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DETECTING THE LOSS OF EXCITATION IN HYDRO GENERATORS USING A NEURO-FUZZY TECHNIQUE

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Abstract: This research explores the impact of using the 3^{rd} harmonics and the positive sequence components on enhancing the performance of the circuits for the detection of Loss of Excitation (LOE) in hydro-generators. In this context, investigations were conducted on a two hydro-generators power station model under a complete Loss of Excitation (LOE) conditions, and a partial Loss of Excitation (LOE) conditions in different generator loading conditions. The results of the investigations are compared with those obtained using other techniques to prove the effectiveness of the proposed solution. The time-domain simulation studies were conducted using PSCAD/EMTDC software. The results obtained are very promising.

Keywords**:** Adaptive Neuro Fuzzy Inference System, Discrete Fourier Transform, Loss of Excitation, Hydro-Generator, Dynamic Performance, Simulation.

1. INTRODUCTION

Protection of synchronous generators against Loss-of-excitation (LOE) is a critical factor for the reliability of any power system. This is because Loss of Excitation (LOE) is a very common fault in synchronous machines and can be caused by short circuit of the field winding, unexpected field breaker open or Loss of Excitation (LOE) relay mal-operation. Loss of Excitation (LOE) may cause severe damages to both generator and system. For the generator; when Loss of Excitation (LOE) happens, a slip occurs which may cause rotor over heating due to the slip frequency in rotor circuits. Also, as the machine operates as an induction machine after Loss of Excitation (LOE) conditions, large amount of reactive power supplied by stator current is required and the stator may suffer over heating because of this large current. While, for the system; its voltage declines after the generator lose its excitation, because the generator operates as an induction machine and absorbs reactive power from the system. In the past, the distance relay was developed for the high speed detection of Loss of Excitation (LOE) faults in synchronous generators. This relay was developed to enhance the selectivity between Loss of Excitation (LOE) conditions and other normal or abnormal operating conditions and to provide fast operating times necessary for protection of both the generator and the system (Berdy, 1975). Over the years, the offset mho relay has been widely accepted for loss of excitation protection. The relay has demonstrated its capability of detecting different excitation system faults and to discriminate between such faults and other operating conditions. The relatively few cases of incorrect operation that have occurred can be referred to incorrect relay connections (major cause), and blown potential transformer fuses. Regardless of this accepted experience, the user worry about the performance of distance type of relaying for loss of excitation protection was initiated. In view of this continuing concern over relay performance, a general study was launched to review the performance of the offset mho Loss of Excitation (LOE) relay different system conditions. Consequently, many methodologies and algorithms have been addressed to solve the generators Loss of Excitation (LOE) problem such as:

- Fuzzy inference mechanism based technique (Morais, *et al.*, 2010).
- ANN based technique (Sharaf and Lie, 1994).
- Adaptive Loss of Excitation relay based on time-derivatives of impedance (Tambay and Paithankar, 2005).
- Adaptive loss of excitation protection relay based on the steady-state stability limit (Liu, *et al.*, 2013).
- Technique based on the derivative of the terminal voltage and the output reactive power of the generator (Amini, *et al.*, 2015).
- Recently, ANFIS scheme based on impedance measurements (R, X) (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016).
- Recently, ANFIS scheme based on terminal voltage and stator current measurements (V_{trms} and I_a) (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016).

Therefore, the necessity for this research work came into sight as the shortage of Loss of Excitation (LOE) distance relays became clear. Moreover; these distance relays behaviour to different Loss of Excitation (LOE) conditions is totally depending on the generator loading and the percentage loss of excitation, consequently, many Loss of Excitation (LOE) conditions are not detected by these relays. As a result, the need for developing an Artificial Intelligent (AI) based relay to overcome these problems appeared.

