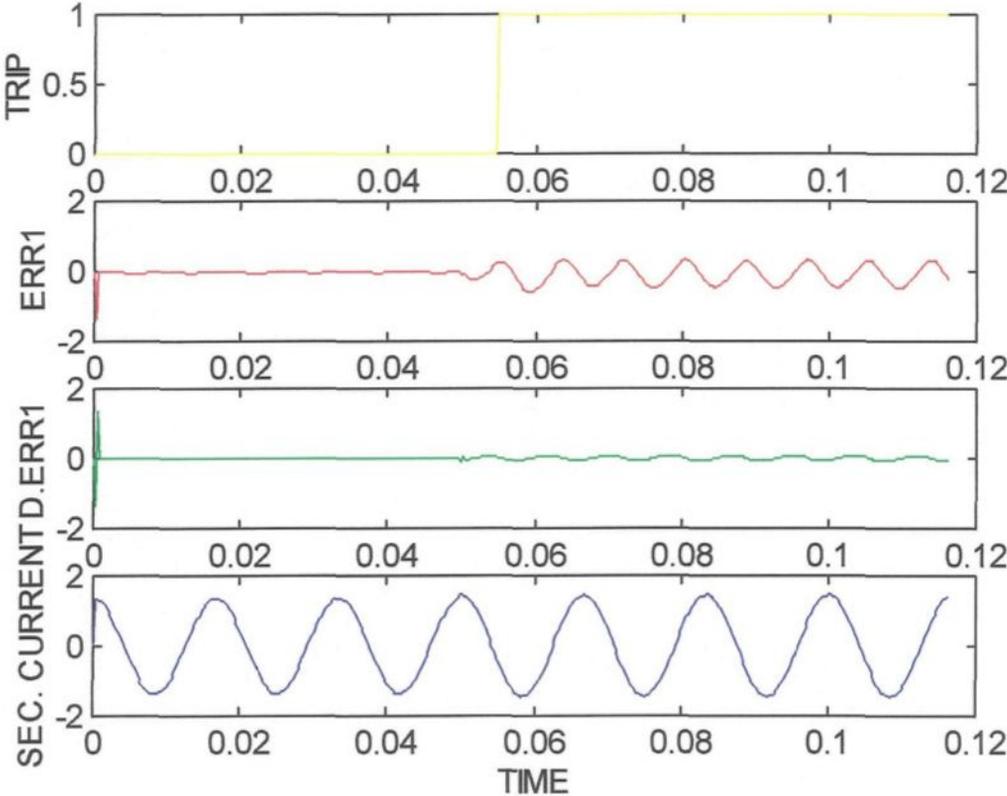


Figure 5.17 : Direct model, validation file T2111233.

Figure 5.18 consists of four subplots. From the bottom, the first subplot shows the primary current of phase α . The second illustrates the difference error of the indirect model, while the third plot shows the error of the indirect model. Finally, the last plot represents the *trip signal*.

