



Original Article

Identification of voltage collapse point in self excited induction generator

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Abstract

This paper presents a direct equilibrium tracing method for identifying the voltage collapse point of a self-excited induction generator (SEIG) without many trials. The technique solves differential and algebraic equations simultaneously to obtain the variables in a single step. The load parameter is also automatically varied during equilibrium tracing and this reduces the computational time significantly. Comparing the simulation results obtained through conventional iterative procedure shows the effectiveness of the technique. An experimental verification on a 1.5KW induction machine validates the simulation results.

Keywords: self-excitation, induction generator, dynamic modeling, voltage collapse

1. Introduction

In recent years, self-excited induction generators have been increasingly used in isolated power supplying systems. If an appropriate 3-phase capacitor bank is connected across the terminals of an externally driven induction machine, an emf is generated. This phenomenon is known as “capacitor self-excitation”. Induced emf and current in the windings will increase up to a level governed by the magnetic saturation of the machine. In order to reach a steady-state generating mode, some remnant magnetism must be present in the machine core initially (Murthy, Singh, Nagamani and Satyanarayana, 1988). A capacitor self-excited induction generator offers certain advantages over conventional synchronous generator, as a source of isolated power supply. Reduced unit cost, brushless rotor (squirrel cage construction), absence of a separate dc source and ease of maintenance are among the advantages. But one of the major limitations of self-excited induction generator is that the terminal voltage decreases as the load increases and it collapses (becomes zero), when the generator

is loaded beyond a critical value. The critical load varies with generator speed and excitation capacitance (Uctug and Demirekler, 1988 and Chan, 1993 and Wang and Lee, 1996). The dynamic performance of the SEIG has been analyzed for different types of loads and the critical load identified by varying the conventional iterative method (Li Wang and Jian-Yi Su, 1999 and Li Wang and Ching Huei Lee, 2000 and Yaw-Juen wang and Shen-yan Huang, 2004 and Dawit Seyoum, Colin Grantham and Mohammed Fazlur Rahman, 2003). In order to know the maximum load ability limit of the SEIG under varying operating condition, the critical load must be identified. Varying the load in many trials, which is time consuming and cannot be used for on-line studies, normally identifies the value. Equilibrium tracing technique is found to be useful in determining the critical load in a single step. In the power system literature, several papers have addressed the issue of voltage collapse phenomena using the equilibrium tracing technique. In this method the system differential and algebraic equations are simultaneously solved, to obtain both the dynamic state variables and the static algebraic variables in one step. The load parameter is also varied continuously during direct equilibrium tracing, which reduces the computational time significantly.

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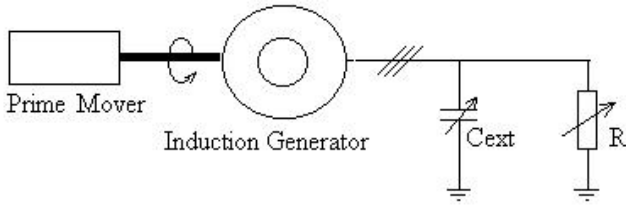


Figure 1. Self-excited induction generator with resistive load

In this paper, the direct equilibrium tracing technique applied to SEIG feeding heating type resistive load is presented. A mathematical model of the SEIG with direct equilibrium tracing technique is developed. The critical load is predicted through simulation for varying excitation capacitances and generated speeds and the results are experimentally verified.

2. Modeling of the components

Figure 1 shows the schematic diagram of the self-excited induction generator considered for study. The mathematical modeling of the system components is discussed below.

2.1 Induction generator model

Figure 2 shows the d-q axis equivalent circuit model of a three-phase symmetrical induction generator with excitation capacitance and resistive load. The leakage inductances of the stator and rotor are assumed constant whereas the magnetizing inductances are considered as a function of the air gap flux.

