Analysis of the Transient Response of a Capacitor-Excited Induction Generator for Unity Power Factor Load Condition using MATLAB/SIMULINK

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Abstract**—**Advantageous features of an induction generators are widely used in a single system like wind or micro turbo etc. It is operated in a capacitor excited or self excited mode to generate electrical energy in remote areas. The Main drawbacks of a CEIG under variable load conditions are poor voltage and frequency regulation .The aim of this paper is to provide a better understanding of the dynamic response of a capacitor-excited, squirrel cage induction generator that is carried out for determining the change in performance under the running condition from no-load to full-load. Voltage control, frequency control and temperature rise due to continuous running of the machine are evaluated using transient analysis. This assessment would hopefully help to develop a better controlled required for CEIG system, operated in remote areas.

Keywords*- CEIG; Transient Response; poor voltage regulation; self excitation; stand-alone system, capacitor bank*

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I. INTRODUCTION

This is very known fact that day by day energy consumption is increasing very rapidly. The world's fossil-fuel supply i.e coal, petroleum and natural gas will be depleted in few hundred years. As a result we will face a shortage of energy i.e energy crisis. But if we use renewable energy resourses such as solar, wind, wave etc then our daily energy demand can be fulfilled. Availability of such energy resources give a great interest for power generation. Recent trend is to generate electricity by using wind turbines due to its stand alone applications. In wind turbines, induction generators are often used due to their ability to produce useful power at varying speeds and their special features like operating in stand alone mode.

Usually, using of induction generators are increased these days because of their relative advantageous features over conventional synchronous generators. Induction generators are i) simple and rugged construction, ii) requiring no brushes or commutators, iii) low capital cost, , iv) self-protection against external short circuit, v) capability to generate power at varying speed. The induction generator operation in stand-alone mode is required to supply remote districts where extension of grid is not economically feasible. Induction generator are capacitor excited by connecting appropriate capacitor bank across its terminals, and the residual magnetism in rotor initiates voltage build up which is increased by capacitor’s current to cause a continuous rise in voltage. Besides the advantages of using induction generator in stand alone mode, there are a lot of problems associated with CEIG. One of them is poor voltage regulation. The output voltage and frequency basically depend on the prime movers speed, load impedance and excitation capacitance. This paper gives an approach to model performance analysis of the transient response of such generator during the application of upf load.

II. LITERATURE REVIEW

The concept of self-excitation of induction machine emerged for the first time in 1935 when Basset and Potter [1] reported that the induction machine can be operated an induction generator in isolated mode by external capacitor. They concluded that the induction machine with capacitive excitation would build up its voltage exactly as does a dc shunt generators, the final value being determined by the saturation curve of the machine and by the value of reactance of the excitation capacitance. The induction generator can be made to handle almost any type load. Doxey [2] in his paper concluded that the basic requirement for the induction motor work as self-excited induction generator is the leading current of correct magnitude. Sutanto et al. [3] in his paper examined the transient behaviour of a three phase SEIG supplying a symmetrical load. They presented an approach to model performance of induction generators to maintain constant terminal voltage under resistive and reactive loads. They explained a modified and analytical method for determining the range of capacitive VAR requirements for maintaining a constant flux and for obtaining performance with a desired level of voltage regulation. The analysis used the steady state equivalent circuit to predict the performance of the generator. Bansal [4], in his paper, presented an exhaustive survey of the literature over 25 years discussing the process of self-excitation, voltage build-up, modeling, steady-state and transient analysis, reactive power control methods and parallel operation of SEIG. Grantham et al. [5] also considered the steady-state and transient analysis of self-excited induction generator. However Hallenius et al. [6] emphasized the importance of cross saturation during self-excitation. Faiz el al. [7] published a paper regarding the design of a self-excited induction generator by minimizing the rotor resistance and increasing the flux density unti the magnetic circuit of the generator saturated. They concluded the best way to optimize the design of an induction generator is to design an induction machine, which can handle the saturated magnetizing current. Levi and Liao [8] provided a purely experimental treatment of a self-excitation process in induction generators. Jain et al. [9] modeled a delta connected self excited induction generator which could handle symmetrical and unsymmetrical load and capacitor configuration. They also discussed the self excited induction generator behaviour under balanced and unbalanced condition considering the main and cross flux saturation for load perturbation, line to line short circuit, opening of one capacitor and opening of single phase load.

Kuo and Wang [10] discussed that it was convenient to simulate the power electronic circuits using circuit oriented simulators, while equation solvers were more appropriate to simulate the various electric machines and control systems.

