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A Secure ANFIS based Relay for Turbo-Generators Phase Backup Protection

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Abstract

This paper presents a new advanced methodology as a solution for the problem due to the current setting of Relay (21) when it is set to provide thermal backup protection for the generator during two common system disturbances, namely a system fault and a sudden application of a large system load. These investigations are carried out using Adaptive Neuro Fuzzy Inference System (ANFIS). The results of the investigations have shown that the ANFIS has a promising effect when applied for turbo-generators phase backup protection. Such an effect varies according to the type of data used for ANFIS testing and validating. The proposed method in this paper proposes the use of two different sets of inputs to the ANFIS, these inputs are the generator terminal impedance measurements (R and X) and the generator three phase terminal voltages and currents (V and I). The dynamic simulations of a test benchmark have been conducted using the PSCAD/EMTDC software. The results obtained from the ANFIS scheme are encouraging.

Keywords: *adaptive neuro fuzzy inference system, distance protection, phase backup protection, turbo-generator, dynamic performance, simulation*

1. Introduction

Protective relaying provides important defense for power grid operation. Conventional backup protection depends on local electrical information to make relevant decisions, and cannot securely distinguish an internal fault from heavy load during flow transfer [1]. This may cause cascading trip events and accelerate power system failure. In addition, the complex setting principle of conventional backup protection may induce hidden failures caused by setting mistakes [2], which would increase the risk of system instability during a disturbance [3, 4].

Moreover, some of the researchers have proved the existence of a potential problem due to the current setting of Relay (21) when it is set according to the present standards and recent related publications for generator thermal backup protection against transmission line uncleared faults, it is found that the current setting of the Relay (21) for generator thermal backup protection restricts the over excitation thermal capability of the generator [5]. Such a restriction does not allow the generator to supply its maximum reactive power during such events. Thus, the necessity of revising the Relay (21) reach to ensure a secure performance for the relay during major system disturbances was initiated, which would allow the generator to fulfill the system requirements during such events to ensure adequate level of voltage stability.

The Relay (21) element is typically set at the smallest of the following three criteria [6]:

1. 120% of the longest line with in-feeds.
2. 50% to 67% of the generator load impedance (Z_{load}) at the rated power factor angle (RPFA) of the generator. This provides a 150% to 200% margin over generator full load.
3. 80% to 90% of the generator load impedance at the maximum torque angle (MTA) of the relay setting (typically 85°) (Z_{GCC}).

In particular situations when the generator distance phase backup protection relay is mainly required to provide thermal backup protection for the generator against transmission line faults, which are not cleared by transmission line relays, Relay (21) is set directly according to the second criterion (which is the setting considered during the investigations of this paper). The

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time delay for Relay (21) should be set longer than the transmission line backup protection (0.8 to 1 second) with appropriate margin for proper coordination.

Here in our paper, when applying this setting to the Relay (21) and when checking the “coordination of generator and transmission systems” requirements reported in the North Electric Reliability Council (NERC), we find that the relay setting must be tested to assure that it will not respond incorrectly for system loading during extreme system conditions when the generator is not at risk of thermal damage. So, the loadability is validated against two operating points. These operating points were selected based on observed unit loading values during the August 14, 2003 blackout as well as other subsequent system events. These two load operating points shall not exceed the Relay (21) setting, and are believed to be a conservatively high level of reactive power out of the generator with a 0.85 per unit high side voltage, such that a relay set to be secure for these conservative operating points will be secure for the wide range of conditions that may challenge the apparent impedance characteristic of the phase distance protection.

During our simulations, these points are calculated and found to be: (400Mw, 400Mvar) and (160Mw, 675Mvar), taking into consideration that these points are evaluated with the generator step-up transformer high-side voltage at 0.85 per unit.

Moreover; Figure 1 depicts the impedance trajectory measured by Relay (21) during and after application of the 400Mvar inductive load while the generator loading was 400Mw. The sudden application of the load at t = 5 sec forces the impedance trajectory to penetrate the relay characteristic and stay inside it, and as a result, the relay will initiate unnecessary trip after the time dedicated time delay.

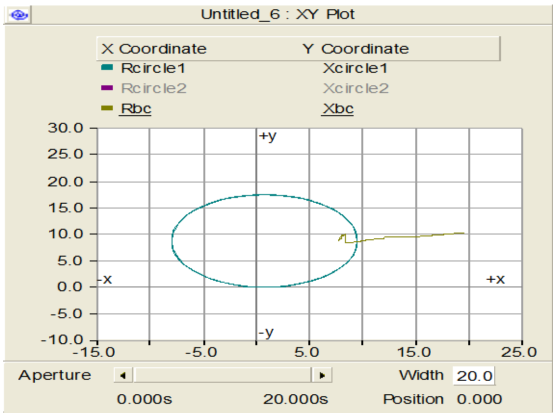

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Figure 1. Impedance trajectory measured by Relay (21) during and after application of the inductive load of 400MVAR

