Fuzzy Technique for Estimation of Capacitance Requirement of Self Excited Induction Generator to Maintain Constant Air Gap Voltage under Variable Speed

Ashish Sharma[1], Dr. Raja Singh Khela[2]

[1]Research Scholar, Punjab Technical University, Kapurthala, India
[2]Director – Principal, Doaba Group of Colleges, Mohali, India

ABSTRACT

Induction generators are widely used in non-conventional systems. In modern times, as the population increases, the demand for electricity also increases. As it is difficult for developing countries to generate that amount of electricity, so induction generators are used as standalone system to provide the electricity to remote areas. But the need for an external supply of reactive power (to produce a rotating magnetic flux wave) limits the application of an induction generator as a standalone generator. It is possible for an induction machine to operate as a Self-excited Induction Generator (SEIG) if capacitors are connected to the stator terminals in order to supply the necessary reactive power to achieve generating electrical energy in remote areas. But with the variation in speed or various parameters, the probability of reduced terminal voltage is more pronounced when power is supplied from an isolated SEIG. So it is significant to regulate exciting capacitance to maintain constant air gap voltage. Thus, computation of that value of capacitance, the fuzzy approach is used.

Keywords: Self Excitation, Induction generator, fuzzy logic, air gap.

Nomenclature:

R_r, X_r = Rotor resistance and reactance
R_s , X_s = Stator resistance and reactance
R_L , X_L = Load resistance and reactance
R_e = Core loss resistance
X_m = Per phase Saturated magnetic reactance
X_{mu} = Unsaturated magnetizing reactance
X_C = Per phase capacitive reactance
F_r = Rated frequency
a = Generated frequency
b = Ratio of actual rotor speed to synchronous speed corresponding to rated frequency
I_s = Stator current
I_L = Load current
I_r = Rotor current
Ic = Capacitive current
E_1 = Air gap voltage per phase at rated frequency
Z = Impedance of complete circuit

I. INTRODUCTION

With depletion of sources of energy, every effort is made to convert other forms of unconventional sources into electrical energy. The self excited induction generator does not require an ac supply system for obtaining ts reactive power. In this generator, a capacitor bank is connected across stator terminals. The capacitor bank provides lagging reactive power of both the induction generator as well as load. When a standalone machine is driven by a mechanical prime mover, residual magnetism in the rotor induces an emf in stator windings at a frequency proportional to rotor speed. Then emf is applied to the capacitors connected to terminals and cause reactive current to flow, so flux is generated in the machine. There is a limit in the final value of stator voltage by magnetic saturation within machine. Therefore, now machine is capable of operating in isolated locations without grid supply. The phenomenon of self excitation can be easily understood. Excitation is the phenomenon by which one can control the excitation of field winding of a generator..This process may take place when a sufficient amount of capacitors is connected at the stator terminals. Unlike synchronous generator, an induction generator does not have an internal magnetization source [1-2]. However, a voltage may build up in an induction generator as the result of a physical process known as self excitation.

This process allows the induction generator to use as a standalone unit. Self excitation is initiated by the residual flux in the induction generator rotor iron. When generator is gained some speed, the residual flux will induce voltage in the stator[4,6]. Under such conditions, the induction generator behaves much like a synchronous generator with permanent magnet rotor. If capacitors are connected at stator terminals, the induced voltage in stator causes the flow of current into the capacitors. Depending upon the generator parameters, value of generator speed and capacitors, a transition from the synchronous mode of operation to the asynchronous mode may take place at some point leading to the self- excitation of the induction generator. Once the self- excitation has started, the induction generator voltage builds up. The capacitor current produced by the stator voltage generates flux into the generator with the same direction as residual flux which further causes higher induced voltage leading to successive increase in current and flux.