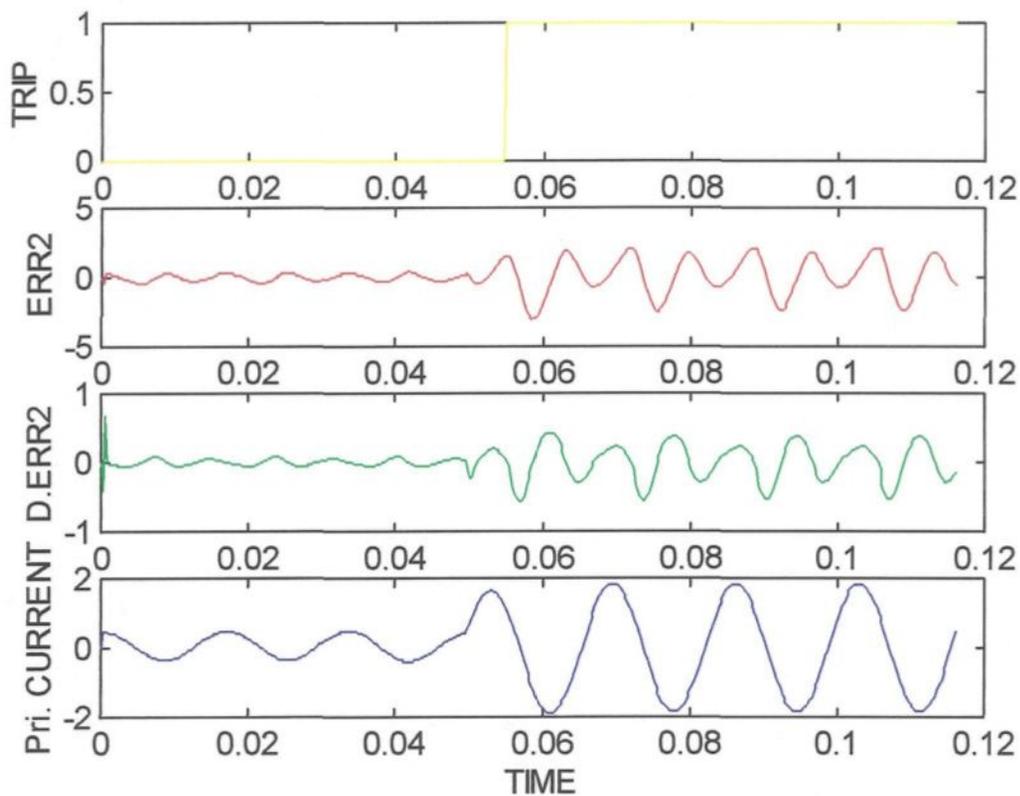


Figure 5.18 : Indirect model, validation file T2111233.

Figure 5.19 consists of four subplots. From the bottom, the first subplot shows the secondary current of phase α . The second illustrates the difference error of the direct model, while the third plot shows the error of the direct model. Finally, the last plot

represents the *trip signal*. This Figure shows that the direct model could predict the secondary current precisely before the occurrence of an internal fault (0.05 sec). Although the error increases after the occurrence of the internal fault, its amplitude is not large enough to issue a trip signal immediately after the internal fault. It results that the direct and indirect models are not sensitive to a small internal fault (3 percentage).

