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Performance analysis of self-excited induction generator using fuzzy technique with variable terminal conditions

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Abstract

In this work steady state analysis of Self Excited Induction Generator (SEIG) is carried out using fuzzy technique to determine the saturated magnetizing reactance and generated frequency. Attempt is made to outline rules in Fuzzy Logic (FL) tool box of MATLAB so that analysis of any SEIG which is generally used for wind power generation. Fuzzy rules are used that avoid long mathematical computations to determine the value of saturated magnetizing reactance and generated frequency. These parameters of self-excited induction generator are determined by varying the speed, load and capacitance in steps. Analytical methods used require large mathematical computations as it involves complex equations and long mathematical calculations. Moreover, it is time consuming and there are chances of errors during computational efforts. The findings obtained from fuzzy logic are compared with the analytical method and found to be in good agreement.

Keywords: self-excited induction generator, magnetizing reactance, generated frequency, artificial neural networks, fuzzy logic, load impedance

1. Introduction

Electricity is the only kind of energy that is used for growth of industry and the country, apart from its daily use in residential purposes. Without electricity it is impossible for the growing countries to cope up with the developed countries. To overcome the problems faced in generation of power from conventional energy sources, government and private generating organizations are looking towards the use of energy generation technologies which do not consume natural resources. Researchers are working on it continuously and find different ways of generating electricity apart from conventional methods like hydro and thermal power generation. Now attempts are made to integrate non-conventional with hydro, thermal power generation. As wind power plants are used in various coastal areas as source of power generation, researchers are focusing their attention towards analyzing the operational feasibility SEIG. SEIGs are widely used in wind power generation due to brush less construction, small size, singly excited system and its self-protection capability. Apart from these induction generators do not require to satisfy the conditions of synchronizing with the existing power lines of the network.

Induction motor connected to power network, when coupled to prime mover and rotated at speeds above the synchronous speed corresponding to grid frequency is capable of generating power to feed it to power system. In this mode, machine draws reactive power for excitation from supply mains but injects real power to bus bar. Induction motor when connected across excitation capacitors and driven by prime mover at speed above critical speed, it generates power that depends upon speed, exciting capacitance and load. Various researchers have attempted to determine two unknown parameters i.e per unit Magnetizing Reactance (Xm) and Generated Frequency (a) using mathematical model of SEIG. Now a days, artificial intelligent techniques are also in use to solve higher order polynomials to determine variables which otherwise involve cumbersome computational efforts. In this paper an attempt is made to determine unknown variable using Fuzzy Logic (FL) technique.

By determining the parameters of the machine it should be possible to determine the machine performance for given speed, capacitance and load conditions. By knowing the terminal voltage and frequency of a machine connected to an infinite bus the calculation of performance is easy. The analysis of machine is difficult due to the magnetic saturation in the machine and there is need to select suitable parameters corresponding to the saturated condition. This paper also discuss the analytical procedure to detect the steady state condition using the operational equivalent circuit of the machine. Then the steady state equivalent circuit is used to compute the steady state response.

2. Equivalent Circuit of SEIG

For steady state analysis, various researchers have used single-phase equivalent circuit of SEIG as shown in figure 1. Conventional methods are used to solve the equivalent circuit to determine unknown parameters. Loop impendence method and nodal admittance method are commonly in use. On solving the equivalent circuit using these methods two nonlinear equation is formed using MATLAB. These two polynomial equations are solved using Newton Rapson (NR) method by separating real and imaginary terms. Latest techniques like genetic algorithm, particle swarm optimization, artificial neural network and fuzzy logic techniques are also implemented to determine variable of complex polynomials which are formed from mathematical models.

Synchronous run test is conducted on induction machine to determine the relationship between generated voltages 'E1' and magnetizing reactance (Xm).
Once the values of 'Xm' and 'a' and E1 are determined, equivalent circuit of figure 1 can be solved for any terminal conditions by simple calculations.