This process of voltage build up comes to a stop when the capacitor voltage curve intersects no load curve of induction generator. At this point, supply of capacitors should be exactly the reactive power needed by the induction generator at no load. When the generator is accelerated with the capacitors connected, self excitation is not possible in the beginning [16]. Then at about 40 Hz, self excitation starts and voltage increases. If the generator speed decreases below a certain frequency self excitation is not possible and the generator demagnetizes. Sometimes the self excitation of induction generator becomes difficult due to low residual flux in the rotor iron. So different methods are used as he solution of this problem. Among them, connecting a dc voltage source like battery to the stator seems to most practical. Other methods such as using high value capacitors or accelerating the generator above nominal speed may cause dangerous over voltages once the self excitation process has started [3]. The SEIG system performance characteristics depend on the following:

Self Excitation Process – The connection of capacitor across the stator terminals (delta or star) and the use of fixed or controlled capacitors have a proportional effect on the performance of system.

Type of prime mover – The performance is affected whether the primary source is hydro, wind biomass or any combinations.

Parameters of Induction Machine – Various machine parameters like stator resistance, rotor resistance, leakage reactance, magnetizing reactance, rotor speed, power factor, operating voltage, rated power directly affect the performance of SEIG system.

Load Parameters – Type of load, power factor, starting/maximum torque and current, generated harmonics all has a great effect on performance of SEIG. A change in load directly affects the machine excitation. This is due to the fact that reactive power of excitation capacitors is shared by both machine and load impedance. So generator voltage drops with increase in load resulting in poor voltage regulation.

II. ANALYTICAL TECHNIQUE FOR CALCULATION

The performance of the SEIG using an analytical model based on a conventional single-phase equivalent circuit with per-unit (p.u.) parameter has been studied [8-9]. The model used in this has been extended for the evaluation of various steady-state performance characteristics of stand-alone generators, like the effect of shaft variation , change in generator pole number and parallel operation etc .In analytical techniques, there are 2 methods mainly – loop impedance method and nodal admittance method [17]. Two non-linear simultaneous equations in a and X_m can be obtained by equating the real and imaginary terms of the complex loop impedances respectively to zero, for any given load and speed. These equations are then solved by the Newton- Raphson method. After knowing the values of a and X_m and with the aid of the magnetization curve, the equivalent circuit is completely solved and the steady-state performance of the SElG can be determined.

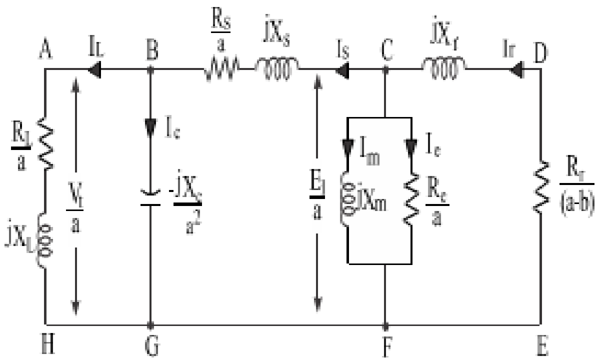

Fig.1. Per phase equivalent circuit of self-excited induction generator

$Z_{AH} = R_L/a + j X_L$

$Z_{BG} = -j Xc /a^2$

$Z_{BC} = R_s/a + jX_s$

$Z_{CF} = R_e/a \,||\, j X_m$

$Z_{CE} = (R_r /(a-b) + j X_r)$

$Z = (Z_{CF}||Z_{CE}) + Z_{BC} + (Z_{AH} + Z_{BG})$ (1)

When we solve the equivalent circuit of Figure 1 it results into a single loop equation i.e $I_s{*}Z = 0$.

For successful voltage build up in SEIG, I_s cannot be zero hence Z should be zero. Thus by separating the real and imaginary components of Z and by putting all the values of parameters we get two non-linear simultaneous equations. These two equations are obtained in terms of machine parameters, speed, capacitive reactance, load resistance/reactance, magnetizing reactance X_m and generated frequency a.