The per-unit stator and rotor voltage equations using Krause transformation (Krause, 1994) are given as follows.

$$V_{qs} = -R_s i_{qs} + \omega \lambda_{ds} + p \lambda_{qs}$$

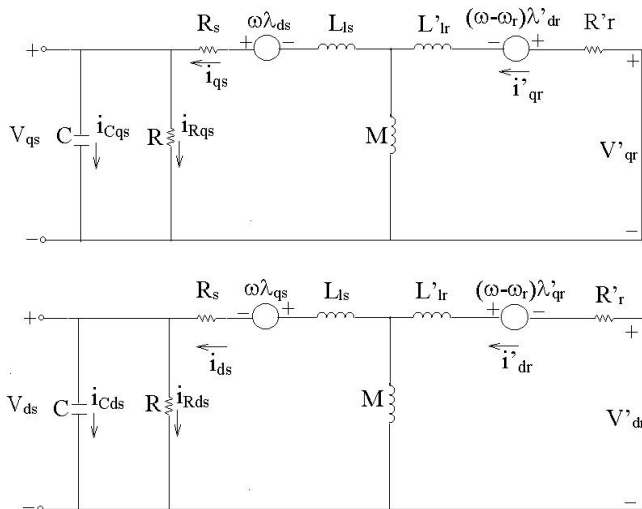


Figure 2. d-q axis equivalent circuit of a 3-phase induction generator with R & C at the stator terminals

$$V_{ds} = -R_s i_{ds} - \omega \lambda_{qs} + p \lambda_{ds}$$

$$V'_{qr} = R'_r i'_{qr} + (\omega - \omega_r) \lambda'_{dr} + p \lambda'_{qr}$$

$$V'_{dr} = R'_r i'_{dr} - (\omega - \omega_r) \lambda'_{qr} + p \lambda'_{dr} \tag{1}$$

Figure 2 d-q axis equivalent circuit of a 3-phase induction generator with R & C at the stator terminals where

$$\lambda_{qs} = -L_{ls} i_{qs} + M(i'_{qr} - i_{qs})$$

$$\lambda_{ds} = -L_{ls} i_{ds} + M(i'_{dr} - i_{ds})$$

$$\lambda'_{qr} = L'_{lr} i'_{qr} + M(i'_{qr} - i_{qs})$$

$$\lambda'_{dr} = L'_{lr} i'_{dr} + M(i'_{dr} - i_{ds}) \tag{2}$$

The superscript ' in the above equations denotes the transformed rotor quantities referred to the stator. For the present study, asynchronously rotating reference frame fixed to the stator is used where $V_{qs} = 0$, and V'_{qr} & V'_{dr} are zero as the rotor is shorted.

The value of the magnetizing inductance M, depends on the degree of magnetic saturation, and it is a non-linear function of the magnetizing current i_m , and is expressed by the following equation

$$i_m = ((i'_{qr} - i_{qs})^2 + (i'_{dr} - i_{ds})^2)^{1/2} \tag{3}$$

The relationship between M and i_m can be obtained by using synchronous speed test, and it is described by the following set of equations (Li Wang and Jian-Yi Su, 1999).

$$M = \begin{cases} 1.41566 / (i_m + 0.1317) & \text{for } 0.3578 < i_m \\ 1.59267 / (i_m + 0.1929) & \text{for } 0.3075 < i_m \leq 0.3578 \\ 1.79031 / (i_m + 0.255) & \text{for } 0.2188 < i_m \leq 0.3075 \\ 2.67838 / (i_m + 0.49) & \text{for } 0.1081 < i_m < 0.2188 \\ 3.997 & \text{for } i_m \leq 0.1081 \end{cases} \tag{4}$$

The resistive load at the stator terminals is defined as

$$R = R_0 / l \tag{5}$$

where R_0 is the base load and l is the load parameter, which varies continuously during equilibrium tracing.

The voltage-current equations of the R-C circuit are given as

$$i_{Rqs} = V_{qs} / R \tag{6}$$

$$i_{cqs} = i_{qs} - i_{Rqs} \tag{7}$$

$$i_{cds} = i_{ds} \tag{8}$$

$$p V_{qs} = (1/C) [i_{qs} - V_{qs} / R_0 - l / R_0] \tag{9}$$

3. Direct equilibrium tracing for self-excited induction generator

The system differential equations together with the algebraic equations are commonly known as DAE representation of the system. In a compact form, they can be simply denoted as

$$\dot{X} = F(X, Y, U, Z) \quad (10)$$

$$0 = G(X, Y, U, Z) \quad (11)$$

where X contains all the system state variables, Y includes the algebraic variables, U is the control vector and Z consists of all the parameters. For a specified set of system control U_0 , the system equilibrium (X_0, Y_0) (it exists) is defined as the solution of (10) and (11) at steady state (*with* $\dot{X} = 0$). Here we directly obtain the equilibrium solutions by simultaneously solving (9) and (10) at steady state (Zhihong Feng, Venkatramana Ajjarapu and Bo Long, 2000).

