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Transient Analysis of Wind Driven Self-Excited Induction Generator under Different Fault Conditions

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ABSTRACT

This paper deals with the transient performance of a self excited induction generator in a wind power plant under different fault conditions. An induction generator and grid equipment may be damaged when a sudden disturbance occurs, for example, a sudden disconnection from the utility grid. The reasons for this are over-voltage and over speed. This paper also made an analysis when there is sudden disconnection of self excitation capacitance .This paper analyzes this phenomena using MATLAB/SIMULINK and coincides with its corresponding mathematical equation. Response of the system to disturbances reveals its excellent transient performance. The system has a good overload capability and is free from operational problems related with short circuit and loss of excitation.

Keywords-SEIG(Self-Excited Induction Generator), Wind Power, MATLAB/SIMULINK, short circuit,excitation capacitance.

1. INTRODUCTION

It is well known that a three-phase induction machine can be made to work as a self-excited induction generator, when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced at its terminals. In a small wind power plant or hydro power plant, the use of a three-phase self-excited induction generator (SEIG) is essential. An SEIG provides capacitor banks to compensate for the power factor, and the active power controller and the reactive power controller are coupled, unlike a synchronous machine. This means that the control of an SEIG is complex; an SEIG can be damaged by overvoltage due to capacitors. In this paper, several phenomena that can be generated in an SEIG under different fault conditions are analyzed. The main objectives of this study were:

• To investigate the influence of different capacitors on over-voltage, resulting from fault or AC network disconnection.

• To derive the planning guidelines for operation of an induction generator.

Three-axes to two-axes transformation is used in the calculation of the dynamic frequency value. Here, the transformation is used to simplify the calculation. The current, speed, torque and voltage generated by the SEIG is also given in this paper. To demonstrate several phenomena of induction generators, MATLAB/SIMULINK was used.

2. MATHEMATICAL MODELLING OF AN SELF EXCITED INDUCTION GENERATOR

The computation is based on model equations (with the usual assumptions**),** referred to **a** quasi stationary d-q reference frame of a poly phase induction machine circuit model shown in Fig. 1.

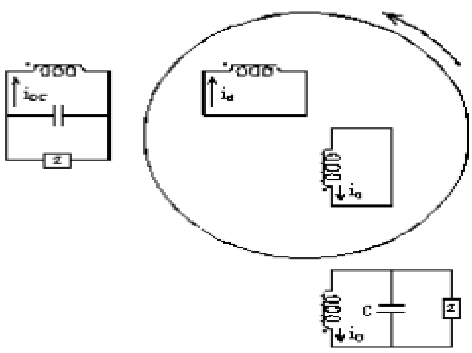


Fig.1. D-Q Model of Induction Generator

The initiation of the self-excitation process is a transient phenomenon and is better understood if the process is analyzed using instantaneous values of current and voltage. Thus, a stationary reference frame will be used to represent the transient analysis of the self-excited induction generator. The stationary reference frame representation of a loaded self-excited symmetrically connected induction generator is shown in Fig. 1 where Z can be one of the following cases:

(a) Z = R + pL (inductive load)

(b) Z = R (pure resistive load)

(c) Z = ∞ (no load)

(d) Z = R + $\frac{1}{pC}$ (capacitive load)

2.1.Model Equations

There are two sets of differential equations to be solved to get transient response of the SEIG.

2.1.1. Machine Side Equations

For a representative impedance Z, the voltage equations may be expressed as:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_1 + L_1 p + \frac{1}{pc} & 0 & Mp & 0 \\ 0 & R_1 + L_1 p + \frac{1}{pc} & 0 & Mp \\ Mp & \omega M & R_2 + L_2 p & \omega L_2 \\ -\omega M & Mp & -\omega L_2 & R_2 + L_2 p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (1)$$