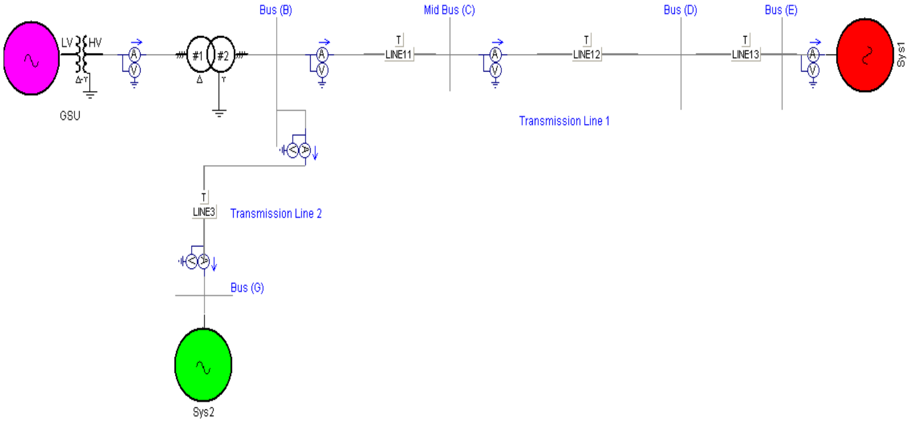


Figure 2. One-line Diagram of the Simulation Model in PSCAD

From this point, the necessity of this research work appeared, to present another solution for the Relay (21) setting rather than that described in [5], which was reducing the Relay (21) reach. This solution is based on the ANFIS algorithm. Virtually, no research work has been reported to solve this problem using ANFIS before.

Two proposed ANFIS algorithms are utilized as inputs, these inputs are the generator terminal impedance measurements (R and X) and the generator three phase terminal voltages and currents (V and I). The effectiveness of the proposed algorithm is proved through the promising obtained results.

The rest of the paper is organized as follows: Section 2 presents the system under study, while Section 3 describes the Adaptive Neuro Fuzzy Inference System technique, on the other hand, Section 4 illuminates the simulation environment and finally, Section 5 presents the results and discussion.

2. System Under Study

The system used in the investigations of this paper is shown in Figure 2. It consists of a steam-generator which is connected via a step-up transformer to two systems through a 300 km and 100 km, 230 kV transmission lines. The data of the steam generator and its capability curve are taken from [7]. The system data are given in Appendix-A. The model used for this study contains the facility to vary the fault type, the fault location, and the loading condition of the generator in order to simulate all possible cases using the PSCAD/EMTDC simulation package [8].

3. Adaptive Neuro Fuzzy Inference System (ANFIS)

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 modeling 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 modeling 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 [9-18].

Neuro-adaptive learning techniques provide a method for the fuzzy modeling 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 [13, 14]:

1. It is zeroth order sugeno-type system.
2. It has a single output, obtained using weighted average defuzzification.
3. All output membership functions are constant.
4. 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.
5. It has unity weight for each rule.

Figure 3 shows the architecture of the ANFIS, comprising by input, fuzzificaiton, inference and defuzzificaiton layers. 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 fuzzificaiton layer. There are F^N rules with F^N neurons in the inference and defuzzificaiton layers. It is assumed one neuron in the output layer.

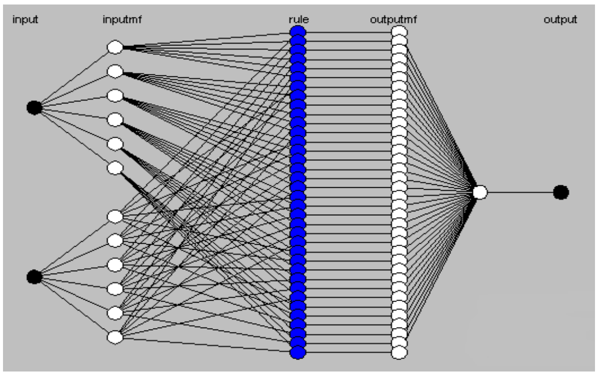


Figure 3. The Architecture of the ANFIS

Regarding the used subtractive clustering, a data clustering is a process of putting similar data into groups. A clustering algorithm partitions a data set into several groups, such that the similarity within a group is larger than among groups. Clustering algorithms are used extensively not only to organize and categorize data, but are also helpful for model construction and data compression. There are different clustering techniques such as k-means clustering, fuzzy c-means clustering, mountain clustering and subtractive clustering. If there is no clear idea how many clusters there should be for a given set of data, subtractive clustering is a fast, one-pass algorithm for estimating the number of clusters [19].

Regarding the number of neurons in the input layer “N”, number of Membership Functions (MF) for each input “M” of the ANFIS, refer to 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 modeling and simulation of power systems and relays. The PSCAD/EMTDC program is used for detailed modeling 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 testing and validating this algorithm will be executed by the PSCAD/EMTDC program.

The data used to train the ANFIS are taken at different phase faults types and application of different inductive loads in addition to different no fault conditions.

The phase fault conditions are carried out at different:

1. Generator loading conditions (65%, 75% and 85%),
2. Phase fault types (line to line and three line),
3. Fault duration (0.3, 0.4, 0.5, 0.6 and 1 sec),
4. Fault Distances (4, 5, 9, 10, 14 and 15 km).

The disturbances due to instantaneous phase faults (which cause stable swings and not considered faults) are carried out at different:

1. Generator loading conditions (65%, 75% and 85%),
2. Phase fault types (line to line and three line),
3. Fault duration (0.2 sec),
4. Fault Distances (4, 5, 9, 10, 14 and 15 km).

The application of sudden inductive loads is carried out at different:

1. Generator loading conditions (100% Prated and 40% Prated).
2. Inductive loads ranging from (10Mvar up to 740Mvar), noting that the maximum inductive load that can be applied to the generator in our case cannot exceed 150% of the generator MVA at 1.0 p.u generator terminal voltage, which is 740Mvar.