III. DEVELOPED SCHEME

The d-q axis model of an induction machine has been widely used in the field of induction motor analysis and control; the model is usually adapted to analyze the machine performance under three-phase balanced conditions.

A schematic diagram of the developed CEIG system is shown in figure (1).

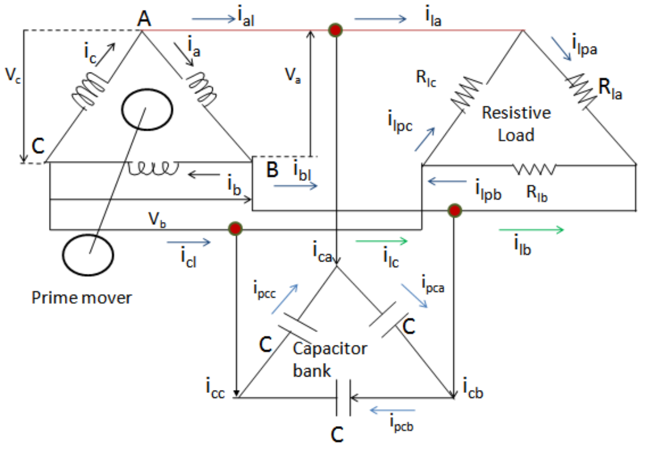

Figure. 1. system configuration

IV. MATHEMATICAL MODELING

The CEIG system consists of an induction generator, capacitor bank and balanced three phase delta connected unity power factor load or resistive load. The mathematical modeling of these system is explained below. Model equations of CEIG are represented by a set of first order non linear differential equations, which are solved to find out the instantaneous values of the desired quantities.

A. Modeling of CEIG

The modeling of the three phase squirrel-cage induction generator is developed by using a stationary d-q axes reference frame and the relevant voltage-current equations of a three phase CEIG are

$$[v] = [R][i] + [L]\mathrm{p}[i] + w_r[G][i]$$

(1)

From which, the current derivative can be expressed as:

$$p[i] = [L]^{-1}\{[v] - [R][i] - w_r[G][i]\} \qquad (2)$$

(2)

Where, $[v]$, $[i]$, $[R]$, $[L]$ and $[G]$ are defined in Appendix I.
The developed electromagnetic torque of the CEIG (T_e) is as

$$T_e = (3\mathrm{P}/4)\, L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \quad (3) \qquad (3)$$

The electromagnetic torque balance equation is as

$$T_{shaft} = \mathrm{J}(2/\mathrm{P}) p w_r + T_e \quad (4) \qquad (4)$$

Where T_{shaft} is the input torque i.e. transmitted to the shaft of the generator from prime mover (typically wind turbine) and T_{shaft} is also can be expressed by,

$$T_{shaft} = \mathrm{a} - \mathrm{b}w_r (5) \qquad (5)$$

The values of 'a' and 'b' for the under test operating as CEIG are given in Appendix I.
The derivative of the rotor speed (w_r) from equation (2.4) is as

$$p w_r = \left(\frac{1}{J}\right)\left(\frac{P}{2}\right)\left(T_{shaft} - T_e\right) \quad (6) \qquad (6)$$

The CEIG operates in the saturation region and it magnetization characteristic is non-linear in nature. Hence the magnetization current (I_m) should be calculated in every step of integration is terms of stator and rotor current as

$$I_m = \frac{\left\{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2\right\}^{\frac{1}{2}}}{\sqrt{2}} \quad (7) \qquad (7)$$

Three-phase currents are obtained by converting direct and quadrature axes components into a, b, c phase currents as follows:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (8) \qquad (8)$$

For the delta connection of the CEIG shown in Fig. 1, the line currents of the SEIG (i_{al}, i_{bl} andi_{cl}) can be expressed in terms of phase currents as:

$$i_{al} = i_c - i_a \quad \ldots\ldots(9)$$

$$i_{bl} = i_a - i_b \quad \ldots..(10)$$

$$i_{cl} = i_b - i_c \quad ...(11)$$

B. Modeling of Capacitor Bank

For delta connection sum of three phase voltages is zero as:

$$v_a + v_b + v_c = 0 \quad (12) \qquad (12)$$

In fig. 1, applying Kirchhoff's current law (KCL) to the static circuit comprising excitation capacitor, consumer load, capacitor line currents equations are as:

$$i_{ca} = i_{pca} - i_{pcc} = Cpv_a - Cpv_c = i_c - i_a - i_{la} \qquad (13)$$

(13)

$$i_{cb} = i_{pcb} - i_{pca} = Cpv_b - Cpv_a = i_a - i_b - i_{lb} \qquad (14)$$

(14)

$$i_{cc} = i_{pcc} - i_{pcb} = Cpv_c - Cpv_b = i_b - i_c - i_{lc} \qquad (15)$$

(15)

Where currentsi_{la}, i_{lb} and i_{lc} are the line currents of delta connection load.