$\text{Real}\,(X_m,a) = P_1X_ma^5 + P_2X_ma^4 + (P_3X_m + P_4)a^3 + (P_5X_m + P_6)a^2 + (P_7X_m + P_8)a + P_9X_m + P_{10}$ (2)

$\text{Imaginary}(X_m,a) = (Q_1X_m + Q_2)a^4 + (Q_3X_m + Q_4)a^3 + (Q_5X_m + Q_6)a^2 + (Q_7X_m + Q_8)a + Q_9$ (3)

The coefficients ($P_1 - P_{10}$) and ($Q_1 - Q_9$) of two characteristics equations are obtained using MATLAB and are given in Appendix 2.These are solved using Newton Raphson method in MATLAB and the values of X_m and a are calculated .Per unit air-gap voltage (E_1) of SEIG is determined from its magnetic characteristics as given in Appendix 1.Various currents and terminal voltage can be computed as follows:

$$I_r = \frac{-E_1/a}{R_r/(a-b) + jX_r}$$

$$I_s = {aE_1}/{jZ_L}$$

$$I_L = I_s \frac{-jX_C/a}{R_L + j(aX_L - X_C/a)}$$

$$V_t = aE_1 - I_s(R_s + jaX_s)$$

The above Polynomial equations are to be solved with Fuzzy logic technique to determine the per unit value of saturated magnetizing reactance X_m and generated frequency a [10]. Fuzzy logic is a simple, rule based approach to solve a problem rather than attempting mathematical modeling. The Fuzzy approach involves the classification of fuzzy sets into various linguistic variables for which different membership functions are to be formed .In this paper, nine inputs and two outputs are taken. The inputs are rotor resistance, stator resistance, rotor and stator leakage reactance, power factor, speed, capacitance, core loss resistance and load admittance in per unit and two outputs are magnetic reactance and generated frequency. The range of all input variables must be chosen very carefully and these should be compatible to real life applications of induction machine as self excited induction generator. The range of stator and rotor resistance can be varied from 4-8 percent. Triangular member ship function is used to create the rule table for fuzzy approach. The calculation of magnetizing reactance and generated frequency is done with the variation of speed. Fuzzification and defuzzification processes are carried out with the help of rule matrix. The purposed fuzzy model is shown in figure 2.

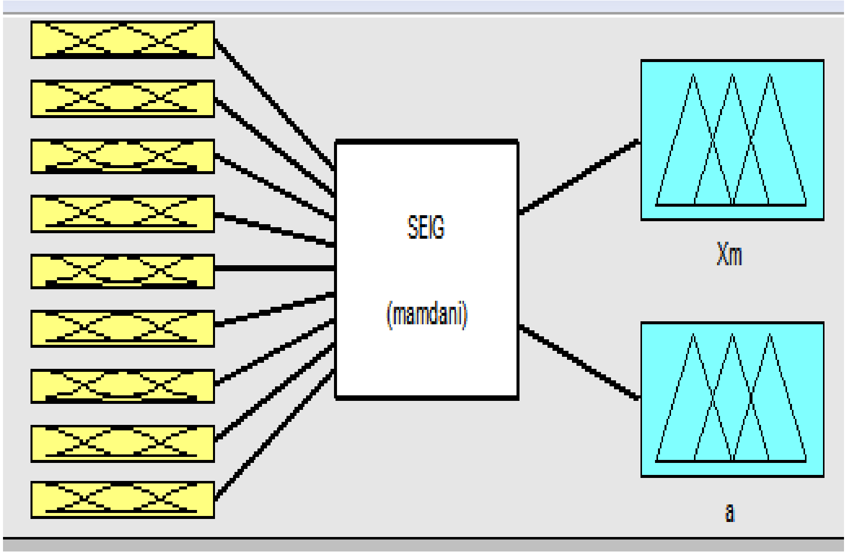

Fig. 2: Fuzzy Model for SEIG to find Magnetizing Reactance and Generated Frequency

The magnetizing reactance (X_m), generated frequency (a) , terminal voltage and output power are calculated using fuzzy system and comparison with analytical values are shown in Table 1and Table 2. As shown in tables the magnetization reactance is varying with the variation in speed. From the magnetization curve of the machine, per unit air gap voltage E_1 can be evaluated by using the value of X_m.

For $X_m < 2.6930$ $E_1 = 1.3818-0.2117X_m$

With the variation in magnetizing reactance, air gap voltage also keeps on varying. The variation in X_m is seen for varying conditions of speed. Air gap is the gap between rotor and stator. An increase of air gap gives an increase in 'reluctance'. In a salient pole induction generator this fact may be used to produce a sinusoidal flux density curve by gradually increasing the length if the air gap around a rotor is not uniform then motor may not start in certain positions. In the induction motor the air gap should be as small as possible if the motor is to act with a high power factor. Small air gap give better performance but also result in mechanical problems in addition to the noise and losses at the slot tooth faces. The main source of low power factor at which the induction motor operates is the air gap.