This article presents a recent optimization algorithm based on Artificial Intelligence (AI) technique. Two techniques are discussed in this article based on the type of inputs to the ANFIS. The positive sequence components of the terminal voltage magnitude, stator current magnitude and angle and the generator stator current 3rd harmonic components (magnitudes and angles) are used as inputs to the ANFIS unit. The proposed techniques results are compared with other techniques. The obtained results from the proposed schemes are very promising. The rest of the paper is organized as follows: Section 2 illustrates the system under study, while Section 3 describes the Adaptive Neuro Fuzzy Inference System technique, on the other hand, Section 4 presents the simulation environment and finally, Section 5 describes the results and discussion.

2. SYSTEM UNDER STUDY

The system used in the investigations of this paper is shown in Figure 1. It consists of two hydro-generators which are connected via transformers to an infinite-bus system through a 300 km, 345 kV transmission line. The system data are given in Appendix-A as given in (Elsamahy, *et al.*, 2010). The PSCAD/EMTDC simulation package is used for in the simulation process (PSCAD/EMTDC software).

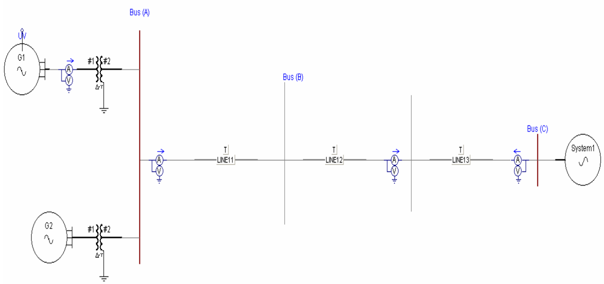

Fig. 1. One-Line Diagram of the Simulation Model in PSCAD.

3. ADAPTIVE NEURO FUZZY INFERENCE SYSTEM

A Fuzzy Logic System (FLS) can be viewed as a non-linear mapping from the input space to the output space. A FLS consists of five main components: Fuzzy Sets, fuzzifiers, fuzzy rules, an inference engine and defuzzifiers. However fuzzy inference system is limited in its application to only modelling ill-defined systems.

These systems have rule structure which is essentially predetermined by the user's interpretation of the characteristic of the variables in the model. It has been considered only fixed membership functions that were chosen arbitrarily. However, in some modelling situations, it cannot be distinguished what the membership functions should look like simply from looking at data. Rather than choosing the parameters associated with a given membership function arbitrarily, these parameters could be chosen so as to tailor the membership functions to the input/output data in order to account for these types of variations in the data values. In such case the necessity of the ANFIS becomes obvious. Adaptive Neuro-Fuzzy networks are enhanced FLSs with learning, generalization, and adaptive capabilities. These networks encode the fuzzy if-then rules into a neural network-like structure and then use appropriate learning algorithms to minimize the output error based on the training/validation data sets (Abdel Aziz, *et al.*, 2011; Abdel Aziz, *et al.*, 2012; Abdel Aziz, *et al.*, 2012; Abdel Aziz, *et al.*, 2011; Kamel, *et al.*, 2011; Kamel, *et al.*, 2012).

Neuro-adaptive learning techniques provide a method for the fuzzy modelling procedure to learn information about a data set. It computes the membership function parameters that best allow the associated fuzzy inference to track the given input/output data.

A network-type structure similar to that of an Artificial Neural Network (ANN) can be used to interpret the input/output map. Therefore, it maps inputs through input membership functions and associated parameters, and then through output membership functions and associated parameters to outputs. These parameters change through the learning process.

The used ANFIS is assumed to have the following properties (Kamel, *et al.*, 2011; Kamel, *et al.*, 2012):

- It is zeroth order sugeno-type system.
- It has a single output, obtained using weighted average defuzzification.
- All output membership functions are constant.
- It has no rule sharing. Different rules do not share the same output membership function; the number of output membership functions must be equal to the number of rules.
- It has unity weight for each rule.