Using the equation (12), equations (13) to (14) reduce to two equations in terms of derivative of phase voltages as:

$$(C + C)pv_a + Cpv_b = i_{ca} \qquad (16) \qquad (16)$$

$$Cpv_a + Cpv_b = i_{cb} \qquad (17) \qquad (17)$$

Solving equations (16) and (17) for derivatives of AC line voltages as:

$$pv_a = \{Ci_{ca} - Ci_{cb}\}/K_{eq} \qquad (18)$$

$$pv_b = \{Ci_{ca} - (C + C)i_{cb}\}/K_{eq} \qquad (19)$$

$$\text{Where } K_{eq} = 3C^2 \qquad (20)$$

For balanced excitation, with equal excitation capacitors: Equation (18) and (19) simplify to:

$$pv_a = \frac{\{i_{ca} - i_{cb}\}}{3C} = \{(i_a - i_{la}) - (i_b - i_{lb})\}/(3C) \qquad (21)$$

$$pv_b = \frac{\{i_{ca} - 2i_{cb}\}}{3C} = \{(i_a - i_{la}) - 2(i_b - i_{lb})\}/(3C) \qquad (22)$$

From three phase voltages (v_a, v_b, v_c) of the CEIG obtained by solving (21), (22) and (12), the d- and q-axes voltages in the stationary reference frame are as follows:

$$v_{ds} = (2/3)\left\{v_a - \left(\frac{v_b}{2}\right) - \left(\frac{v_c}{2}\right)\right\} \qquad (23)$$

$$v_{qs} = (2/3)\left\{\left(\frac{\sqrt{3}v_b}{2}\right) - \left(\frac{\sqrt{3}v_c}{2}\right)\right\} \qquad (24)$$

C. Modeling of Unity Power Factor Load

For the three phase-phase resistive load, the model equations for line currents from fig. 1 are defined as follows:

$$i_{la} = \left(\frac{v_a}{R_{la}}\right) - \left(\frac{v_c}{R_{lc}}\right) \qquad (25)$$

$$i_{lb} = \left(\frac{v_b}{R_{lb}}\right) - \left(\frac{v_a}{R_{la}}\right) \qquad (26)$$

$$i_{lc} = \left(\frac{v_c}{R_{lc}}\right) - \left(\frac{v_b}{R_{lb}}\right) \qquad (27)$$

The line currents of the load are defined in terms of phase currents as:

$$i_{la} = i_{lpa} - i_{lpc} \qquad (28)$$

$$i_{lb} = i_{lpb} - i_{lpa} \qquad (29)$$

$$i_{lc} = i_{lpc} - i_{lpb}$$

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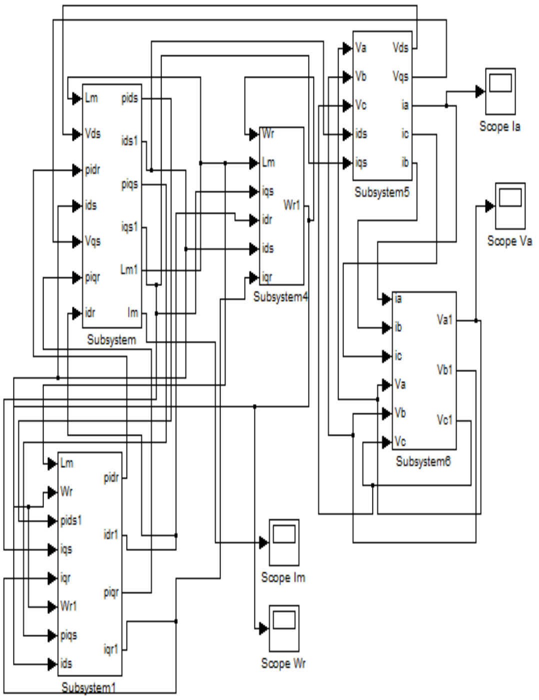
V. SIMULINK MODEL OF A WHOLE SYSTEM

To perform the analysis of the CEIG system, we need to develop a model by using the mathematical equations, derived in the previous section. For this purpose we have used MATLAB/SIMULINK, which is considered as a useful software tool for modeling and simulation purposes. The overall proposed SIMULINK model of CEIG has been implemented by using different blocks, which are developed to represent the corresponding equations.