III. FUZZY APPROCH TO MAINTAIN AIR GAP VOLTAGE CONSTANT

With the variation in terminal parameters, there is a probability of reducing terminal voltage. So to keep the load voltages at rated level, it is significant to regulate the exciting capacitance to generate constant air gap voltage. Using Fuzzy model, the capacitance requirements will be computed to maintain the air gap voltage constant. In the previous calculation, there were nine inputs as rotor resistance, stator resistance, rotor leakage reactance, stator leakage reactance, power factor, speed, capacitance, load admittance and core loss resistance and for considering the air gap constant, there is an additional input change in capacitance (ΔC) in per unit is required and two outputs are magnetic reactance and generated frequency. For air gap constant, the magnetizing reactance should be constant. So here, there are ten inputs out of which eight inputs are taken constant within the range of machine parameters.

The range of all input variables must be chosen very carefully and these should be compatible to real life applications of induction machine as self excited induction generator. For maintaining the air gap voltage constant for varying speed under constant load admittance and excitation capacitance, membership function for all parameters except speed and change in capacitance are taken as constant. There are five membership functions for speed as extreme low, very low, medium, high and very high and five for change in capacitance as negatively large, negatively medium, negatively small, positively small and positively large. Output variable X_m has membership function as low, medium and high & a has membership functions as very low, low, medium, very high and extreme high. The fuzzy rules are shown in Table 3 and 4. For example the first rule is when speed is extreme low (EL) and ΔC is negatively small then magnetizing reactance is high and generated frequency is very low. Fig. 3 shows the fuzzy view rules for magnetizing reactance and generated frequency taking value of speed = 0.9386.

Table 1: Magnetizing Reactance and Generated Frequency with Varying Speed

Load = 165 ohm Capacitance = 25.46 uF				
	Analytical		Fuzzy Logic	
Speed (pu)	Magnetizing Reactance (pu)	Generated Frequency (pu)	Magnetizing Reactance (pu)	Generated Frequency (pu)
0.903	1.8386	0.8737	1.88	0.865
0.912	1.7632	0.8916	1.76	0.895
0.9386	1.7021	0.907	1.75	0.895
0.9533	1.6441	0.9223	1.63	0.931
0.9706	1.5714	0.9528	1.56	0.959
0.99	1.5155	0.9594	1.52	0.964
1.014	1.4826	0.9697	1.48	0.964
1.036	1.4143	0.992	1.43	0.99

Table 2: Terminal Voltage and Output Power with varying Speed

Load = 165 ohm Capacitance = 25.46 uF				
	Analytical		Fuzzy Logic	
Speed (pu)	Terminal Voltage (pu)	Output Power (pu)	Terminal Voltage(pu)	Output Power (pu)
0.903	0.7937	2.4804	0.7793	2.3536
0.912	0.8217	2.7493	0.8256	2.7939
0.9386	0.8462	3.0039	0.8274	2.8055
0.9533	0.87	3.2737	0.8803	3.4115
0.9706	0.9015	3.6664	0.9181	3.9372
0.99	0.9267	4.0145	0.9301	4.0847
1.014	0.9422	4.2451	0.9375	4.1497
1.036	0.9755	4.78643	0.9707	4.7174