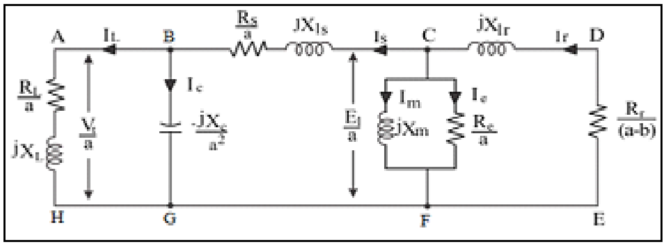

Fig 1: Equivalent circuit of self-excited induction generator

Single phase equivalent circuit of SEIG as shown in figure 1 using nodal admittance or impedance method can be solved as:

$$Z_{BC} = \left(\frac{R_S}{a} + jX_{ls}\right)$$

$$Z_{BG} = \frac{\frac{-jX_c}{a^2}\left(\frac{R_L}{a} + jX_L\right)}{\left(\frac{R_L}{a} + jX_L\right) + \frac{-jX_c}{a^2}}$$

$$Z_{CF} = \frac{(jX_m \;//\; R_e \;/\; a)\left[\frac{R_r}{a-b} + jX_{lr}\right]}{(jX_m \;//\; R_e \;/\; a) + \left[\frac{R_r}{a-b} + jX_{lr}\right]}$$

$$Z_S = Z_{BC} + Z_{BG} + Z_{CF}$$

For voltage build up
Z *Is = 0
Is cannot be zero, Hence Zs = 0 (1)

Two polynomials are obtained by separating the real and imaginary parts of this equation. Two non-linear polynomials are:
Real $(X_m, a) = P_1 X_m a^5 + P_2 X_m a^4 + (P_3 X_m + P_4) a^3 + (P_5 X_m + P_6) a^2 + (P_7 X_m + A_8) a + P_9 X_m + P_{10}$ (2)

Imaginary $(X_m, a) = (Q_1 X_m + Q_2) a^4 + (Q_3 X_m + Q_4) a^3 + (Q_5 X_m + Q_6) a^2 + (Q_7 X_m + Q_8) a + Q_9$ (3)

The coefficients (P1 – P10) and (Q1 – Q9) of two equations can be determined using MATLAB and are given in Appendix B.

3. Fuzzy techniques for solving equivalent circuit

Solving the polynomial equations 2 and 3 is lengthy and difficult task so attempt is made to solve these polynomial equations using Fuzzy logic technique to find the per unit value of generated frequency (a) and saturated magnetizing reactance (Xm) [7, 8]. Rule based method is used to solve this complex problem. Limits of each parameter are fixed and rules are made which are discussed in next section. Instead of doing long mathematical calculation and programming which were in practice earlier. Methodology used in this work to determine unknown variables is simple and compact. Other techniques like ANN, GA are also implemented by various authors [9-12].

3.1 Fuzzy Model of SEIG

In this method we classify the fuzzy sets into various linguistic variables. For these linguistic variables the different membership functions are formed. In this case for solving the equivalent circuit, there are two outputs and nine inputs. Given inputs are rotor leakage reactance 'Xr' and stator leakage reactance 'Xs' power factor 'Pf', rotor resistance 'Rr', stator resistance 'Rs', speed 'N', capacitance 'C', load admittance 'Y' and Resistance of Core loss branch 'Re'. All values are in per unit and output are taken as generated frequency 'a' and magnetizing reactance 'Xm'. Accuracy of the results depends on the selection of these membership functions. After defining the range of membership function, the name to member ship function is given for forming rules. Membership functions for these parameters are extreme low, very low, low, medium, high and very high. Output variables 'Xm' & 'a' also have six membership functions as tremendous low, very low, low, below average, above average and high. In this approach the range of the membership function can be adjusted as per our requirement. More the range of membership function more rules are formed and more accuracy in result can be achieved. In the first case for finding results in this paper, all parameters apart from load admittance, speed in second case and capacitance in third case are taken as constant as terminal conditions. To calculate the value of frequency and magnetizing reactance for already known speed, capacitance and load, input and output membership functions are formed.