Table 1. Testing Data for the Proposed (R and X) ANFIS Scheme for Phase Faults

Generator Loading %	Fault type	Fault Inc. Time (sec)	Fault Distance (Km)	Fault Duration (sec)	Testing time (sec)	R value	X value	Cal. Index "I_{R21}"	Exp. Index
85%	L-L	5	10	0.5	5.95	5.138	5.969	1.027	1
85%	L-L	5	10	0.5	7.08	8.186	12.068	1.127	1
85%	L-L	5	10	0.5	4.04	15.072	9.348	0.05	0
65%	3L	5	5	0.5	6.03	3.153	5.087	1.043	1
65%	3L	5	5	0.5	8.03	1.384	14.6606	0.976	1
65%	3L	5	5	0.5	4.53	19.018	12.223	0.011	0
75%	3L	5	9	0.4	6.03	1.706	10.981	0.998	1
75%	3L	5	9	0.4	8.03	2.971	14.1803	1.037	1
75%	3L	5	9	0.4	4.04	17.0407	10.666	0.037	0
Disturbances due to Phase faults									
85%	3L	5	5	0.2	5.62	9.504	6.899	0.07	0
85%	3L	5	5	0.2	7.03	12.517	8.866	0.04	0
75%	3L	5	15	0.2	5.83	12.972	9.956	0.014	0
75%	3L	5	15	0.2	8.03	14.213	10.164	0.02	0
65%	L-L	5	5	0.2	6.03	18.716	14.845	0.18	0
65%	L-L	5	5	0.2	9.03	18.214	11.707	0.018	0
85%	3L	5	14	0.2	5.53	8.536	6.497	0.07	0
85%	3L	5	14	0.2	8.53	14.2701	10.223	0.02	0

Two proposed types of data are utilized as inputs to the ANFIS unit in this paper, one is based on the generator impedance measurements (R and X) and the other is based on the generator three phase terminal voltages and currents (V and I).

Testing data are chosen randomly from the data that were included in the training process, while the validation data are chosen at different conditions data that not were included in the training process to ensure the proposed method proficiency.

5. Results and Discussion

The system was simulated using PSCAD/EMTDC as well as Matlab and the results of simulation are discussed below. Two different schemes are proposed based on the type of inputs to ANFIS Technique. The 1st scheme is based on (R and X) as inputs, while the 2nd scheme is based on (V and I) as inputs. The results of these proposed schemes are discussed in the following sub sections.

5.1. The Proposed (R and X) Protection Scheme

The inputs to the ANFIS unit are the generator terminal impedance measurements (R and X) which are obtained from the generator terminal voltage and stator current values, and the testing data are chosen to have data from the training process while the validation data are chosen to have data not included in the training process.

All phase fault cases are expected to give output index of "1", while the actual overloading conditions are supposed to give "2", on the other hand, the no phase fault, no overloading conditions and stable swings due to the instantaneous phase faults (after which the system recovers and become stable again) are expected to give "0".

All applied inductive loads less than or equal to 675Mvar during generator loading of 160Mw "40% of Prated" and inductive loads less than or equal to 400Mvar during generator loading of 400Mw "100% of Prated" are considered no overloading conditions while inductive loads larger than these loads during the corresponding generator loadings are considered overloading conditions and the generator must be disconnected (the North Electric Reliability Council (NERC)).

Table 1 and 2 present the testing data of the proposed (R and X) ANFIS scheme for the purpose of protecting the generator against system phase faults and a sudden application of large inductive load.

For example, the 1st row in Table 1 describes when a line to line fault occurs, 10 km away from the generator, the fault occurred at t=5 sec and the fault duration was 0.5 sec, while the generator was loaded by 85% of its' full load, the proposed (R and X) ANFIS scheme when tested at time 5.95 sec, gave us the calculated index “IR21” of “1.027” which is near to the expected value “1”. Also, for example, the 10th row in Table (1) presents when a stable swing results as a result of three line fault occurs, 5 km away from the generator, the fault occurred at t=5 sec and the fault duration was 0.2 sec, while the generator was loaded by 85% of its' full load, the proposed (R and X) ANFIS scheme when tested at time 5.62 sec, gave us the calculated index “IR21” of “0.07” which is near to the correct expected value “0”.

Table 2. Testing Data for the Proposed (R and X) ANFIS Scheme for Overload Conditions

Generator Loading%	Fault type	Fault Inc. Time (sec)	Applied Load (Mvar)	Testing time (sec)	R value	X value	Cal. Index “I_{R21}”	Exp. Index
100%	O.L	5	550	6.03	7.0401	7.8107	1.94	2
100%	O.L	5	550	7.53	6.358	8.251	2.014	2
100%	O.L	5	550	4.53	15.221	9.383	0.05	0
100%	O.L	5	700	6.53	5.762	8.8234	2.015	2
100%	O.L	5	700	9.03	5.217	7.395	1.83	2
100%	O.L	5	700	2.04	15.304	9.478	0.05	0
40%	O.L	5	710	6.53	8.825	16.914	1.96	2
40%	O.L	5	710	9.03	7.586	17.0164	1.94	2
40%	O.L	5	710	3.54	54.171	1.982	0.002	0
40%	O.L	5	725	6.83	7.9018	16.857	2.175	2
40%	O.L	5	725	7.53	7.521	16.715	2.139	2
40%	O.L	5	725	1.54	53.942	1.819	0.012	0
100%	No O.L	5	250	5.2	13.446	9.539	0.03	0
100%	No O.L	5	250	5.7	10.707	8.974	0.02	0
100%	No O.L	5	100	5.33	13.982	9.538	0.03	0
100%	No O.L	5	100	5.91	12.817	9.439	0.02	0
40%	No O.L	5	550	5.7	19.714	17.401	0.04	0
40%	No O.L	5	550	6.2	13.378	19.239	0.01	0
40%	No O.L	5	300	5.53	32.505	18.278	0.05	0
40%	No O.L	5	300	6.53	22.532	24.493	0.017	0