Table 3: Fuzzy Rules for Magnetization Reactance under Varying Speed

ΔC N	NL	NM	NS	PS	PL
EL	H	H	H	M	L
VL	H	H	M	M	L
M	H	H	M	L	L
VH	H	M	L	L	L
EH	M	M	L	L	L

Table 4: Fuzzy Rules for Generated Frequency under Varying Speed

ΔC N	NL	NM	NS	PS	PL
EL	VL	VL	L	L	H
VL	L	L	M	M	L
M	M	M	H	VH	M
VH	H	H	H	EH	H
EH	VH	VH	VH	EH	EH

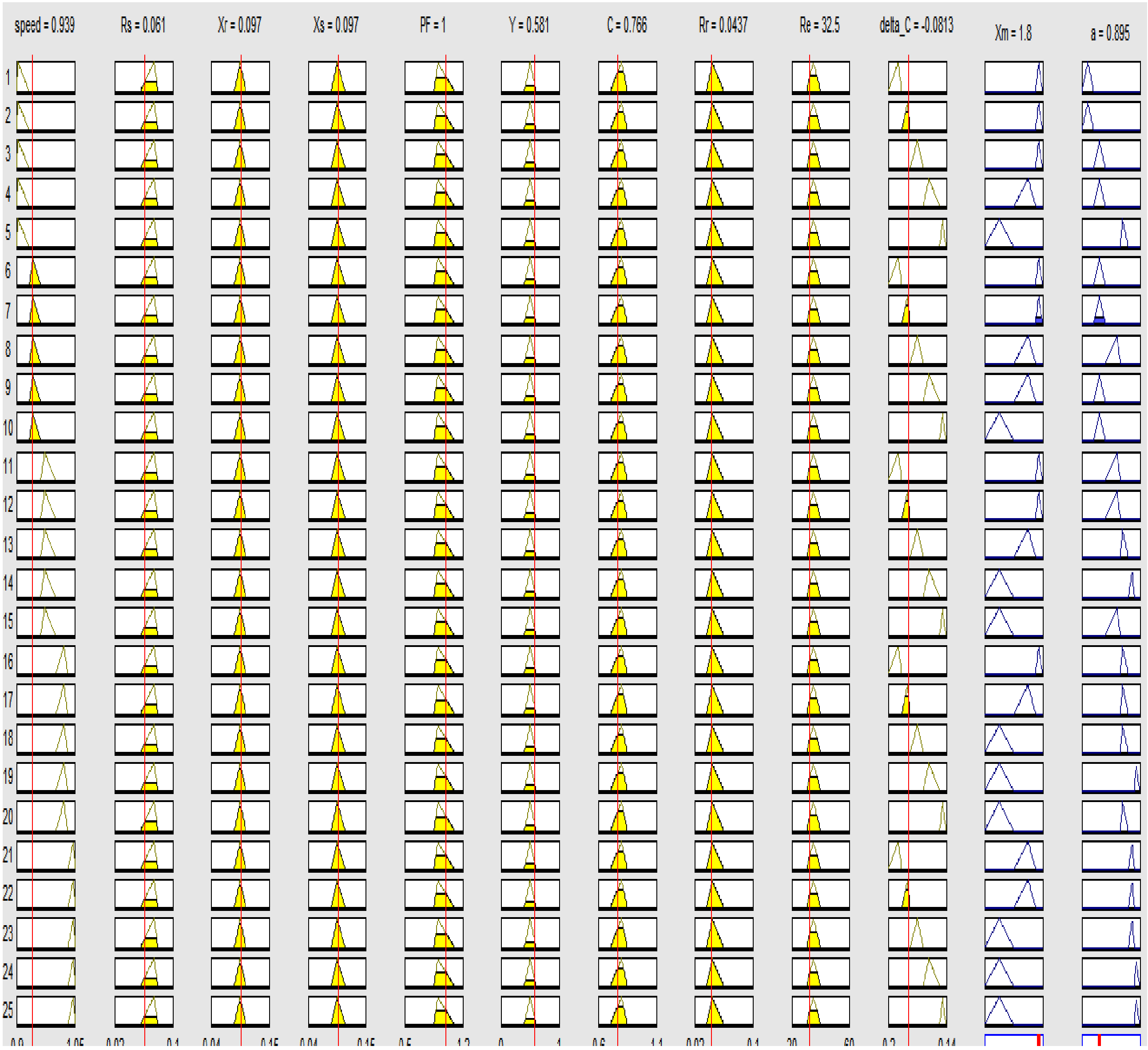

Fig. 3: Fuzzy Rules for Constant Air Gap under Varying Speed

Table 5: Capacitance Requirements with Varying Speed

Load = 165 ohm Capacitance = 25.46 uF						
Speed (pu)	ΔC (pu)	X_m (pu)	a (pu)	Air Gap Voltage (pu)	Capacitance Required(C+ΔC) (pu)	Terminal Voltage (pu)
0.903	-0.1822	1.8	0.865	1	0.5838	0.7921
0.912	-0.1221	1.8	0.865	1	0.6439	0.7921
0.9386	-0.0813	1.8	0.895	1	0.6847	0.8181
0.9533	-0.0623	1.8	0.931	1	0.7037	0.8491
0.9706	-0.0399	1.8	0.959	1	0.7261	0.8732
0.99	0.0246	1.8	0.978	1	0.7906	0.8894
1.014	0.0712	1.8	0.992	1	0.8372	0.9014
1.036	0.1211	1.8	0.992	1	0.8871	0.9014

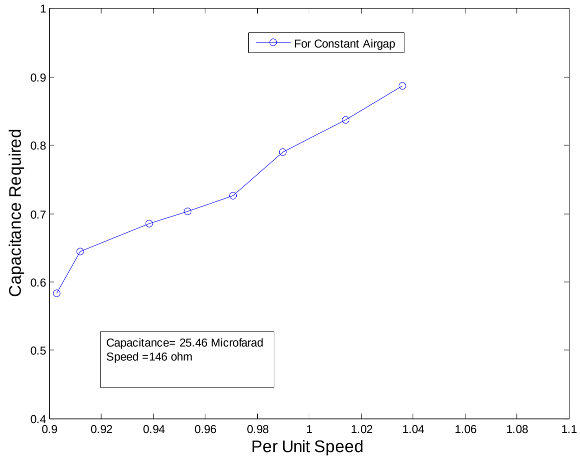

Fig. 4: Capacitance Requirements for Varying Speed

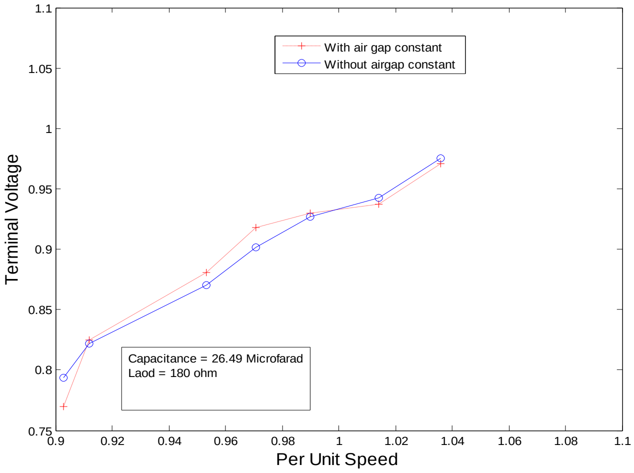

Fig. 5: Comparison of Terminal Voltage with and without Air Gap Constant under Varying Speed

IV. EXPERIMENTAL SETUP

In the laboratory test, single phase 1.7 kW, 415V, 4.33A, 1500rpm, 50Hz squirrel cage induction machine was used to determine the electrical parameters. It is obtained by conducting dc resistance, no load and blocked rotor test. The various machine parameters comes to be R_s= 5.76ohm, R_r = 4.19 ohm, R_e = 3118 ohm , X_s = 9.37 ohm ,X_r =9.37 ohm, X_{mu}=285 ohm .

V. CONCLUSION

The self excited induction generator is gaining importance for the renewable energy sources due to its isolated mode. Excitation capacitance connected across the stator terminal of machine plays very important role for the successful operation of induction generator. The terminal voltage, magnetizing reactance and generated frequency are affected by the speed when excitation capacitance and load are kept constant. The capacitor bank supplies the reactive power not only to self-excite the machine but also contributes to meet the requirements of reactive power of the load. There are probabilities of reduced terminal voltage at rated or near full load are more affected when power is supplied from an isolated self excited induction generator due to variations in terminal conditions. So to keep the load voltages at rated level under wide range of load variations, it is significant to regulate the exciting capacitance to generate constant air gap voltage. In this paper, using Fuzzy model, the capacitance requirements are evaluated under varying conditions of speed.