3.2 Fuzzy rules and Implementation

The purposed fuzzy rules are designed from input-out parameters calculated from any analytical technique by using various methods. MATLAB programming is be used to find these input parameters. The range of all input variables are such that they must be applicable to actual life applications of induction machine as self-excited induction generator. The range is selected such that value of rotor and stator parameters can be considered from 4-8 percent. In this work centroid member ship function is used to frame the rules in fuzzy approach. This fuzzy model of self-excited induction generator is implemented to decide the generated frequency and magnetic reactance requirements under varying conditions of load, speed and capacitance. Resistive load application is considered to maintain unity power factor. Three cases are discussed one by one in the coming sections. In the first case the all other parameter of machine are kept constant and the load is varied in steps. In fuzzy logic range of each parameter can be varied as per requirement. The range can be varied even one percent and the output can be fuzzified and defuzzified accordingly. Thus, machine parameters used as input to the fuzzy logic are chosen to vary from 0.01 – 0.11 per unit for stator and rotor resistance. The range for rotor and stator leakage reactance is varied from 0.03 to 0.17. Load is varied from no load to full load. Since induction machine does not have the ability to generate reactive power, the load power factor range is restricted to 0.85 lagging to unity power factor. The operational speed of induction machine operating as generator is arranged within the lower and higher limits of 85% - 120% of base speed matching to rated frequency. The excitation capacitance is selected very carefully so that there should not be overvoltage. Due to this minimum capacitance requirement for excitation at minimum level of operating speeds and operating voltage at full load, the range of capacitance is selected such that its range vary from 65% - 110%. The range of all parameters of SEIG is selected by taking into consideration the real life situation for machine operation. The value of generated frequency and magnetizing reactance can be obtained from analytical technique for given set of parameters. Once the rules are formed, by implementing the fuzzy logic model the output is determined for any set of given inputs within the defined range of parameters.

3.2.1 Operation of SEIG with Variable Load

In this case load is varied in steps for variable load operation of machine, as per requirement by maintaining speed and excitation capacitance constant. In first case the rules of fuzzy are tried for variable load operation with excitation capacitance of 27.57 micro farad and 1485 Rpm speed. The output obtained from Fuzzy logic is always in fuzzified output (value lies between 0.10 and 0.90) this need to be defuzzified for comparing with the results obtained from analytical techniques. The magnetizing reactance and generated frequency of SEIG which is obtained by fuzzy method is shown in Table 1 for comparison with analytical data. The accuracy of results validates the acceptance of the proposed fuzzy technique. The evaluation results are shown in figure 2 and figure 3 for closeness of results.

Table1: Effect of load on generated frequency and magnetizing reactance of SEIG

Load Admittance (pu)	Magnetizing reactance (Xm) (pu)		Generated Frequency (a) (pu)	
	Fuzzy model Xm	Analytical Model Xm	Fuzzy (a)	Analytical Model (a)
0.2250	1.2271	1.2323	0.9760	0.9757
0.4131	1.3359	1.3401	0.9680	0.9671
0.5384	1.4306	1.4342	0.9620	0.9616
0.5808	1.4663	1.4710	0.9600	0.9598
0.6389	1.5250	1.5261	0.9560	0.9573
0.8191	1.7485	1.7404	0.9510	0.9499
0.8712	1.8276	1.8179	0.9476	0.9478
0.9489	1.9550	1.9501	0.9460	0.9448

3.2.2 Operation of SEIG with variable Speed

The rules of Fuzzy model which are formed in this paper for self-excited induction generator is applied for machine operation with 22 micro farad excitation capacitance and 230 ohm load which is resistive in nature. Now by changing the speed in steps and result obtained from fuzzy technique is recorded in Table 2 for comparison of different values of magnetizing reactance and generated frequency. Results obtained are compared graphically with results of analytical technique as in Figure 4 and figure 5

3.2.3 Operation of SEIG with Variable Capacitance

Fuzzy model of SEIG is also implemented for finding the magnetizing reactance and generated frequency of machine by varying excitation capacitance. The results are obtained for speed of 1430 Rpm and resistive load of 178 ohms. The results obtained are recorded in Table 3 for judgment. The results obtained from fuzzy model are compared with analytical solution for varying terminal capacitance are shown graphically in figure 6 and 7.