The architecture of the ANFIS, comprising by input, Fuzzification, Inference and Defuzzification layers could be obtained from the Graphical User Interface (GUI) of the Matlab dealing with ANFIS. The network can be visualized as consisting of inputs, with N neurons in the input layer and F input membership functions for each input, with F * N neurons in the Fuzzification layer. There are F^N rules with F^N neurons in the inference and Defuzzification layers. It is assumed one neuron in the output layer.

The proposed ANFIS unit consists of two neurons in the input layer i.e. N=2, six Membership Functions (MF) for each input i.e. M=6 and constant membership function for the output layer, Appendix-B.

4. SIMULATION ENVIRONMENT

The simulation environment based on the MATLAB software package (The Math Works, Natick, Massachusetts, USA) is selected as the main engineering tool for performing modelling and simulation of power systems and relays. The PSCAD/EMTDC program is used for detailed modelling of a power network and simulation of interesting events. Scenario setting and a relaying algorithm will be implemented in the MATLAB program, while the data generation for training and testing of this algorithm will be executed by the PSCAD/EMTDC program. The used training data to train the ANFIS are taken at Loss of Excitation (LOE) fault conditions and no-fault conditions.

The fault conditions are carried out at different Loss of Excitation (LOE) fault types:

- Partial Loss of Excitation (LOE) faults.
- Complete Loss of Excitation (LOE) faults.

These fault conditions are carried out at different generators loading conditions (18.5%, 25%, 35%, 40%, 50%, 55%, 60%, 65%, 70% and 80%) with inception fault time T_f= 5 sec and different Loss of Excitation (LOE) cases (20%, 25%, 50%, 60%, 70%, 75%, 80% and 100%).

The two proposed methods are compared with each other in this article for the purpose of Loss of Excitation detection, the first scheme is based on the positive sequence components of the voltage magnitude, phase current magnitude and angle ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$), while; the second scheme is based on the stator current 3rd harmonics components (magnitudes and angles). The obtained results from these schemes are better than the results obtained from other algorithms such as (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016) and (USTA, *et al.*, 2007; Shi, *et al.*, 2012). Figure 2 shows the flowchart for the Loss of Excitation detection procedure of the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$), on the other hand; Figure 3 provides the flow chart for the proposed stator current 3rd harmonics components scheme.

5. RESULTS AND DISCUSSION

The system was simulated using PSCAD/EMTDC as well as Matlab and the results of simulation are illustrated in the paper.

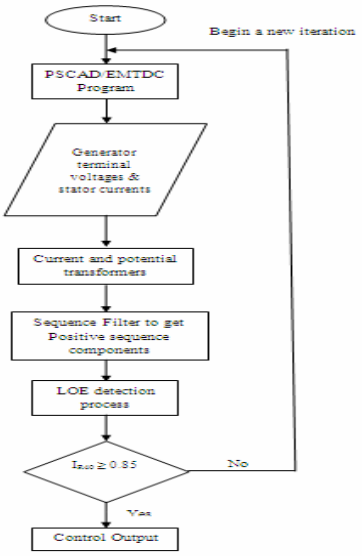

Fig. 2. Flowchart for the Loss of Excitation (LOE) Detection Procedure based on ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$).

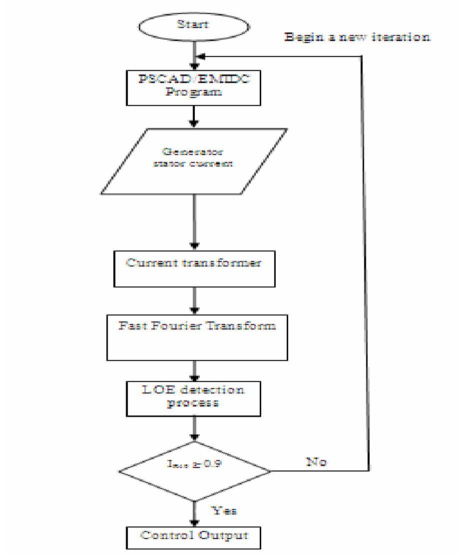

Fig. 3. Flowchart for the Loss of Excitation (LOE) Detection Procedure based on (the stator current 3rd harmonics components).