In self-excited induction generator, the d and q-axis voltages and current are chosen as the state variables(X), the load R_0/λ is considered as the algebraic variables, the generator speed as the control vector (U) and the Z consists of R_s, R_r, L_s, L_r and C.

3.1 Detection of voltage collapse point

Two methods, namely direct and continuation methods, so far have been applied to detect the voltage collapse point [Zhihong Feng, Venkatramana Ajjarapu and Bo Long, 2000 and Seydel, 1988 and Canizares and Alvarado, 1993 and Yuan Zhou and Venkatarmna Ajjarapu, 2001 and Venkataramana Ajjarapu, Quin Wang and Hwachang song, 2006). In the continuation method the load parameter l is varied continuously until the voltage collapses, i.e. saddle node bifurcation occurs. The continuation method involves a prediction and correction scheme. To find the response of the system, a simple step-by-step procedure is given below.

Step 1: Initially, an equilibrium point is assumed at base load and the Jacobian matrix is formed from the system state equation $F(X, \lambda) = 0$.

Step 2: In this prediction stage, a tangent vector is solved using (12).

$$-\begin{bmatrix} F_x & F_\lambda \\ 0 & 1 \end{bmatrix} \begin{bmatrix} dx \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (12)$$

where F_x, F_λ are the partial derivatives of $F(X, Y)$ with respect to X and l and $\begin{bmatrix} dx \\ d\lambda \end{bmatrix}$ is the tangent vector with all the elements equal to zero except for the k^{th} one which corresponds to the current continuation parameter.

Step 3: The values of dx and dy obtained in step 2 are added with the corresponding initial values assumed in step 1.

$$X(\text{new}) = X(\text{old}) + dx \\ \lambda(\text{new}) = \lambda(\text{old}) + d\lambda$$

Step 4: Once the prediction is made with the tangent vector, the following correction is applied to find the equilibrium point.

$$-\begin{bmatrix} F_x & F_\lambda \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} F(X, \lambda) \\ 0 \end{bmatrix} \quad (13)$$

This iterative process is continued until two consecutive values of ΔX and $\Delta \lambda$ are equal.

Step 5: The corrected values of ΔX and λ are added with the $X(\text{new})$ $\lambda(\text{new})$ to calculate the new equilibrium point.

This process is repeated until voltage collapse occurs.

In equation (9) and (10) F_λ cannot be a null vector even at the base case. In prediction, a relatively larger step is used to trace the point and null d_λ is detected at some point then the step is reduced where bifurcation point is easily detected (Venkataramana Ajjarapu, Quin Wang and Hwachang song, 2006). From (12), it is seen that the tangent vector indicates some kind of sensitivity of the system variables to the current continuation parameter. Since F_λ cannot be null vectors even at the base case ($\lambda=0$) the singularity of the augmented matrix can be easily avoided by appropriately selecting the continuation parameters. Since λ is introduced to parameterize the system generation and load level, it increases monotonically. Hence d_λ is positive before λ reaches it's maximum, and negative afterwards. This can be clearly seen as follows.

If null $d\lambda$ is indicated at some step, then (12) reduces to

$$[F_x] x [dx] = [J_{\text{dyn}}] x [dx] = [0] \quad (14)$$

Since one of the components from dX is ± 1 , $[dX]$ is not a null vector and (14) implies the system is dynamic Jacobian J_{dyn} singular (Zhihong Feng, Venkatramana Ajjarapu and Bo Long, 2000).