For Table 2, the 1st row illustrates when an inductive load of 550Mvar is applied suddenly at t=5 sec, while the generator was loaded by 100% of its' full load (which is considered overload condition), the proposed (R and X) ANFIS scheme when examined at time 6.03 sec, gave us the calculated index “IR21” of “1.94” which is near to the expected value “2”.

Table 3 and 4 illustrate the validation data of the proposed (R and X) scheme. The validation data are not included in the training process and are chosen at different generator loading and phase fault/overloading conditions.

The 4th row in Table (3) depicts when a three line fault occurs, 10 km away from the generator, the fault occurred at t=5 sec and the fault duration was 0.4 sec, while the generator was loaded by 75% of its' full load, the proposed (R and X) ANFIS scheme detects this fault at time 5.37 sec, through the calculated index “I_{R21}”which is “1.108” which is very near to the expected value “1”.

Table 3. Validation Data for the Proposed (R and X) ANFIS Scheme for Phase Faults

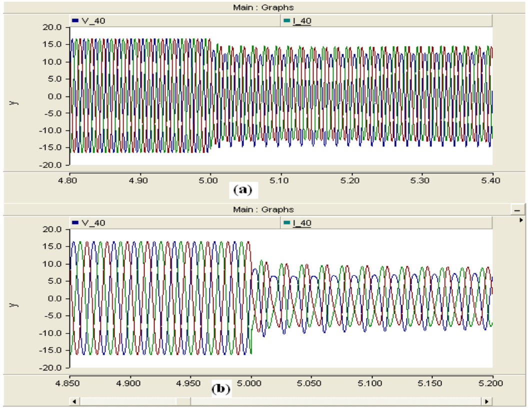
Generator Loading %	Fault type	Fault Inc. Time (sec)	Fault Distance (Km)	Fault Duration (sec)	Testing time (sec)	R value	X value	Cal. Index “I_{R21}”	Exp. Index
85%	3L	5	5	0.4	5.6	4.44003	5.151	0.94	1
85%	3L	5	5	0.4	6	2.656	9.519	1.035	1
85%	3L	5	5	0.4	4	15.245	9.399	0.05	0
75%	3L	5	10	0.4	5.37	7.101	6.247	1.108	1
75%	3L	5	10	0.4	6.58	1.842	13.306	0.997	1
75%	3L	5	10	0.4	3.54	16.964	10.623	0.03	0
85%	L-L	5	9	0.5	5.41	4.36503	6.845	0.92	1
85%	L-L	5	9	0.5	8.2	5.309	23.726	1.09	1
85%	L-L	5	9	0.5	2.54	15.117	9.3665	0.05	0
65%	3L	5	14	0.5	5.53	5.474	5.599	0.98	1
65%	3L	5	14	0.5	8.03	2.195	14.663	1.006	1
65%	3L	5	14	0.5	1.49	18.974	12.364	0.006	0
85%	3L	5	10	0.3	5.45	6.869	5.874	1.028	1
85%	3L	5	10	0.3	5.91	2.306	5.498	1.028	1
85%	3L	5	10	0.3	1.04	16.974	9.793	0.06	0
Disturbances due to Phase faults									
85%	3L	5	15	0.2	5.2	9.243	6.982	0.06	0
85%	3L	5	15	0.2	5.53	8.473	6.473	0.08	0
75%	3L	5	5	0.2	5.2	10.583	7.877	0.05	0
75%	3L	5	5	0.2	5.83	14.075	10.599	0.006	0
65%	3L	5	15	0.2	5.33	11.607	8.571	0.04	0
65%	3L	5	15	0.2	5.62	12.079	8.635	0.04	0
85%	L-L	5	9	0.2	5.41	9.228	7.6607	0.04	0
85%	L-L	5	9	0.2	5.7	10.807	7.9807	0.05	0

Table 4. Validation Data for the Proposed (R and X) ANFIS Scheme for Overload Conditions

Generator Loading%	Fault type	Fault Inc. Time(sec)	Applied Load(Mvar)	Testing time(sec)	R value	X value	Cal. Index“I_{R21}”	Exp. Index
100%	O.L	5	710	5.74	7.016	7.4503	1.9	2
100%	O.L	5	710	6.33	5.768	7.855	1.96	2
100%	O.L	5	710	4.49	15.225	9.386	0.05	0
40%	O.L	5	728	6.33	9.469	16.511	1.9	2
40%	O.L	5	728	7.03	7.628	16.811	2.2	2
40%	O.L	5	728	3.04	54.303	1.974	0.01	0
100%	O.L	5	560	5.95	7.107	7.687	1.9	2
100%	O.L	5	560	6.53	6.804	9.472	2.05	2
100%	O.L	5	560	1.54	15.528	9.623	0.05	0
40%	O.L	5	712	6.12	11.052	16.559	1.93	2
40%	O.L	5	712	7.03	7.843	17.037	1.85	2
40%	O.L	5	712	2.04	54.159	2.208	0.001	0
100%	No O.L	5	50	5.53	14.231	9.451	0.043	0
100%	No O.L	5	50	6.53	14.064	9.799	0.03	0
40%	No O.L	5	470	5.83	19.647	19.428	0.026	0
40%	No O.L	5	470	6.53	14.045	21.114	0.01	0
40%	No O.L	5	520	5.58	23.381	16.635	0.039	0
40%	No O.L	5	520	7.03	11.602	20.293	0.004	0

The proposed ANFIS scheme also responds correctly to stable swings through the calculated indices which are close to “0”, as illuminated in Table (3) in the 16th, 17th, 18th, 19th, and 20th and till 23th rows.