5.1 The Proposed ($|V_{+Ve}|$, $|I_{+Ve}|$ And $\angle I_{+Ve}$) Protection Scheme

On this scheme, the inputs to the ANFIS unit are the positive sequence components of the generator voltage magnitude, current magnitude and angle ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) which are obtained from the generator terminal voltage and stator current values. The testing data are chosen randomly to have data from the training process while the validation data are chosen to have data not included in the training process.

Table (1) displays the testing data of the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme. Table (2) illustrates the validation data of the proposed scheme.

Tables (1) and (3) offer the good results of the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme in detecting the generator Loss of Excitation (LOE) under different loading conditions in a marginally small time compared to other schemes.

For example, the 1st row in Table (2) illustrates when the generator losses 50% of its excitation at T_f = 5 sec while it was loaded by 80% of its' full load, the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme will detect this fault at "5.6 sec" which means that the fault will be detected after its inception time by "0.6 sec" through the calculated index "I_{R40}" which is greater than the threshold value "0.85".

Also, the 4th row in Table (2) shows when the generator losses 75% of its excitation at T_f = 5 sec while it was loaded by 70% of its' full load, the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme will detect this fault at "5.5 sec" which means that the fault will be detected after its inception time by "0.5 sec".

From the below Tables (1) and (2) calculated indices (I_{R40}) it is easy to understand that the output of the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme should be reasonably chosen as:

- $I_{R40} \geq 0.85$ for Loss of Excitation (LOE) conditions.
- $I_{R40} \leq 0.24$ for no-fault conditions.

From the results illustrated in Tables (1) and (2), it is obvious that the proposed positive sequence based ANFIS scheme detects the Loss of Excitation (LOE) conditions within about (500-1000 msec) after the fault inception under different generator loading conditions from (18.5% to 80%) of its' rating and under various Loss of Excitation (LOE) percentages, which is better than the other (R and X) and (V_{trms} and I_a) ANFIS schemes (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016).

5.2 The Proposed Stator Current 3rd Harmonics Components Protection Scheme

This scheme utilizes the generator stator current 3rd harmonics components (magnitudes and angles) as inputs to the ANFIS unit.

Tables (3) and (4) demonstrate the testing and validation data of the proposed 3rd harmonics components ANFIS scheme respectively.

These Tables offer the promising results of the proposed 3rd harmonics components ANFIS scheme in detecting all the generator Loss of Excitation (LOE) conditions under all the different loading conditions in a very small time compared to the positive sequence ANFIS scheme.

For example, the 1st row in Table (4) provides when the generator losses 50% of its excitation at T_f = 5 sec while it was loaded by 80% of its' full load, the proposed ANFIS scheme will detect this fault at "5.2 sec" which means that the fault will be detected after its inception time by "0.2 sec" through the calculated index "I_{R40}" which is greater than the threshold value "0.9".

Also, the 4th row in Table (4) shows when the generator losses 75% of its excitation at T_f = 5 sec while it was loaded by 70% of its' full load, the proposed ANFIS scheme will detect this fault at "5.2 sec".

From the below Tables (3) and (4) calculated indices (I_{R40}), it is easy to terminate that the output of this proposed ANFIS scheme should be logically chosen as:

- $I_{R40} \geq 0.9$ for Loss of Excitation (LOE) conditions.
- $I_{R40} \leq 0.325$ for no-fault conditions.

The indicated results in the below Tables (3) and (4), show that the proposed stator current 3rd harmonics components based ANFIS scheme detects the Loss of Excitation (LOE) conditions within about (40-200 msec) after the fault inception under all generator loading conditions and under various Loss of Excitation (LOE) percentages. These results are better than those obtained from the other ANFIS schemes (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016).