4. Simulation results

The mathematical model of the SEIG using equilibrium tracing technique is simulated using the 1.5KW induction machine data given in Table 1. Figure 3(a) shows the stator voltage variation with load parameter for C_{max} . It is observed from the figure that the load parameter at which the voltage collapses is increasing with decreasing speed. For example, generator speed of 1100 rpm, $\lambda = 690$ whereas for 1200 rpm, $\lambda = 302$. Figure 3(b) and Figure 3(c) show the

Table 1. Induction motor rating and parameters

Power	1.5Kw
Voltage	415 V
Speed	1400 Rpm
Frequency	50 Hz
Current	3.4 A
Connection	Star
$R_s \& R_r$	5
$L_{ls} \& L'_{lr}$	30mH
C_{min}	20 μ F
C_{max}	42 μ F
$C_{critical}$	32 μ F

stator voltage variation for $C_{critical}$ and C_{min} . It is further observed that there is a minimum speed for every excitation below which self-excitation fails. The value increases with decreasing capacitance.

5. Comparison with the conventional technique

The simulation of the SEIG is carried out with the conventional iterative method to show the effectiveness of equilibrium tracing technique. In the conventional technique the load is varied in steps after the steady state is reached for every load condition. Figure 4 shows the voltage build up of the SEIG and stator voltage variation for step changes in load at generator speed of 1100 rpm and $C=42\mu F$. It is seen from the figure that at $t=0$, self-excitation begins and voltage builds and reaches the steady state value at about 8 seconds. At time $t=8$ seconds, rated load is applied to study the transient behavior of the stator voltage. It is observed that the voltage decreases until a new steady state is reached at $t=12$ seconds. The various steps in the load cycle are repeated and finally, for a load resistance of 145 ohms, the stator voltage reduces to zero due to excitation failure. The critical value is identified at about 100 seconds, whereas equilibrium tracing technique identified this value within a few milliseconds and the computation time is very much reduced.

6. Experimental results

In the laboratory experiment, the dc motor is used to drive the SEIG. The prime mover speed is kept constant and the load is increased in steps. It is found that the stator voltage decreases with increasing load (decreasing load resistance). The critical load is noted below which the stator voltage becomes zero. The procedure is repeated for different generator speeds and capacitances and the readings are presented in Table 2. The corresponding simulation results using equilibrium tracing technique are also given for comparison. The simulation result closely agrees with the experimental values, thus validating the equilibrium tracing technique for SEIG.