CEIG system model



VI. RESULTS AND DISCUSSIONS

Since the studied CEIG must be excited by injecting a leading reactive power into the stator, a fixed capacitor bank with 50µF/phase is used to supply the required reactive power under the over-excitation condition, which ensures the generated voltage can be sustained under a no-load condition. The analysis of the CEIG system is illustrated using the following conditions.

1. A three-phase balanced unity power factor load that remains constant throughout the simulation. The resistance value of each phase is 5 kilo-ohm. It is used to simulate the no-load condition of the CEIG system.

2. A three-phase balanced unity power factor load that decreases after a certain time from 5kilo-ohm to 300 ohm to perform the transient analysis and observe the change in voltage and current waveforms during this time period.

For the first condition, the waveform of the magnetizing current of the CEIG is shown in fig. 2. The developed phase voltage across the stator terminals due to application of AC supply is illustrated in the fig. 3. The stator phase current is also represented in fig. 4 to represent the current waveform under no-load condition.

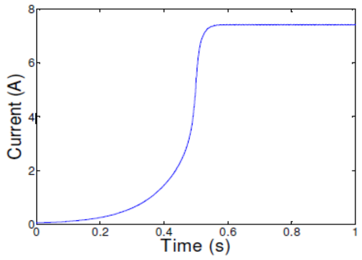


fig. 2**:** Magnetizing current under no-load condition

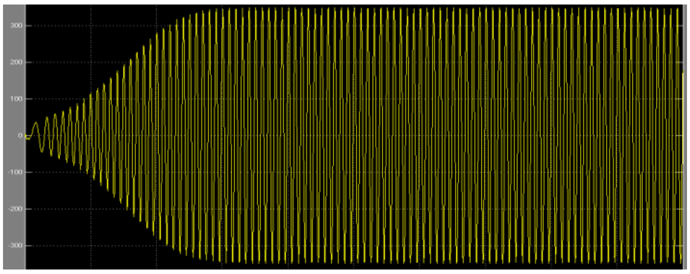


fig. 3 : Developed Phase Voltage across the stator terminals of CEIG under no-load Condition

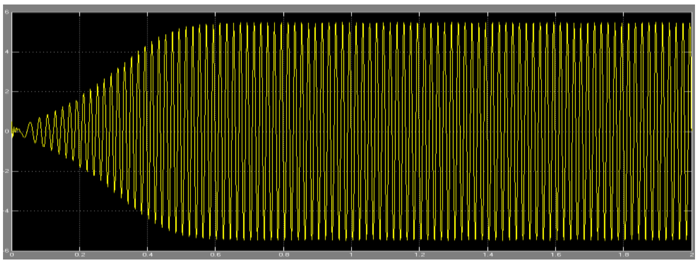


fig. 4 Phase current through the stator terminals of CEIG under no-load condition

The CEIG takes 0.6 sec to build up the rated voltage. Initially the voltage is at very low value. It increases rapidly and reaches the steady state value due to saturation of the magnetization characteristics.In fig. 3 and 4, the waveform of phase voltage and current reach the steady-state when t=0.7 sec. and attains their steady-state peak value of 349.282V and 5.48A respectively.

For the second condition, a sudden change is employed in the balanced three-phase upf load to observe the transient responses of CEIG. During the simulation of the model the resistive load in each phase is changed from 5 kilo-ohm to 300 ohm after t=2.0 sec. and as a result the changes in phase voltage and phase current obtained from MATLAB/SIMULINK are shown in fig.6 and fig..7 respectively. The corresponding waveform of magnetizing current under this condition are exhibited in fig. 5.