It is clear that the generator stator current 3rd harmonics components as inputs for the ANFIS units gives advanced results more efficient than the other ANFIS schemes and better than other used techniques as in (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016) and (USTA, *et al.*, 2007; Shi, *et al.*, 2012), and the calculated indices "I_{R40}" are very close to the expected indices. Finally, Table (5) summarizes a comparison between the proposed Loss of Excitation (LOE) ANFIS techniques discussed in this article and other techniques. This comparison is based on the generator loading conditions, threshold values and the response time.

6. CONCLUSIONS

This research work presents a secure scheme for Hydro-generators different Loss of Excitation (LOE) protection using Adaptive Neuro Fuzzy Inference System (ANFIS). The Proposed Artificial Intelligent Approach demonstrates successful performance for Loss of Excitation (LOE) faults detection. Two schemes are utilized in this article; they are classified according to the type of the inputs to the proposed ANFIS unit. The results have been compared with each other and with those obtained using other algorithms. It is obvious from the comparison that the proposed ANFIS approach provides a notable performance in the Loss of Excitation (LOE) detection process. It was found that the stator current 3rd harmonics play an essential rule in the Loss of Excitation (LOE) detection process. The obtained results are very brilliant.

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APPENDICES

APPENDIX-A:

Data of the system under study

Generators

Rating = 300 MVA

Rated Voltage = 23 kV

Xd = j1.15 p.u.

Xq = j0.75 p.u.

Generator Step Up (GSU) Transformers

300 MVA, 23 kVΔ / 345 kV Yg

Leakage reactance = j0.1 p.u.

Transmission Line

Length = 300 km

Positive sequence impedance Z1 = 0.51 $\angle 85.98^{\circ}$ ohm/km.

Loss of Excitation Relay setting

Zone1 radius = 8.805 ohm

Zone2 radius = 10.125 ohm

Offset of the mho circles = -Xd'/2 = -2.76 ohm.

APPENDIX-B:

The different membership functions and the corresponding calculated percentage error values for the proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS scheme are shown in Figure (B-1).

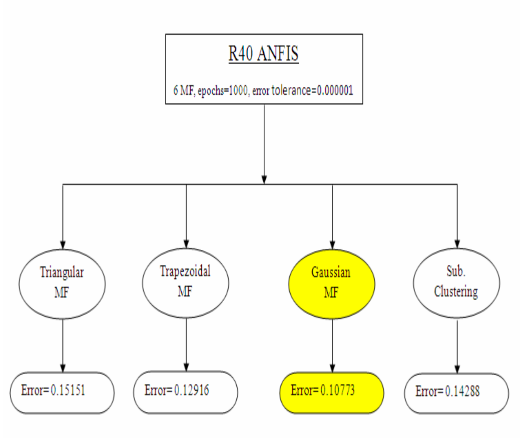

Fig. (B-1): The Different Membership Functions and the Corresponding Errors for the ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS Scheme.

While the corresponding calculated percentage error values versus the different membership functions for the proposed (stator current 3rd harmonics components) ANFIS scheme are illustrated in Figure (B-2).

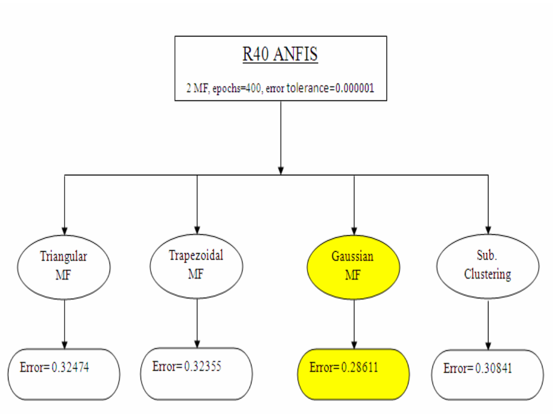

Fig. (B-2). The Different Membership Functions and the Corresponding Errors for the (stator current 3rd harmonics components) ANFIS Scheme.