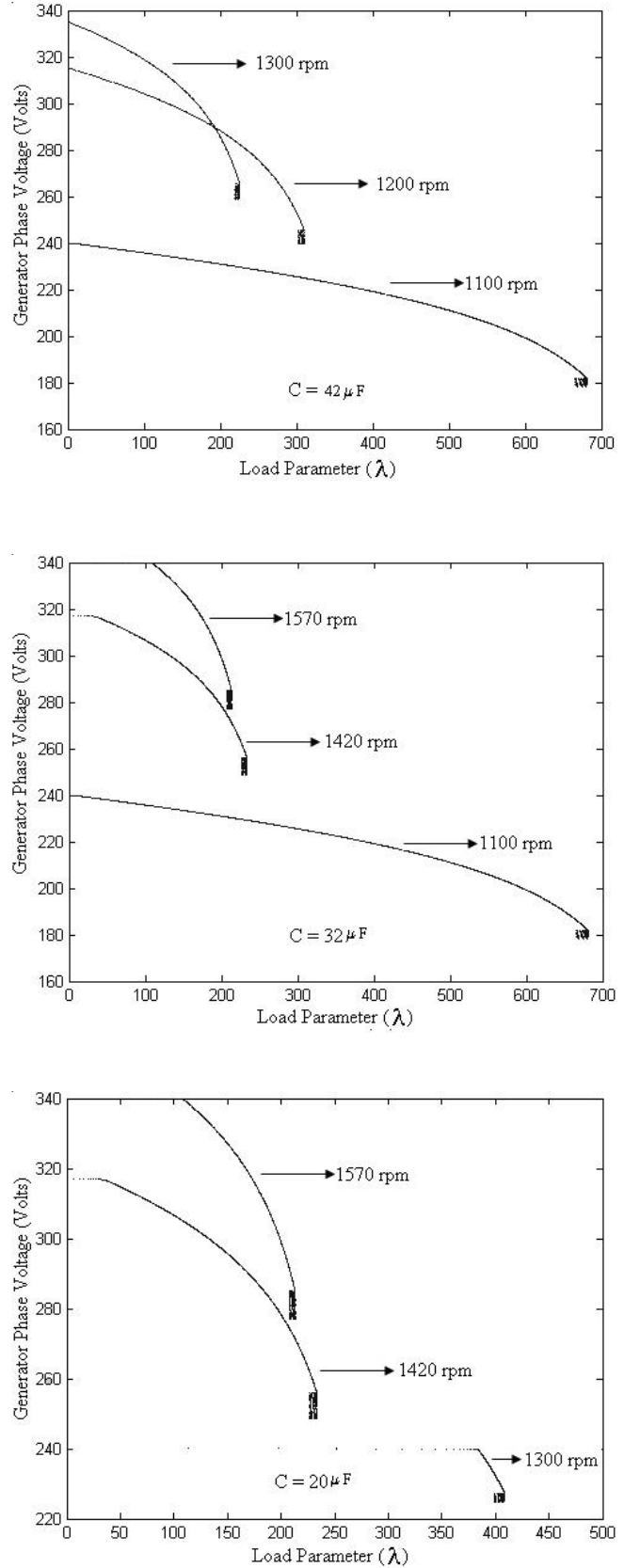


Figure 3. Stator voltage variation with load parameter for an excitation capacitance of (a) 42 μ F (b) 32 μ F (c) 20 μ F

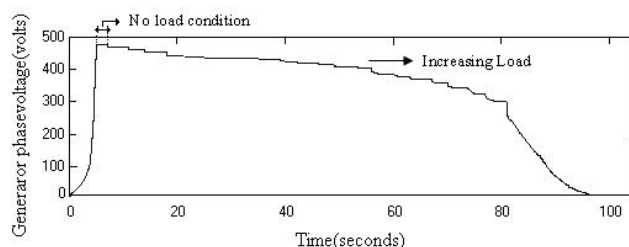


Figure 4. Load voltage variation of the self-excited induction generator using the conventional technique

7. Conclusion

A dynamic model of the SEIG is developed and equilibrium tracing technique is applied to identify the critical load in a single step without many trials. The simulation time for finding the critical value by equilibrium tracing is in the order of milliseconds whereas step-by-step method takes about 100 seconds. Comparing the experimental results with the predicted loads obtained through simulation validates the technique. Therefore, the method can be used for on-line studies when the generator is used as a stand-alone power supply in remote areas.

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Table 2. Load parameter values for excitation capacitances and different generator speeds

Excitation Capacitance (μF)	Generator Speed (rpm)	Generator voltage/phase(volts)		Critical Load(ohms)	
		Simulation	Experimental	Simulation	Experimental
42 μF	1100	169.70	166	145	139
	1200	224.15	220	331	327
	1300	240.42	235	455	450
32 μF	1100	169.70	165	149	145
	1420	224.15	220	440	436
	1570	240.42	234	476	472
20 μF	1300	169.70	165	250	247
	1420	224.15	220	434	429
	1570	240.42	235	483	480

Nomenclature

- R_s = Per-phase stator resistance
 R_r = Per-phase rotor resistance referred to stator
 i_{qs} = Stator q-axis current
 i_{ds} = Stator d-axis current
 i'_{qr} = Rotor q-axis current
 i'_{dr} = Rotor d-axis current
 ω = Arbitrary reference frame speed
 ω_r = Rotor speed in rad/sec
 λ_{qs} = Flux linkages of stator in q -axis
 λ_{ds} = Flux linkages of stator in d- axis
 λ_{qr} = Flux linkages of rotor in q-axis
 λ_{dr} = Flux linkages of rotor in d-axis
 L_{ls} = Stator Leakage reactance
 L'_{lr} = Rotor Leakage reactance referred to stator
 M = Magnetizing inductance of inductance generator
 $C_{min}, C_{max}, C_{critical}$ = Minimum, Maximum, Critical Capacitance