For Table 4, the 1st row illustrates when an inductive load of 710Mvar is applied suddenly at t=5 sec, while the generator was loaded by 100% of its’ full load, the proposed (R and X) ANFIS scheme detects this overload conditions at time 5.74 sec, through the calculated index “IR21” of “1.9” which is near to the expected value “2”.



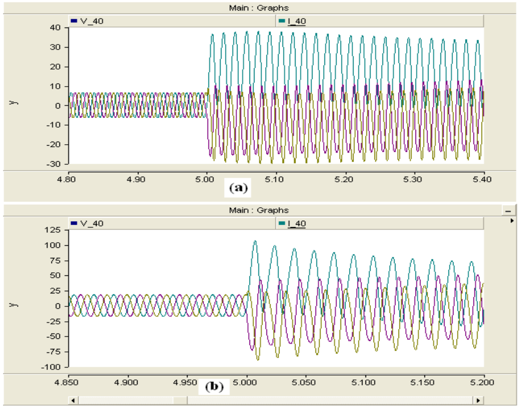


Figure 4. Generator Terminal Voltage Waveforms due to: (a) Overload condition due to Inductive Load, (b) Three Line Fault

Figure 5. Generator Current Waveforms due to: (a) Overload condition due to Inductive Load, (b) Three Line Fault

Also, the 4th row in the same Table shows when an inductive load of 728Mvar is applied suddenly at t=5 sec, while the generator was loaded by 40% of its’ full load, the proposed (R and X) ANFIS scheme detects this overload conditions at time 6.33 sec, through the calculated index “IR21” of “1.9” which is near to the expected value “2”.

Table 3 and 4 depict the promising accuracy of the proposed (R and X) ANFIS in protecting the generator against system phase faults and overload conditions.

From the Table 1, 2, 3 and 4 calculated indices (I_{R21}) it is easy to conclude that the output of the proposed (R and X) ANFIS unit should be fairly chosen as:

1. $0.9 \leq I_{R21} \leq 1.15$ for Phase faults,
2. $1.8 \leq I_{R21} \leq 2.25$ for Over load conditions,
3. $I_{R21} \leq 0.2$ for no faults condition

The proposed (R and X) ANFIS relay detects (R, X) ANFIS based relay detects phase faults within (370-600 msec) and detects over load conditions within (1030-1830 msec), under various faults, overload, generator loading conditions. The proposed relay also solved the problem associated with the Relay (21) setting as reported in [5].

5.2. The Proposed (V and I) Protection Scheme

On this scheme, the inputs to the ANFIS unit are considered to be the generator three phase terminal voltages and currents (V and I).

Tables 5 and 6 illustrate the testing data of the proposed (V and I) ANFIS scheme, while Table 7 and 8 depict the validation data of this proposed scheme. The validation data are not included in the training process and are chosen at different generator loading and different phase fault and overloading conditions.

Table 5, 6, 7 and 8 show that the proposed (V and I) ANFIS scheme is not accurate, as it cannot discriminate between phase faults, over load conditions and the stable disturbances due to phase faults. This is due to the similarity of the waveforms of the voltage and current due to these conditions, as described below.

Table 5.Testing Data for the Proposed (V and I) ANFIS Scheme for Phase Faults

Generator Loading %	Fault type	Fault Inc. Time (sec)	Fault Distance (Km)	Fault Duration (sec)	Testing time (sec)	V_a (kV)	V_b (kV)	V_c (kV)	I_a (kA)	I_b (kA)	I_c (kA)	Cal. Index “I_{R21}”	Exp. Index
85%	L-L	5	10	0.5	5.33	1.259	-9.607	8.3475	-18.444	-3.214	21.658	0.91	1
85%	L-L	5	10	0.5	7.08	7.917	-11.899	3.9822	-6.3876	-32.503	38.8908	1.13	1
85%	L-L	5	10	0.5	4.04	2.189	12.9322	-15.122	12.639	6.944	-19.583	0.07	0
65%	3L	5	5	0.5	6.03	-7.996	-2.526	10.523	-30.153	46.4109	-16.257	1.28	1
65%	3L	5	5	0.5	8.12	-8.978	-2.019	10.998	-20.855	44.385	-23.529	1.37	1
65%	3L	5	5	0.5	4.53	5.848	10.297	-16.145	12.584	1.7177	-14.302	0.09	0
75%	3L	5	9	0.4	5.99	-12.012	-6.1902	18.202	-14.998	6.553	8.445	0.86	1
75%	3L	5	9	0.4	8.03	-5.382	14.947	-9.565	17.605	22.414	-40.02	0.82	1
75%	3L	5	9	0.4	4.04	3.599	12.0105	-15.61	12.353	4.602	-16.956	0.1	0
Disturbances due to Phase faults													
85%	3L	5	5	0.2	5.62	2.215	13.234	-15.449	17.937	7.922	-25.86	0.27	0
85%	3L	5	5	0.2	7.03	10.178	6.053	-16.231	16.743	-3.371	-13.371	0.01	0
75%	3L	5	15	0.2	5.83	-11.828	-4.8501	16.678	-12.345	6.0608	6.284	0.43	0
75%	3L	5	15	0.2	8.03	9.3561	6.486	-15.842	20.735	-2.751	-17.984	0.02	0
65%	L-L	5	5	0.2	6.03	11.216	5.134	-16.35	12.371	-4.577	-7.794	0.11	0
65%	L-L	5	5	0.2	9.03	13.415	1.2584	-14.673	17.448	-7.963	-9.484	0.13	0
85%	3L	5	14	0.2	5.53	-3.561	14.988	-11.427	14.306	19.557	-33.864	0.51	0
85%	3L	5	14	0.2	8.53	14.971	-1.157	-13.813	12.373	-8.7603	-3.613	0.06	0