Table 1.Testing Data for the Proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS Scheme

Generator Loading %	**LOE%**	**LOE Inception Time (sec)**	**Testing time (sec)**	**$\|V+\|$ (Volt)**	**$\|I+\|$ (Ampere)**	**$\angle$I+ (rad)**	**Calculated Index “I_{R40}”**	**Expected Index**	**Error %**
80%	75%	5	6	63.6528	3.0888	-1.4919	1.128	1	12.8
80%	75%	5	8	57.2561	3.8416	-1.0871	0.965	1	3.5
80%	75%	5	7	60.0502	3.4385	-1.25609	0.998	1	0.2
80%	75%	5	6.5	61.7497	3.2403	-1.3646	1.063	1	6.3

50%	25%	5	7.5	66.9926	1.9706	-1.5305	1.233	1	23.3
50%	25%	5	8	66.6335	2.01203	-1.4866	1.203	1	20.3
50%	25%	5	2	69.7145	1.7805	-1.84809	0.095	0	9.5
50%	25%	5	3.5	69.68907	1.7808	-1.8473	0.09	0	9
70%	25%	5	6.1	65.0116	2.64506	-1.5918	0.949	1	5.1
70%	25%	5	7	63.6877	2.7499	-1.48203	1.043	1	4.3
70%	25%	5	8.5	62.0989	2.9294	-1.3457	1.005	1	0.5
70%	25%	5	3	66.67502	2.5578	-1.7212	0.109	0	10.9
70%	25%	5	4	66.6766	2.5575	-1.7214	0.106	0	10.6

Table 2. Validation Data for the Proposed ($|V_{+ve}|$, $|I_{+ve}|$ and $\angle I_{+ve}$) ANFIS Scheme

Generator Loading %	**LOE%**	**LOE Inception Time (sec)**	**Testing time (sec)**	**$\lvert V+ \rvert$ (Volt)**	**$\lvert I+ \rvert$ (Ampere)**	**$\angle I+$ (rad)**	**Calculated Index "IR40"**	**Expected Index**	**Error %**
80%	50%	5	5.6	65.3611	2.9558	-1.6172	0.882	1	11.8
80%	50%	5	7.5	60.2405	3.4013	-1.2657	1.002	1	0.2
80%	50%	5	4	66.6805	2.8995	-1.7076	0.122	0	12.2
70%	75%	5	5.5	65.3121	2.6216	-1.6158	0.874	1	12.6
70%	75%	5	6	63.7606	2.7377	-1.5021	1.048	1	4.8
70%	75%	5	8	58.4471	3.4044	-1.1287	0.974	1	2.6
70%	75%	5	2.5	66.6806	2.5565	-1.7213	0.109	0	10.9
70%	75%	5	3.5	66.6758	2.5568	-1.7213	0.107	0	10.7
35%	75%	5	5.9	64.8125	1.5545	-1.4413	0.855	1	14.5
35%	75%	5	6	64.51303	1.59109	-1.4067	0.884	1	11.6
35%	75%	5	9	60.4687	2.3527	-1.0397	1.015	1	1.5
35%	75%	5	4.5	66.7379	1.3563	-1.68902	0.028	0	2.8
25%	80%	5	6	64.7303	1.2908	-1.3106	0.865	1	13.5
25%	80%	5	7.5	62.0522	1.8087	-1.0484	1.054	1	5.4
25%	80%	5	8.5	61.0001	2.0609	-0.9762	1.023	1	2.3
25%	80%	5	4	66.7837	1.0233	-1.6151	0.24	0	24
80%	20%	5	5.8	65.5917	2.9675	-1.6185	0.859	1	14.1
80%	20%	5	7.5	62.7272	3.1756	-1.4055	1.095	1	9.5
80%	20%	5	15	56.4409	4.0775	-1.0064	0.984	1	1.6
80%	20%	5	1.5	67.0944	2.8991	-1.71802	0.002	0	0.2
80%	20%	5	3	67.0101	2.9033	-1.7157	0.022	0	2.2