It is observed that with the change in exciting capacitance (ΔC) the air gap voltage at E_1 = 1 pu is constant, so the voltage of SEIG remains within tolerable limits, so enhancing the capability of machine to supply power at rated voltage. Figure 4 shows the capacitor requirement for maintaining the air gap voltage constant under the varying conditions of speed. The effect on terminal voltage can be compared easily between the constant air gap and the variable air gap from the Figure 5. Without air gap constant, there is wide range of variation in terminal voltage while in case of constant air gap, this range is very less which is very useful in reduction of fluctuation of voltage.

Appendix 1

Magnetization curve of machine (pu values)
$X_m < 2.6930$ $E_1 = 1.3818-0.2117\ X_m$
$X_m < 2.8386\ \&\ X_m >= 2.6930$ $E_1 = 2.1697- 0.5057\ X_m$
$X_m < 2.9716\ \&\ X_m >= 2.8386$ $E_1 = 3.8732- 1.1057\ X_m$
$X_m > 2.9716$ $E_1 = 0$

Machine specifications

$V_{base} = 415V$
$I_{base} = 4.33A$
$P_{base} = 1797VA$
$C_{base} = 33.21\ uF$
$f = 50Hz$
$R_s = 5.76ohm = 0.061\ pu$
$R_r = 4.19ohm = 0.0437\ pu$
$X_s = 9.37ohm = 0.097\ pu$
$X_r = 9.37ohm = 0.097\ pu$
$R_e = 3118ohm = 32.53\ pu$
$X_{mu} = 285ohm = 2.973\ pu$
$Z_{base} = V_{base} / I_{base} = 95.84ohm$
$b_{base} = 1500\ rpm$

Appendix 2

Coefficients are given as:
$P_1 = -(X_s X_r X_{L)}$
$P_2 = (X_s X_r X_L)*b$
$P_3=X_s*(R_r*R_L+R_e*R_L+X_r*X_c)+X_r*(R_e*R_s+X_c*X_s+ R_s*R_L)+X_s*(R_e*R_r+ R_e*R_s+ R_s*R_r)$
$P_4 = X_s*R_e*(X_r*R_L +R_r*X_L)+R_e*R_s*X_r*X_L$
$P_5=-X_s*(X_r*X_c +R_e*R_L)*b- X_r*(R_s*R_L+R_e*R_L+ X_c*X_L)*b-(R_s*R_e*X_L)*b$
$P_6 = -X_r*R_e*(R_s*X_L+X_s*R_L)*b$
$P_7 = -X_c*R_r*(R_s+ R_L)-X_c*R_e* (R_s+ R_L+ R_r)$
$P_8=-(R_e*X_r*X_c*(R_L+R_s))-(R_e*R_r*X_c*(X_L+X_s))-(R_e*R_s*R_r*R_L)$
$P_9 = R_e*X_c* (R_s+ R_L)*b$
$P_{10}= X_c*X_r*R_e*(R_L+R_s)*b$
$Q_1 = X_s*X_L*(R_e+ R_r)+X_s*X_r*R_L+X_r*X_L*(R_e+ R_s)$
$Q_2 = X_s *X_r*X_L*R_e$
$Q_3 = -X_s*(R_e*X_L+X_r*R_L)*b-X_r*X_L*(R_s+ R_e)*b$
$Q_4 = -(X_s*X_r*X_L*R_e)*b$
$Q_5=-X_c*R_e*(X_s+X_r+X_L)-R_L*R_e*(R_s+Rr)-R_L*(X_r*X_c+R_r*R_s)-X_c*(R_s*X_r+X_s*R_r+X_L*R_r)$
$Q_6=-R_eX_r*(X_s*X_c+X_c*X_L+R_s*R_L)-R_r *R_e*(X_s*R_L+R_s*X_L)$
$Q_7=R_e*(X_r*X_c+X_s*X_c+ X_L+R_s*R_L)*b+X_c*X_r*(R_s+$
$R_L)*b$
$Q_8 = R_e*X_r*(X_s*X_c+ X_c*X_L)*b+ (X_r*R_e*R_L*R_s)*b$
$Q_9 = R_e*X_c* R_r*(R_L+R_s)$