The mathematical equation that relates the wind turbine output torque with the electromagnetic torque of the induction generator is given by:

$$T_m = J\frac{d}{dt}\omega_m + \beta\omega_m + T_e \quad (2)$$

Where V_{qs}, V_{ds}, i_{qs} and i_{ds} are the stator voltages and currents respectively. V_{qr}, V_{dr} are the rotor voltages. λ_{qr} and λ_{dr} are the rotor fluxes. R_s, L_s, R_r and L_r are the resistance and self inductance of the stator and the rotor respectively. L_m is the mutual inductance. ω_m, J, β are the mechanical angular speeds of the wind turbine, the effective inertia of the wind turbine, the induction generator and friction coefficient respectively. Since no external voltage is applied and the rotor is short-circuited, the direct-axis stator current will be

$$i_D = \frac{0}{\left(R_1 + L_1 p + \frac{Z}{1+ZpC} - \frac{M^2\delta p}{\Delta}\right)^2 + \left(\frac{M^2\omega R_2 p}{\Delta}\right)^2} \quad (3)$$

Where $\delta = L_2p^2 + R_2p + \omega^2 L_2$ and $\Delta = (R_2 + L_2p)^2 + (\omega L_2)^2$

The characteristic equation which represents the self excitation process of an induction generator and which satisfies all types of loads, is obtained from equation 1 as

$$A_4f^4 + A_3f^3 + A_2f^2 + A_1f + A_0 = 0 \quad (4)$$

The self-excitation process will start when the polynomial presented in equation (4) has one root having a positive real root

$$C_e = \frac{af+b}{cf^3+df+e} \quad (5)$$

The computed results reveal that there exist critical values of load impedance or speed below which the induction generator fails to excite irrespective of the value of capacitance used.
The values of constants a,b,c,d,e are given in the APPENDIX.

2.1.2. Load Side Equations

$$[V_s] = R_L p[V_e] + (l/Ce)[V_e] \quad (6)$$

Where $[V_s] = [V_{sd}\ V_{sq}]^T$

2.1.3. Analysis of SEIG with unbalance in self excited capacitance

When the induction machine operates as a motor or a grid connected generator, it assumes voltage and frequency from the grid. The machine side equations given in are sufficient to evaluate transient performance of the machine in these two modes. Thus, there are five unknown variables i.e. currents and the speed to be solved from five first order differential equations. But in the case of an SEIG, there will be four additional variables involved (d and q components of charges)for the external excitation, thus making a total of nine variables to be solved from nine first order differential equations. The model equations for the prediction of transient performance of the short shunt SEIG can now be written in a form, solvable by computer simulation as follows:

$$\left.\begin{aligned} & p[i] = [L]^{-1}\{[V][R][i] - \omega_r[G][i]\} \\ & p[\omega_r] = \frac{2}{J}(T_{shaft} - T_e) \\ & p[V_e] = \frac{1}{R_L}\{[V_s] - \frac{1}{C_e}[V_e]\} \end{aligned}\right\} \quad (7)$$

2.2 Analysis of SEIG with unbalance in self excited capacitance

The contribution of this paper is also to derive the dynamic equations of a SElG under unbalance excitation capacitors using a three-phase induction-machine model .Experimental results obtained from a laboratory 3.5 kW induction machine and three excitation capacitors are also performed and compared with the simulated results. Transient responses of the studied SEIG subject to sudden disconnection of one or two of the excitation capacitors are investigated.