Table 3. Testing Data for the Proposed (Stator Current 3rd Harmonic Components) ANFIS Scheme

Generator Loading %	LOE %	LOE Inception Time (sec)	Conv. Distance Relay trip time (sec)	Testing time (sec)	│Ia│ (Amp)	│Ib│ (Amp)	│Ic│ (Amp)	∟Ia (rad)	∟Ib (rad)	∟Ic (rad)	Calculated Index "IR40"	Expected Index	Error %
80%	75%	5	11.8	6	0.00119	0.00092	0.00184	-1.558	-2.5705	1.15011	0.992	1	0.8
80%	75%	5	11.8	8	0.000573	0.001359	0.001029	-1.999	1.90505	-0.8437	0.948	1	5.2
80%	75%	5	11.8	7	0.000496	0.001321	0.001498	-1.976	2.93846	0.12358	0.948	1	5.2
80%	75%	5	11.8	6.5	0.001249	0.000848	0.001825	-1.595	-2.6377	1.1358	0.993	1	0.7
50%	25%	5	-	7.5	0.000213	0.000277	0.00044	-2.598	2.80402	0.04059	0.956	1	4.4
50%	25%	5	-	8	0.000126	0.000325	0.000315	-2.622	1.82616	-0.9322	0.956	1	4.4
50%	25%	5	-	2	0.000012	0.000018	0.00002	-2.445	-0.4218	2.04761	0.317	0	31.7
50%	25%	5	-	3.5	0.000022	0.000015	0.000017	-2.1804	0.29706	1.82466	0.154	0	15.4
70%	25%	5	35	6.1	0.000525	0.000395	0.000796	-1.55066	-2.6076	1.15053	0.992	1	0.8
70%	25%	5	35	7	0.000228	0.000535	0.000654	-2.186047	2.92747	0.10993	0.95	1	5
70%	25%	5	35	8.5	0.000177	0.000456	0.000416	-2.428878	1.85948	-0.8948	0.954	1	4.6
70%	25%	5	35	3	0.000031	0.00002	0.000025	-2.243365	0.09598	1.76697	0.215	0	21.5
70%	25%	5	35	4	0.000034	0.000028	0.000017	-2.260575	0.46491	2.02554	0.094	0	9.4

Table 4. Validation Data for the Proposed (Stator Current 3rd Harmonic Components) ANFIS Scheme