Table 2: Effect of speed on magnetizing reactance and generated frequency of SEIG

Speed (pu)	Magnetizing Reactance (Xm)		Generated Frequency (a)	
	Fuzzy	Analytical model	Fuzzy	Analytical Model
0.9233	1.9687	1.9697	0.9030	0.9036
0.9307	1.9385	1.9378	0.9101	0.9107
0.9533	1.8465	1.8441	0.9320	0.9327
0.9900	1.7070	1.7058	0.9676	0.9683
1.0140	1.6215	1.6233	0.9926	0.9916
1.0467	1.5147	1.5201	1.0237	1.0233
1.0713	1.4436	1.4484	1.0475	1.0472
1.0967	1.3757	1.3797	1.0715	1.0718

Table 3: Effect of terminal capacitance on magnetizing reactance and generated frequency of SEIG

Variable capacitance	Magnetizing Reactance (Xm)		Generated Frequency (a)	
	Fuzzy	Analytical	Fuzzy	Analytical
0.6082	2.2045	2.2004	0.9976	0.9971
0.6494	2.0454	2.0421	0.9974	0.9969
0.6657	1.9865	1.9857	0.9972	0.9968
0.7100	1.8460	1.8465	0.9968	0.9965
0.7647	1.6965	1.6985	0.9966	0.9961
0.7964	1.6210	1.6232	0.9960	0.9959
0.8301	1.5470	1.5498	0.9962	0.9955