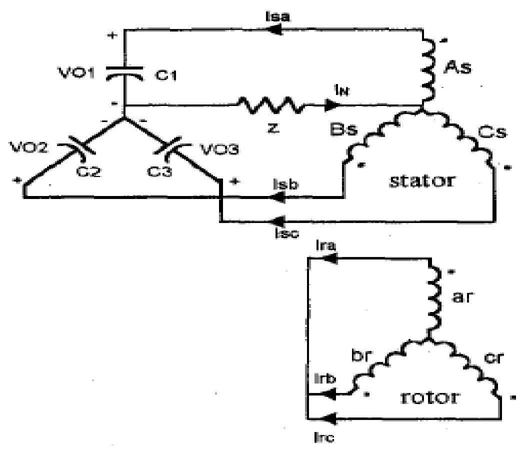


Fig.2. Three phase connection diagram of a SEIG with excitation capacitors

2.3. Machine model

Fig. 2shows the three-phase connection diagram of a SEIG connected with an excitation capacitor bank. The Stator and rotor windings of the induction machine and the excitation capacitor bank are all Y-connected. The output terminals of the rotor windings are short-circuit together. The neutral points of the stator windings and the excitation capacitor bank are connected through a neutral line with impedance of Z. Such connection structure is the well known three-phase four-wire system. It is worth noting that the three excitation capacitors, C_1,C_2, and C_3, shown in Fig. 2 may have different values and, consequently, the unbalanced self excitation of the SEIG will happen. One the other hand, the three excitation capacitors may be independently switched off and, hence, the resulting self excitation can be obtained by only one capacitor or two capacitors. To clearly examine the transient performance of the SEIG under different excitation capacitors and suddenly switching off the excitation capacitors, the dynamic equations of the machine and excitation capacitors must be derived.

The v-i equations of the three excitation capacitors can be expressed as below.

$$\left.\begin{aligned} &(C_l).pV_{01} = I_{sa} \\ &(C_2).pV_{02} = I_{sb} \\ &(C_3).\ pV_0 = I_{sc} \end{aligned}\right\} \quad (8)$$

All quantities in the above equations are based on SI units. Proper system bases may be selected to transform them to per-unit quantities.

3. System Description and Simulation

Fig. 3 shows the system studied. The simulation cases were:

a. The simulation cases were:
b. The influence of the CB disconnection
c. The influence of the capacitor
d. The influence of the load rate of the induction generator
e. The influence of the induction generator according to fault kinds

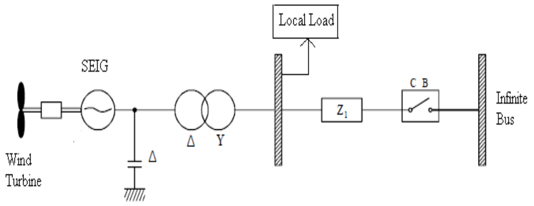


Fig.3 System Model for Study

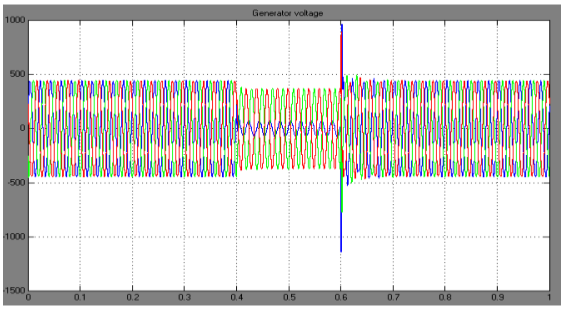
4. Transient Analyses under Different Unbalanced Conditions

In this section, transient responses are presented using the proposed approaches will be described with MATLAB/SIMULINK under different unbalanced conditions. To have detailed simulations, two computer programs with different state variables are respectively employed to simulate the transient performance of the SEIG subject to sudden disconnection of excitation capacitors, sudden loading and short circuit.The following figure shows the responses under different unbalanced conditions. Three capacitors are selected to be C_1= C_2 = C_3 =15μF.

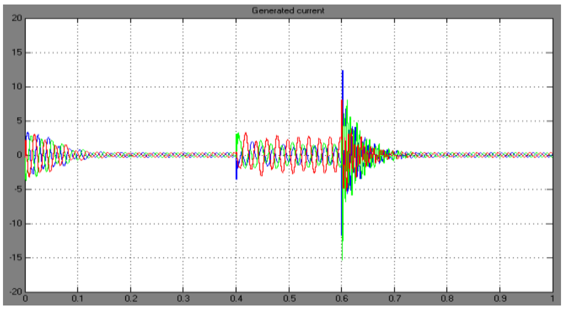
In this section, initially transient behavior of sudden application of load at grid connected to SEIG is studied, followed by that of the short circuit at grid and the sudden disconnection of one excitation capacitance.