Figure 4 shows the generator three phase voltage waveforms due to overloading condition (a) and three line fault (b). Moreover, Figure 5 presents the generator three phase currents waveforms due to overloading condition (a) and three line fault (b).

These similarities make the choice of using the generator three phase voltages and current as inputs to the ANFIS unsuitable choice. The results obtained from this scheme are discussed below. For example, the 16th row in Table (7) shows when a stable swing results due to a three line fault occurs, 15 km away from the generator, the fault occurred at t=5 sec and the fault duration was 0.2 sec, while the generator was loaded by 85% of its' full load, the proposed (R and X) ANFIS scheme when tested at time 5.2 sec, gave us the calculated index "IR21" of "0.42" which is very far from the expected value "0". On the other hand, for the 1st row in Table (8), shows when an inductive load of 710Mvar is applied suddenly at t=5 sec, while the generator was loaded by 100% of its' full load, the proposed (V and I) ANFIS scheme is not capable of detecting the overload condition, as the expected ANFIS output shall be "2", while the calculated is "0.977" which is near to "1". Also, for the 15th row in Table (8), when an inductive load of 470Mvar is applied suddenly at t=5 sec, while the generator was loaded by 40% of its' full load, the proposed (V and I) ANFIS scheme calculated output is "0.49", which is far from the expected index "0" for no overload condition.

Table 6.Testing Data for the Proposed (V and I) ANFIS Scheme for Overload Conditions

Generator Loading %	Fault type	Fault Inc. Time (sec)	Applied Load (Mvar)	Testing time (sec)	V_a(kV)	V_b(kV)	V_c(kV)	I_a(kA)	I_b(kA)	I_c(kA)	Cal. Index "I_{R21}"	Exp. Index
100%	O.L	5	550	6.03	3.888	10.6504	-14.538	33.955	-4.914	-29.041	1.3	2
100%	O.L	5	550	7.53	7.882	7.359	-15.242	30.825	-12.469	-18.355	1.27	2
100%	O.L	5	550	4.53	3.342	12.178	-15.521	13.586	5.6238	-19.21	0.08	0
100%	O.L	5	700	6.53	7.8803	7.464	-15.344	32.615	-15.622	-16.993	1.66	2
100%	O.L	5	700	9.03	8.418	6.359	-14.777	34.001	-16.618	-17.383	1.61	2
100%	O.L	5	700	2.04	-2.794	15.344	-12.549	7.36002	12.223	-19.583	0.03	0
40%	O.L	5	710	6.53	10.216	4.341	-14.557	21.132	-14.932	-6.2005	1.01	2
40%	O.L	5	710	9.03	13.571	-0.953	-12.617	13.945	-16.554	2.608	1.008	2
40%	O.L	5	710	3.54	5.6402	10.649	-16.289	2.464	4.047	-6.511	0.04	0
40%	O.L	5	725	6.83	-10.631	-4.309	14.941	-13.041	12.556	0.485	0.978	2
40%	O.L	5	725	7.53	11.606	2.488	-14.095	17.883	-15.445	-2.437	0.977	2
40%	O.L	5	725	1.54	0.793	13.957	-14.751	0.6418	5.312	-5.954	0.005	0
100%	No O.L	5	250	5.2	3.978	10.777	-14.755	26.062	-0.352	-25.709	0.6	0
100%	No O.L	5	250	5.7	3.642	11.181	-14.823	26.922	0.585	-27.508	0.74	0
100%	No O.L	5	100	5.33	-4.042	-11.232	15.274	-14.059	-3.806	17.866	0.09	0
100%	No O.L	5	100	5.91	-5.7402	-10.105	15.845	-15.735	-1.049	16.785	0.15	0
40%	No O.L	5	550	5.7	9.094	5.506	-14.601	22.742	-12.436	-10.306	0.76	0
40%	No O.L	5	550	6.2	9.956	4.868	-14.824	20.627	-12.459	-8.168	0.75	0
40%	No O.L	5	300	5.53	9.2505	5.914	-15.165	17.088	-7.0204	-10.068	0.22	0
40%	No O.L	5	300	6.53	11.085	4.048	-15.134	15.075	-7.717	-7.358	0.2	0