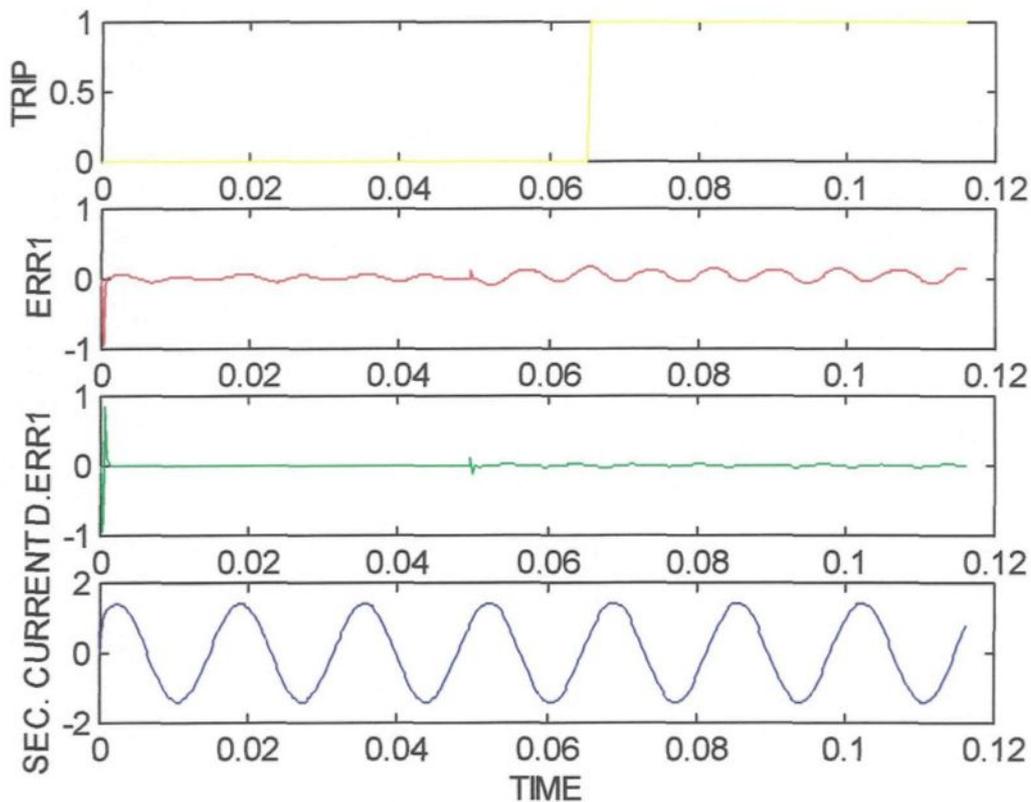


Figure 5.19 : Direct model, validation file 5111242.

Figures 5.20 consists of four subplots. From the bottom, the first subplot shows the primary current of phase α . The second illustrates the difference error of the indirect

model, while the third plot shows the error of the indirect model. Finally, the last plot represents the *trip signal*.

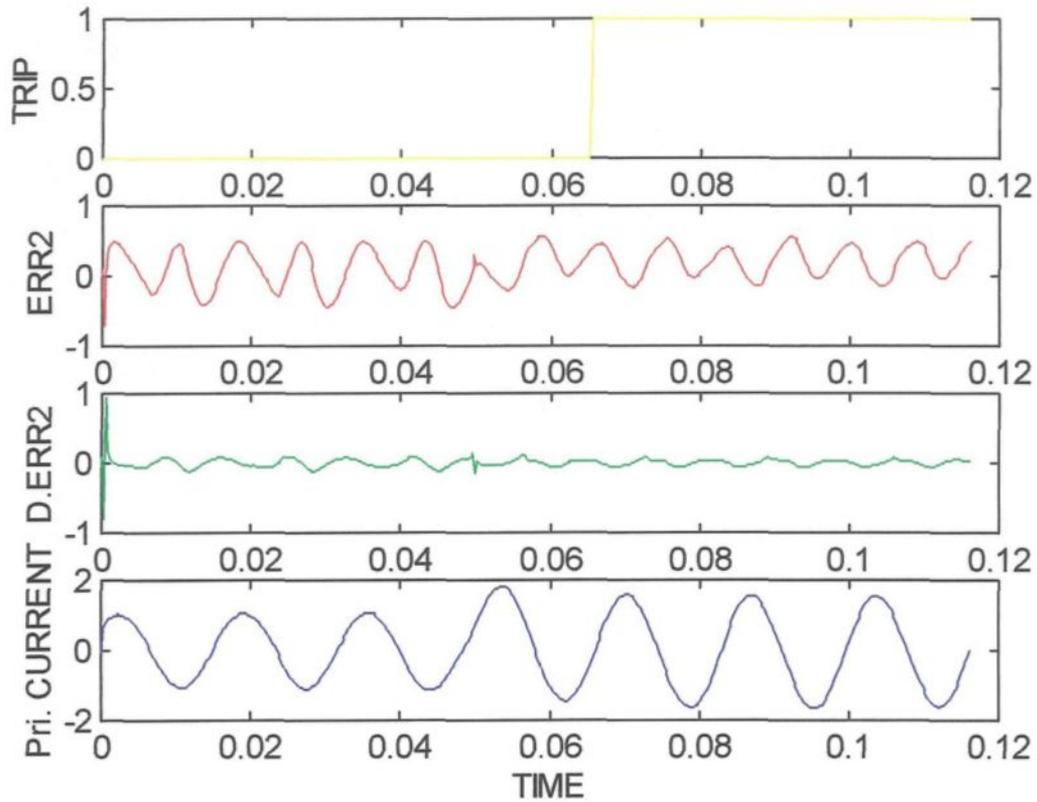


Figure 5.20 : Indirect model, validation file 5111242.