4.1.Load Perturbation

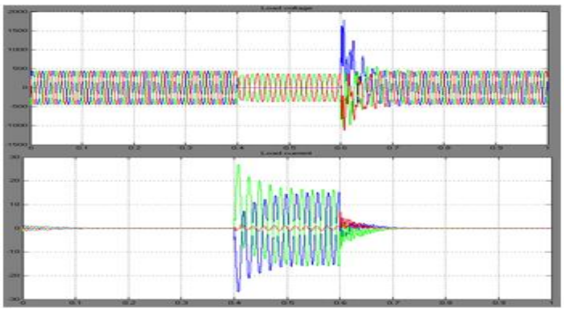
Fig. 4 shows the transient response of the system on the sudden application and removal of load after the SEIG is brought up to rated voltage at no load.



(a) Generated voltage



(b) Line current



(c).Load voltage and load current

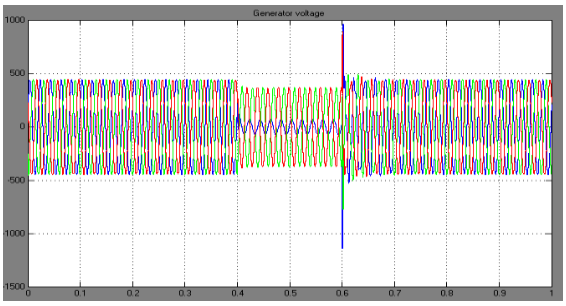
Fig.4.Response of SEIG under load perturbation condition

As can be seen, the voltages and currents settle to respective new steady state values, revealing the high over load capability and good transient stability of the SEIG. For this load, the winding current and the load voltage are 5amp and 320volts, respectively. Again, during application and removal of the load, there is no severe voltage/current dip/overshoot. Fig.4 shows the results of the simulation of the CB disconnection for wind power. In Fig. 4 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator. The application of load is in between 0.4 to 0.6secs.

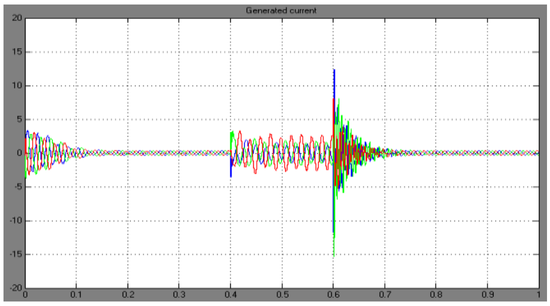
4.2. Sudden short circuit

From the above observations, it can be easily predicted that the SEIG can not sustain self excitation on a short circuit across the load. As shown in Fig. 5, on the application of a three-phase short circuit across the load, there is a sudden rush of current of very short duration, magnitude of which depends upon the voltage existing at the capacitor terminals at the instant of short circuit. No appreciable surges are noticed in the voltage, which collapses almost immediately as the machine de-excites. Although, in some cases loss of excitation of the SEIG due to overload or short circuit may be of advantage, it could be disastrous in application like aircraft's power supplies. The problem is further aggravated by the uncertainty of the machine to re-excite after a short circuit, unless some charge is provided. This is a crucial aspect to be tackled in the operation of the SEIG under field conditions. Users in far flung areas have often reported difficulty in re-exciting the generator after short circuit t or sustained overloading, as a major hurdle affecting continuity and reliability of the supply. Also, the de excitation of the machine is so fast that it is not capable of adequately sustaining the fault current, to trip the over current protective devices. Thus, for many critical applications, some type of excitation support system is required f o r self excited generators. These systems, often referred as field forcing schemes , produce more than rated generator current for sufficient t time to ensure that the fault are cleared quickly and selectively enough to preserve the integrity of the power system.