Generator Loading %	LOE %	LOE Inception Time (sec)	Conv. Distance Relay trip time (sec)	Testing time (sec)	│Ia│ (Amp)	│Ib│ (Amp)	│Ic│ (Amp)	∟Ia (rad)	∟Ib (rad)	∟Ic (rad)	Calculated Index "IR40"	Expected Index	Error %
80%	50%	5	14.5	5.2	0.000332	0.000509	0.000767	-1.36121	-2.2324	1.25377	0.98	1	2
80%	50%	5	14.5	7.5	0.0004209	0.000909	0.001149	-2.25375	2.89879	0.09008	0.952	1	4.8
80%	50%	5	14.5	4	0.0000399	0.000032	0.00002	-2.25116	0.47738	1.98263	0.096	0	9.6
70%	75%	5	13.2	5.2	0.0004378	0.000569	0.000915	-1.42515	-2.2927	1.22745	0.98	1	2
70%	75%	5	13.2	6	0.0010745	0.000753	0.001592	-1.5875	-2.6251	1.13785	0.993	1	0.68
70%	75%	5	13.2	8	0.000414	0.001059	0.000865	-2.15075	1.88382	-0.8797	0.95	1	5
70%	75%	5	13.2	2.5	0.00003	0.000022	0.000021	-2.32908	0.14996	1.84553	0.17	0	17
70%	75%	5	13.2	3.5	0.0000323	0.00002	0.000025	-2.25334	0.11647	1.73005	0.232	0	23.2
35%	75%	5	36	5.1	0.0003889	0.000132	0.000438	-0.6378	-2.0045	2.20408	0.902	1	9.8
35%	75%	5	36	6	0.0008504	0.000418	0.001072	-1.68088	-2.8824	1.09104	0.997	1	0.3
35%	75%	5	36	9	0.0001462	0.000395	0.000412	-2.79447	1.82386	-0.9592	0.958	1	4.2
35%	75%	5	36	4.5	0.0000191	0.000014	0.000009	-2.22671	0.53057	1.92457	0.097	0	9.7
25%	80%	5	-	5.04	0.0001273	0.000037	0.000136	-0.69166	-2.1957	2.17758	0.937	1	6.3
25%	80%	5	-	7.5	0.0003867	0.000406	0.000715	-2.67847	2.7098	-0.0017	0.957	1	4.3
25%	80%	5	-	8.5	0.0001638	0.0004	0.000463	-3.11979	1.77613	-1.0101	0.96	1	4
25%	80%	5	-	4	0.0000146	0.00001	0.000007	-2.27178	0.41557	1.81808	0.13	0	13
80%	20%	5	24	5.2	0.0002197	0.000329	0.000509	-1.40593	-2.1944	1.26871	0.98	1	2
80%	20%	5	24	7.5	0.0002853	0.000576	0.000754	-2.32999	2.89821	0.08701	0.953	1	4.7
80%	20%	5	24	10	0.0003124	0.000473	0.000213	-2.72066	0.76253	-1.856	0.959	1	4.1
80%	20%	5	24	1.5	0.0000228	0.000032	0.000018	-3.13813	-0.3135	2.38546	0.26	0	26
80%	20%	5	24	3	0.0000354	0.000021	0.000029	-2.22811	0.06876	1.73131	0.24	0	24

Table 5. Comparison between Different Loss of Excitation (LOE) Techniques

ANFIS Technique	**Generator Loading %**	**Threshold Values**	**Response Time (sec)**
LOE ANFIS relay based on (R and X). (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016)	All loading conditions (from 18.5% to 80%).	• $I_{R40} \geq 0.85$ for Loss of Excitation (LOE) conditions. • $I_{R40} \leq 0.2$ for no-fault conditions.	(300-1400 msec).
LOE ANFIS relay based on (V_{trms} and I_a). (Abdel Aziz, *et al.*, 2016; Abdel Aziz, *et al.*, 2016)	Higher than 50%.	• $I_{R40} \geq 0.85$ for Loss of Excitation (LOE) conditions. • $I_{R40} \leq 0.25$ for no-fault conditions.	(500-900 msec).
LOE ANFIS relay based on ($\lvert V_{+ve} \rvert$, $\lvert I_{+ve} \rvert$ and $\angle I_{+ve}$).	All loading conditions (from 18.5% to 80%).	• $I_{R40} \geq 0.85$ for Loss of Excitation (LOE) conditions. • $I_{R40} \leq 0.24$ for no-fault conditions.	(500-1000 msec).
LOE ANFIS relay based on stator current 3rd harmonic components (magnitudes and angles).	All loading conditions (from 18.5% to 80%).	• $I_{R40} \geq 0.9$ for Loss of Excitation (LOE) conditions. • $I_{R40} \leq 0.325$ for no-fault conditions.	(40-200 msec).
Other technique based on “generator reactive power output and its pull out curve”. (USTA, *et al.*, 2007)	10% and 50%	-	Within 1120 msec.
Other technique based on “R-X with directional element scheme”. (Shi, *et al.*, 2012)	40% and 80%	-	6.931 and 4.175 sec.