Table 7. Validation Data for the Proposed (V and I) ANFIS Schemefor Phase Faults

Generator Loading %	Fault type	Fault Inc. Time (sec)	Fault Distance (Km)	Fault Duration (sec)	Testing time (sec)	V_a (kV)	V_b (kV)	V_c (kV)	I_a (kA)	I_b (kA)	I_c (kA)	Cal. Index "I_{R21}"	Exp. Index
85%	3L	5	5	0.4	5.41	7.649	-9.521	1.871	13.391	-38.089	24.697	1.15	1
85%	3L	5	5	0.4	6	-1.526	-10.436	11.963	-38.065	38.391	-0.325	1.05	1
85%	3L	5	5	0.4	4	2.1904	12.932	-15.122	12.477	6.926	-19.403	0.08	0
75%	3L	5	10	0.4	5.49	10.121	-10.946	0.824	4.919	-38.346	33.426	0.91	1
75%	3L	5	10	0.4	6.83	9.118	-14.724	5.606	-8.997	-31.328	40.325	1.04	1
75%	3L	5	10	0.4	3.54	2.368	12.8206	-15.189	11.407	5.904	-17.312	0.1	0
85%	L-L	5	9	0.5	5.16	-2.891	-8.964	11.855	-23.625	11.821	11.803	1.005	1
85%	L-L	5	9	0.5	8.03	17.676	-6.559	-11.117	1.4308	-9.044	7.613	0.81	1
85%	L-L	5	9	0.5	2.54	-1.496	14.839	-13.343	8.849	10.926	-19.776	0.001	0
65%	3L	5	14	0.5	5.45	-6.2995	7.3201	-1.0205	30.053	33.041	-63.094	0.803	1
65%	3L	5	14	0.5	7.83	-17.439	9.424	8.014	6.274	3.374	-9.648	0.97	1
65%	3L	5	14	0.5	1.49	1.436	-14.875	13.439	-7.547	-8.3406	15.887	0.15	0
85%	3L	5	10	0.3	5.53	-11.341	9.817	1.524	-8.078	42.232	-34.154	0.804	1
85%	3L	5	10	0.3	6.28	16.404	-14.465	-1.938	-23.91	3.613	20.296	0.9	1
85%	3L	5	10	0.3	1.04	-5.072	16.107	-11.034	4.983	14.208	-19.191	0.1	0
Disturbances due to Phase faults													
85%	3L	5	15	0.2	5.2	0.746	8.963	-9.7103	27.396	-3.6207	-23.776	0.42	0
85%	3L	5	15	0.2	5.53	-3.804	15.004	-11.2	14.051	20.112	-34.163	0.52	0
75%	3L	5	5	0.2	5.2	4.924	8.347	-13.271	42.459	-29.486	-12.973	1.78	0
75%	3L	5	5	0.2	5.83	-11.365	-5.407	16.773	-12.627	5.364	7.262	0.36	0
65%	3L	5	15	0.2	5.33	-2.838	-12.752	15.591	-16.154	-7.027	23.182	0.04	0
65%	3L	5	15	0.2	5.62	6.976	10.021	-16.997	17.206	0.0176	-17.224	0.12	0
85%	L-L	5	9	0.2	5.41	-0.798	-13.69	14.488	-16.352	-10.766	27.119	0.12	0
85%	L-L	5	9	0.2	5.7	6.739	10.014	-16.754	16.877	0.676	-17.554	0.06	0

The proposed (V and I) ANFIS scheme is not good, as it cannot discriminate between phase faults, over load conditions and the stable disturbances due to phase faults. This is due to the similarity of the waveforms of the voltage and current due to these conditions.

Finally, Table (9) summarizes a comparison between the different proposed ANFIS techniques discussed in this article. This comparison is based on the threshold values of each technique and its' the response time.

Table 8. Validation Data for the Proposed (V and I) ANFIS Schemefor Overload Conditions

Generator Loading %	Fault type	Fault Inc. Time (sec)	Applied Load (Mvar)	Testing time (sec)	V_a (kV)	V_b (kV)	V_c (kV)	I_a (kA)	I_b (kA)	I_c (kA)	Cal. Index “I_{R21}”	Exp. Index
100%	O.L	5	710	5.74	2.591	-12.766	10.1751	-16.22	-13.263	29.486	0.977	2
100%	O.L	5	710	6.33	-6.201	-9.193	15.395	-24.538	11.086	13.452	1.45	2
100%	O.L	5	710	4.49	-3.241	-12.247	15.488	-13.496	-5.743	19.239	0.006	0
40%	O.L	5	728	6.33	-9.602	-5.636	15.238	-11.613	10.553	1.0602	0.89	2
40%	O.L	5	728	7.03	10.862	3.535	-14.398	19.548	-15.174	-4.374	0.997	2
40%	O.L	5	728	3.04	4.447	11.578	-16.026	2.003	4.432	-6.435	0.04	0
100%	O.L	5	560	5.95	2.492	11.457	-13.949	34.29	-1.786	-32.512	1.33	2
100%	O.L	5	560	6.53	7.499	7.958	-15.457	31.412	-12.442	-18.969	1.39	2
100%	O.L	5	560	1.54	-3.882	15.743	-11.86	6.151	13.074	-19.225	0.06	0
40%	O.L	5	712	6.12	9.419	5.181	-14.601	23.585	-14.842	-8.743	1.04	2
40%	O.L	5	712	7.03	10.898	3.512	-14.41	19.365	-14.95	-4.415	0.96	2
40%	O.L	5	712	2.04	1.994	13.237	-15.231	1.059	5.119	-6.1792	0.01	0
100%	No O.L	5	50	5.53	5.194	10.617	-15.811	18.335	2.187	-20.523	0.08	0
100%	No O.L	5	50	6.53	7.7702	8.447	-16.218	19.842	-1.542	-18.299	0.13	0
40%	No O.L	5	470	5.83	-9.075	-6.575	15.6507	-5.165	4.022	1.143	0.49	0
40%	No O.L	5	470	6.53	10.688	4.178	-14.866	18.031	-11.092	-6.939	0.55	0
40%	No O.L	5	520	5.58	-8.237	-7.167	15.404	-3.617	2.853	0.7645	0.49	0
40%	No O.L	5	520	7.03	11.338	3.235	-14.574	17.072	-12.019	-5.052	0.6	0