Chapter 6

Conclusion and Further Works

The work presented in this thesis was undertaken to identify a three-phase nonlinear power transformer by neuro-fuzzy systems, and to employ this identification system as a model-based protective relay for the power transformer. Standard identification and control systems deal with systems that can be represented by a set of differential equations. In practice, most of the systems cannot be defined by mathematical equations. Therefore, new approaches like fuzzy logic are employed to identify a system by a set of input/output data. While other approaches require accurate equations to model real-world behaviors, fuzzy design can accommodate the ambiguities of real-world human language and logic. However, there are some very important drawbacks:

- No standard methods exist for transforming human knowledge or experience into the rule base and database of a fuzzy inference system;
- There is a need for effective methods for tuning the membership function so as to minimize the output error measure;
- Computing time could be long, because of the complex operations such as fuzzification and particularly defuzzification.

Neuro-fuzzy systems, which combine the properties of neural networks and fuzzy logic systems, are a new branch of system identification. It is concerned with the construction of a fuzzy inference system that can predict and hopefully explain the behavior of an unknown system described by a set of sample data. The aim of neuro-fuzzy

systems is to combine collectively the benefits of both approaches. Simply, the operation of the system is expressed as linguistic fuzzy expressions, and learning schemes of neural networks are used to train the system. In addition, neuro-fuzzy systems allow incorporation of both numerical and linguistic data. The neuro-fuzzy system is also capable of extracting fuzzy knowledge from numerical data. The main advantages of neuro-fuzzy systems are:

- No need to represent the system by a set of mathematical equations;
- It is possible to implement expert knowledge and experience using comprehensible linguistic rules;
- It is possible to identify nonlinear systems.

In this research, two neuro-fuzzy models, one direct and one indirect, are developed. The models were trained by the hybrid learning algorithm which comprises the *Least-Squares Estimator (LSE)* and *Gradient Descent (GD)* methods. Several training files (including the rated conditions of the power transformer, over load conditions, and external faults) were employed during the training procedure.

Several unseen data files were applied to the models in order to verify the validation and the generalization of the models. These data files included the rated conditions and different types of internal faults. The validation procedure showed that the direct and indirect models could identify the power transformer accurately during rated conditions and the amplitude of their errors were small and negligible. However, the errors increased

considerably as soon as an internal fault occurred. Therefore, the errors of both models were used to detect the internal faults. They detected all the internal faults immediately (except the 3% internal faults in the primary side of the power transformer). Although they could not detect the 3% internal faults in the primary side of the transformer immediately, the internal faults were detected after one cycle. This showed that neuro-fuzzy systems can be employed as an identification and protection system for a power transformer.

A typical modeling problem includes *structure determination* and *parameter identification*. The structure determination problem, which deals with the partition style, the number of membership function for each input, and the number of fuzzy *if-then* rules, and so on, is now an active research topic in the field. As it was explained in chapter 4, the grid partition was employed. This partition style causes problems, usually referred to as the *curse of dimensionality*, in the case of a moderately large number of inputs. It is suggested to employ another partition style like the tree partition, the scatter partition, CART (classification and regression tree), and various clustering algorithms to avoid this problem. This can also decrease the training time.

The identification of the parameters determines a feasible set of parameters under the given structure. Though the parameter identification problems can be speeded up by introducing the least-squares estimator into the learning cycle, the gradient descent method still slows down the training process and the training time could be prohibitively long for a complicated task like identification of a nonlinear power transformer. Therefore, the need

to search for better learning algorithms in order to speed up the training process is very important.

Detecting an internal fault can be considered as a clustering problem. In this work, the internal faults were detected based on the amplitude of the errors of both the direct and indirect models. In other words, if the amplitude of the errors are larger than a threshold value, a trip signal is issued. Otherwise, it declares that there is no internal fault. However, determining the threshold value is a time consuming procedure. Therefore, the errors can be clustered into two groups. Integrating the fuzzy clustering, which is a data clustering technique where each data point belongs to a cluster to a degree specified by a membership grade, into the models can improve and automate the fault diagnosis process.

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