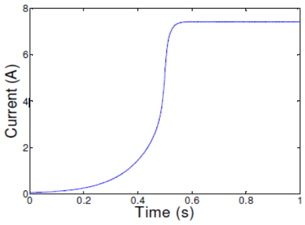


fig. 5: Magnetizing current at transient condition

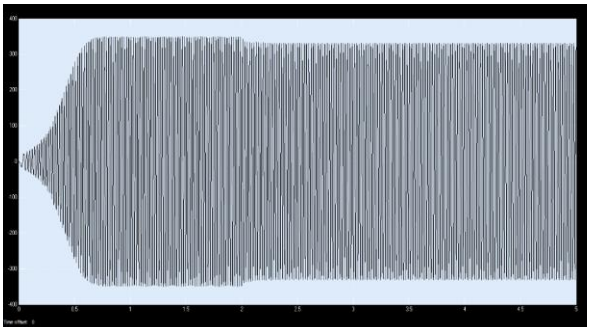


fig 6: Phase voltage across the stator terminals of CEIG at transient condition

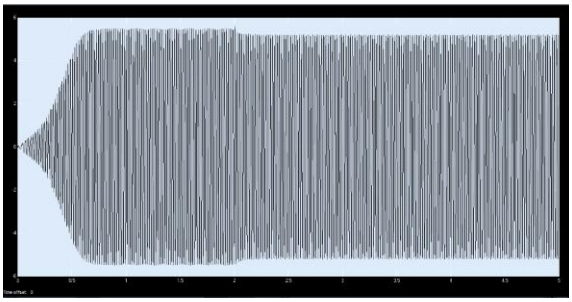


fig.7 Phase current through the stator terminals of CEIG at transient condition

The transient behavior of CEIG system can be observed due to the MATLAB/SIMULINK simulation of the CEIG system model from fig. 6. and fig. 7.

Fig. 6 illustrates the transient waveform of CEIG phase voltage (v_a, v_b and v_c) during the voltage buildup of the CEIG. We can observe when suddenly applied unity power factor load, peak phase voltage reduces to 331.5635V form 349.282V after t=2.388 sec. From t=2.0 sec. to t=2.388 sec. the system exhibits transient responses and after t=2.388 sec. the system reaches to its steady-state condition for the new applied resistive load.

A similar transient waveform can also be observed in case of phase current (i_a, i_b and i_c) through the terminals of CEIG (in fig. 7). Due to the change in load, the peak value of the phase current reduces to 5.2A from 5.48A.

VII. CONCLUSION

The cost and simplicity of an induction generator offers many advantages in today’s renewable energy industry. The limitation of an induction generator can be overcome by connecting a three-phase capacitor bank to its stator terminals.

This paper presents an analysis of the transient response of capacitor-excited induction generator (CEIG) when operating in stand-alone mode, subject to balanced unity power factor loading conditions. Transient analysis has been carried out for simulating time domain response of a three-phase CEIG under three-phase unity power factor balanced load condition. Dynamic models are developed using d-q axes stationary reference frame for determining transient response condition.The developed model is tested by simulating the transient response for certain application of three-phase upf loads. Voltage drop with load occurs as expected. The transient analysis plays a vital role to predict the operation of CEIG to obtain better performance.

VIII. APPENDICES

Appendix-1: Parameters of CEIG

Parameters of CEIG 2.2 kW, 230 V, 50 Hz,7.8 A, 4-pole, 3-ph squirrel cage induction machine is operated at capacitor excited mode.

The parameters are as follows:

P = 4;

Lls = 0.0142H/14.2mH;

Llr = 0.0142H/14.2mH;

Rs = 2.88Ω;

Rr = 2.88Ω;

C = 0.00005F/50µF;

J = 0.0842kg/sq. m;

Coefficients in the shaft torque equation of the generator (i.e. $T_{shaft} = a - bw_r$) as

a = 249.39;

b = 0.7875;

Appendix-2: Main Equations and Matrices

Matrices of (1) are defined as

$[v] = [v_{ds}\ v_{qs}\ v_{dr}\ v_{qr}]^T$

$[i] = [i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}]^T$

v_{dr} and v_{qr} , are zero since the rotor terminals are short-circuited in the squirrel cage induction generator.

[R], [L] and [G] in (1) represents 4x4 matrices of resistance, transformer inductance and speed inductance respectively, and are defined as

$$[R] = \mathrm{diag}[R_s\ R_s\ R_r\ R_r]$$

$$[G] = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & -L_{rr} \\ L_m & 0 & L_{rr} & 0 \end{pmatrix}$$

$$[L] = \begin{pmatrix} L_{ss} & 0 & L_m & 0 \\ 0 & L_{ss} & 0 & L_m \\ L_m & 0 & L_{rr} & 0 \\ 0 & L_m & 0 & L_{rr} \end{pmatrix}$$

Where, $L_{ss} = L_{ls} + L_m$

and $L_{rr} = L_{lr} + L_m$

Magnetizing Characteristic

$$L_m = 0.3177 \quad (\text{for } I_m \le 0.75)$$

$$= 0.3502 - 0.0349\ I_m + 0.0017\ I_m^2 \quad (\text{for } 0.75 < I_m \le 4.25)$$

$$= 0.17677 \quad (\text{for } I_m > 4.25)$$

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