Table 9. Comparison Between The Proposed ANFIS Schemes

ANFIS Technique	Threshold Values	Response Time (sec)
ANFIS relay based on (R and X)	1. $0.9 \le I_{R21} \le 1.15$ for Phase faults, 2. $1.8 \le I_{R21} \le 2.25$ for Over load conditions, 3. $I_{R21} \le 0.2$ for no faults condition.	Detects phase faults within (370-600 msec) and detects over load conditions within (740-1330 msec).
ANFIS relay based on (V and I).	This relay cannot discriminate between phase faults, over load conditions and the stable disturbances due to phase faults. This is due to the similarity of the waveforms of the voltage and current due to these conditions.	

6. Conclusion

This research work presents a solution for the Relay (21) setting problem when it is set to provide thermal backup protection for the generator during system phase faults and sudden application of large system load using the Adaptive Neuro Fuzzy Inference System (ANFIS). Previous researches demonstrated the existence of a potential problem due to the current setting of the Relay (21) and highlighted the necessity of revising the Relay (21) reach. In this paper a solution for this problem is introduced through utilizing two different sets of data as inputs to the ANFIS.

The 1st scheme is based on the generator terminal impedance measurements (R and X), while the 2nd scheme is based on the generator three phase voltages and currents (V and I). It is found that the generator terminal impedance measurements (R and X) play the essential rule in the generator thermal backup protection process. The used data for testing and validation are of both kinds of data: used in training and not used in training respectively. Suggested indices for occurrence of the system phase faults and overloading conditions were introduced. The obtained results are very promising and encouraging.

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Appendixes

1. *APPENDIX-A:*

Data of the system under study:
Generators
Rating = 492 MVA Rated Voltage = 20 kV
Xd = j1.1888p.u.
Xd’ = j0.20577p.u.
Xd’’ = j0.17847p.u.
Generator Step Up (GSU) Transformer
492 MVA, 20 kV∆ / 230 kV Yg, XT = j0.1 p.u.
Transmission Line
Transmission line voltage = 230 kV.
Transmission line lengths Line 1 = 300 km, Line 2 = 100 km.
Z1 = 0.51 ∟85.98^{O} ohm/km.
Distance phase backup protection Relay
Relay 21 reach 16.75∟85^{o}ohm.
Rc = 3600, Rv = 166.67.

2. APPENDIX-B:

The different membership functions and the corresponding calculated errors for the proposed (R and X) ANFIS scheme are depicted in Figure (B-1).

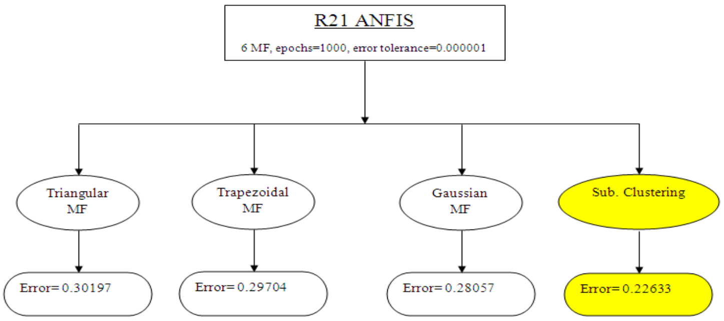

Figure B-1. The Different Membership Functions and the Corresponding Errors for the (R and X) ANFIS Scheme

The different membership functions and the corresponding calculated errors for the proposed (V and I) ANFIS scheme are illuminated in Figure (B-2).

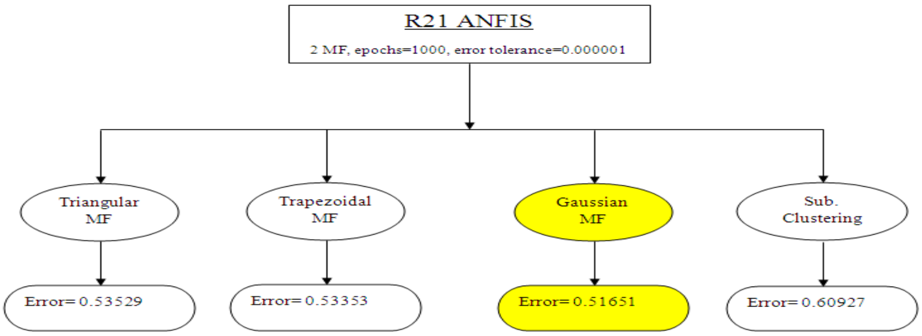

Figure B-2. The Different Membership Functions and the Corresponding Errors for the (V and I) ANFIS Scheme