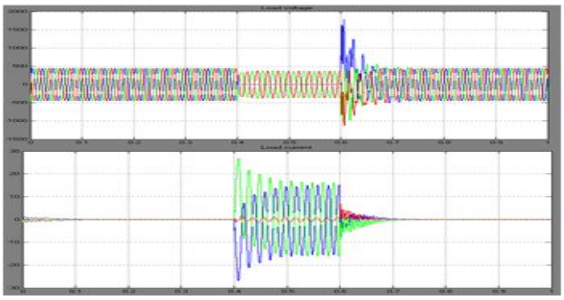
Fig. 5 shows the transient response of the system on the short circuit at load after the SEIG is brought up to rated voltage. As can be seen, the voltages and currents settle to respective new steady state values, revealing the high over load capability and good transient stability of the SEIG. For this load, the winding current and the load voltage are 8ampers and 350volts, respectively. Again, during application and removal of the load, there is no severe voltage/current dip/overshoot. Fig.4 shows the results of the simulation of the three phase short circuit at three phase load. In Fig. 5 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator. The short circuit is applied in between 0.4 to 0.6secs.



(a) Generated voltage



(b) Line current



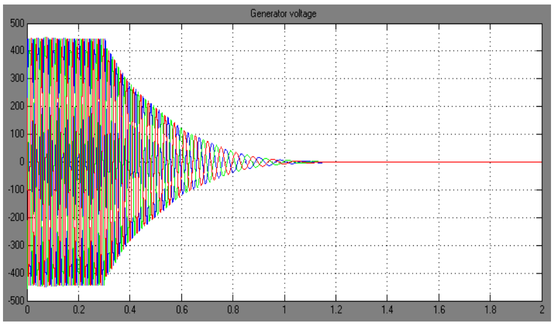
(c).Load voltage and load current

Fig.5.Response of SEIG under sudden short circuit at load condition

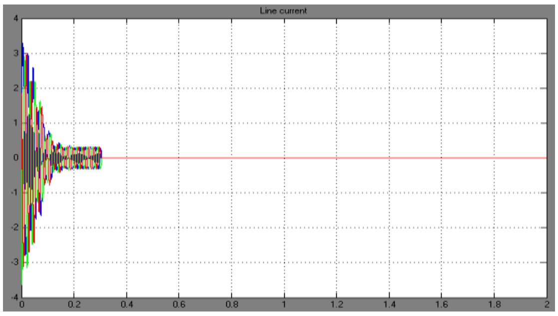
4.3. Sudden disconnection of excitation capacitance

Figs.6 shows the transient responses of simulated results of the loaded SEIG subject to a sudden Switching off the self excited capacitor under the loading conditions .From these figures we can clearly find out that the responses of case connected to grid, quickly reach zero value at about t =1.2sec.When the excitation capacitor is switched off, the capacitive load provides some limited source of excitation and thus time delays the transition from saturated state and the corresponding changes in X_m. For this case the self excitation capacitance is disconnected from the machine after it reaches steady state condition. Since the excitation capacitance is disconnected the machine losts its generating mode. Hence the speed is decreased from the super synchronous speed to the speed of the wind turbine. Because of the lost of generating mode now the generated voltage and line current is also becoming zero. Due to this the active and reactive power is also zero.The response curves of the taken condition are as shown in the fig.6.Capacitors are disconnected at t=0.3sec.

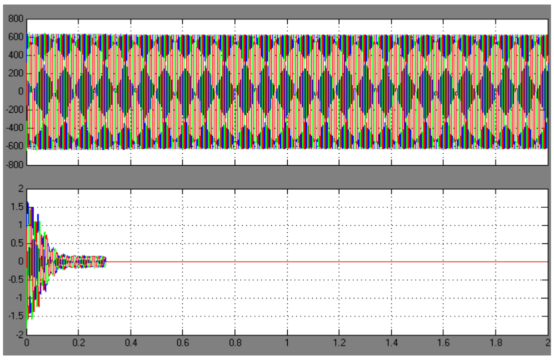
In Fig. 6 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator.