REFERENCES

[1]. R.C. Bansal, “Three- Phase Self- Excited Induction Genrator: An Overview”, IEEE Transactions on Energy Conversion, Vol. 20, no. 2, pp. 292-299, June 2005.
[2]. G.K. Singh,”Self- excited Induction Generator Research- a Survey”, Electric Power Systems Research, Vol.69, no.2-3, pp. 107-114, May 2004.
[3]. S.S. Murthy, O.P. Malik and A.K. Tandon, “Analysis of Self –excited Induction Generators”, IEE Proceedings on Generation, Transmission and Distribution, Vol.129, no.6, pp.260-265, November 1982.
[4]. S.S Murthy, B.P. Singh et.al, “Studies on the use of conventional induction motors as self excited induction generators”, IEEE Transactions on Energy Conversion, Vol. 3, no. 4, Dec 1988.
[5]. B. Singh, “Induction generator- A prospective”, Electric Machines and Power Systems, Vol.23, pp. 163-177, 1995.
[6]. J. M. Elder et.al, “The process of self excitation in induction generators”, IEEE Proceedings on Electric Power Applications, Vol. 130, no. 2, pp. 103-108, March 1983.
[7]. L. Wang et.al, “Determination of minimum and maximum capacitances of an isolated SEIG using eigen value sensitivity approach”, IEE Proceedings on Telecommunication Energy, pp. 396-403, Oct 2003.

[8]. T.F. Chan, "Steady State Analysis of self excited induction generators", IEEE Transactions on Energy Conversion, Vol. 9, pp.288-296, June 1994.

[9]. A. K. Tandon, S. S. Murthy, and G. J. Berg, "Steady state analysis of capacitor self-excited induction generators," IEEE Trans. Power App. Syst., vol. PAS-103, no. 3, pp. 612–618, Mar. 1984.

[10]. H.F. Soliman et. ol, "Fuzzy algorithm for supervisory control of self excited induction generator", JKAU: Engineering Science, Vol. 17, pp. 19-40, 2006.

[11]. Lalit Goyal et.al, "A survey of Self Excited Induction Generator Research", IJEEE, Vol. 2, Issue 1, Feb 2013.

[12]. Harish Kumar and Neel Kamal, "Steady State Analysis of Self Excited Induction Generator", IJCSE, Vol. 1, issue -5, November 2011.

[13]. Raja Singh Khela et. al., "Cascaded ANN for Evaluation of Frequency and Air-gap Voltage of Self-Excited Induction Generator ," International Journal of Electrical and Electronics Engineering 1:1 2007

[14]. K.S. Sandhu et. al., "ANN Model for Estimation of Capacitance Requirements to Maintain Constant Air-Gap Voltage of Self-Excited Induction Generator with Variable Load", IJCST Vol. 2, Issue 4, Oct. - Dec. 2011.

[15]. D. Joshi, K. S. Sandhu, and M. K. Soni, "Performance Analysis of Self-Excited Induction Generator Using Artificial Neural Network," Iranian journal of electrical and computer engineering, vol. 5, no. 1, winter-spring 2006.

[16]. A. Abbou, M. Barara et. al., "Capacitance Required Analysis for Self-Excited Induction Generator", Journal of Theoretical and Applied Information Technology 30th.Vol.55. No.30, September 2013

[17]. Vineet P. Chandran ,Shelly Vadhera " Comparison of nodal admittance and loop Impedance methods for self excited induction Generator", IJAET/Vol.III/ Issue I/January-March, 2012.

[18]. Shakuntla Boora, "On-Set Theory of Self-Excitation in Induction Generator," International Journal of Recent Trends in Engineering, Vol 2, No. 5, November 2009.

ABOUT THE AUTHORS

[1]**Er. Ashish Sharma** passed B.Tech in 2001 and M.Tech in 2006 from Punjab Technical university Kapurthala. He is pursuing his PhD from Punjab Technical Univeristy, Kapurthala, Punjab.

[2]**Dr Raja Singh Khela** graduated in Electrical Engg. From Institution of Engineers, Calcutta in 1985. He passed his Masters Degree (with Distinction) from Punjab University, Chandigarh. Presently, he is serving as Director at Doaba Group of colleges, Mohali, Punjab.