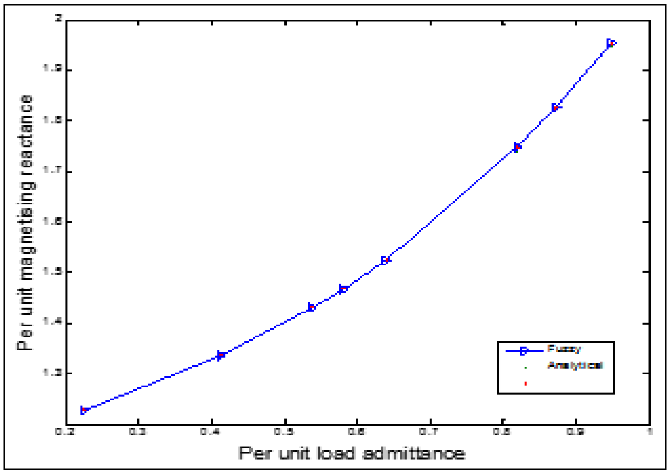

Fig 2: Effect of load admittance on Magnetizing Reactance

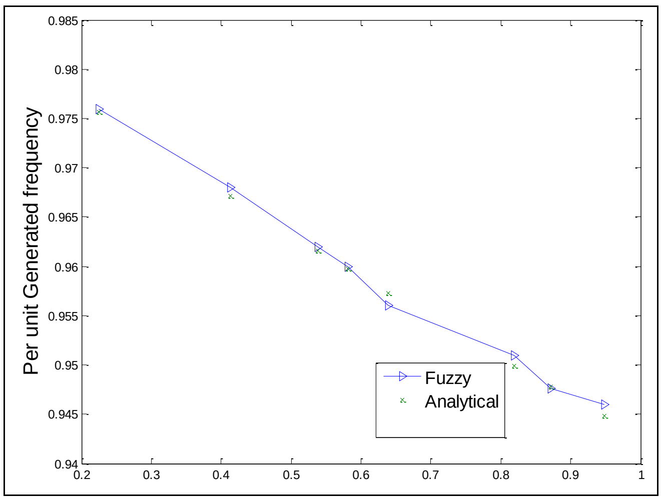

Fig 3: Effect of load admittance on generate frequency

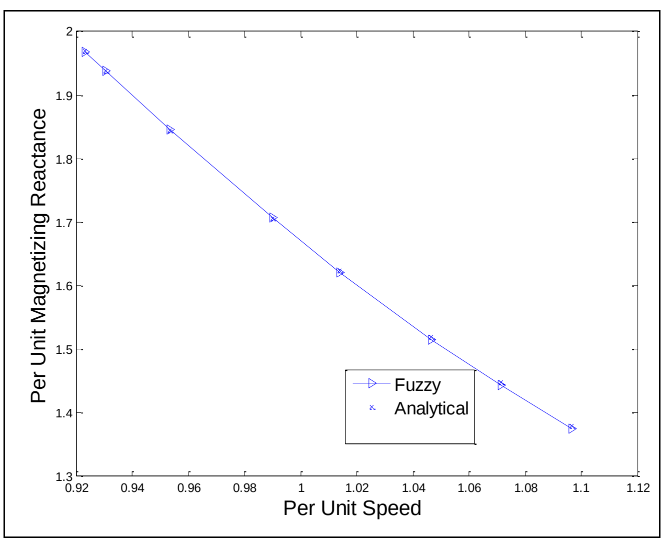

Fig 4: Effect of speed on magnetizing Reactance

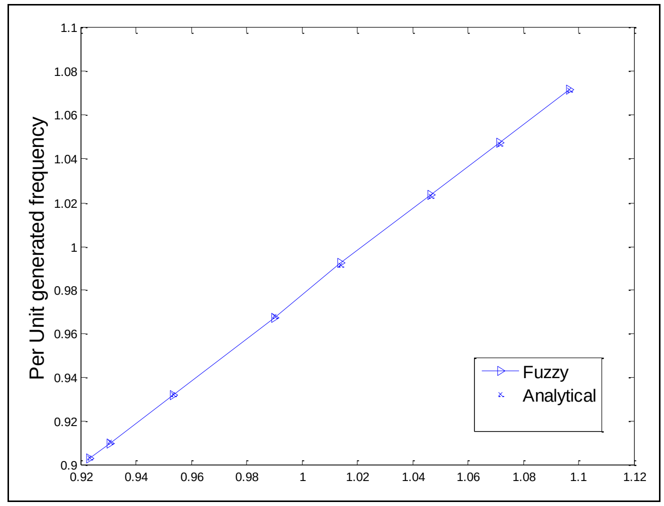

Fig 5: Effect of speed on generated frequency

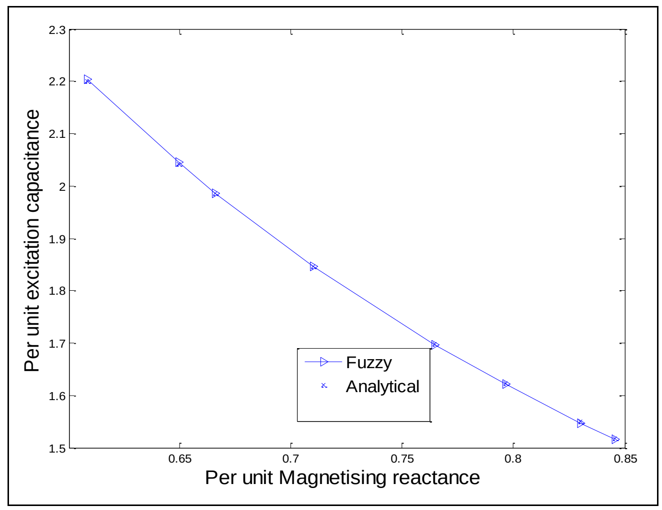

Fig 6: Effect of excitation capacitance on magnetizing reactance

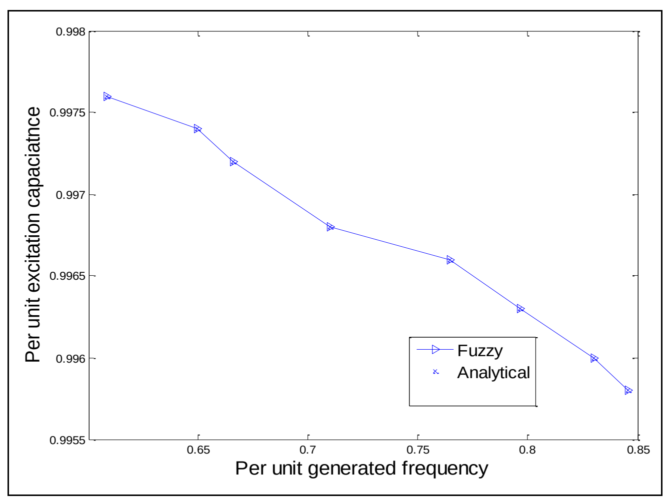

Fig 7: Effect of excitation capacitance on Generated frequency

4. Conclusions

A soft computing oriented fuzzy technique has been developed to analyze the steady state performance of a capacitor excited self-excited induction generator. Fuzzy rules are established to estimate the performance of self-excited induction generator as it is very easy to use and computationally cheap. The machine parameters are varied from 4 to 8 percent. It is established that results obtained from fuzzy logic model are in good agreement with the results of analytical technique. Thus it validates the technique used for the analysis of SEIG. This technique can also be extended for experimental verification of results. Thus it is concluded that fuzzy logic method can also be used in concurrence with conventional methods. This technique can be extended to improve the accuracy by using trapezoidal and other member ship function and by simultaneously varying the machine parameters and changing the linguistic variable for and by adding more fuzzy rules.

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