(a) Generated voltage



(b) Line current

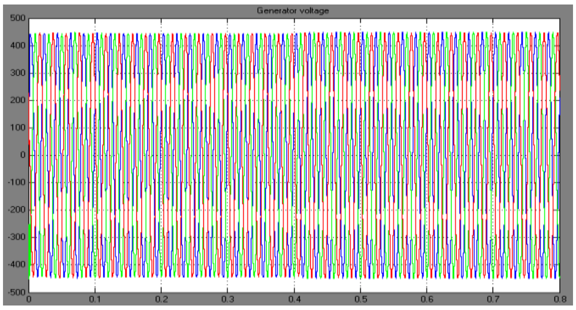


(c)Load voltage and load current

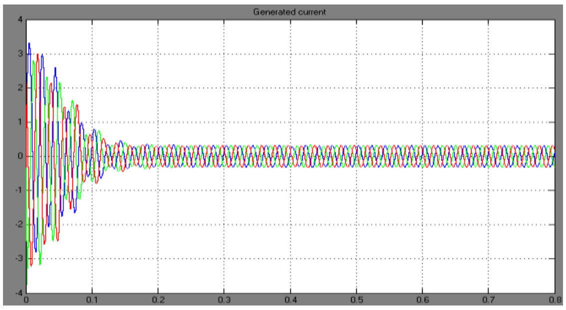
Fig.6.Response of SEIG under sudden disconnection self excitation capacitance

4.4. Sudden disconnection of load

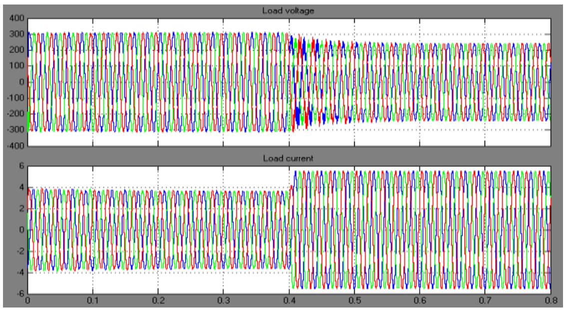
Figs. 7shows the response of SEIG under sudden disconnection of grid and is based on the simulated results. The new steady state values can be quickly reached when the load is suddenly switched off. It is seen that without any voltage or current surge, the generator quickly settles to a new steady state condition. In Fig. 7 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator. The disconnection of load from the SEIG is at t=0.3sec.



(a) Generated voltage



(b) Line current



(c) Load voltage and load current

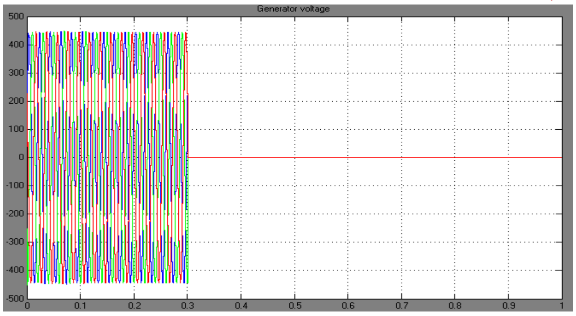
Fig.7.Response of SEIG under sudden disconnection of load

4.5. Sudden short circuit at machine terminals

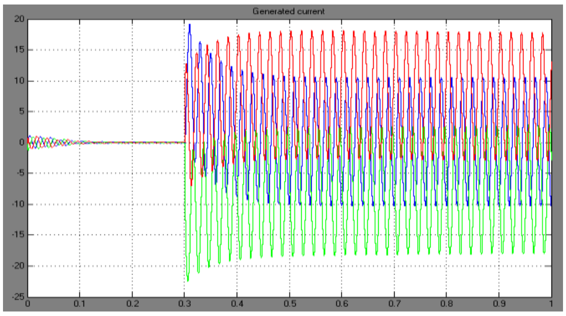
This case is similar to the short circuit described for simple shunt SEIG, wherein the machine immediately de excites and the voltage collapses, as seen from Fig.8.

In Fig. 8 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator. The short circuit is applied at t=0.3sec and reaches to zero voltage at t=0.3sec.

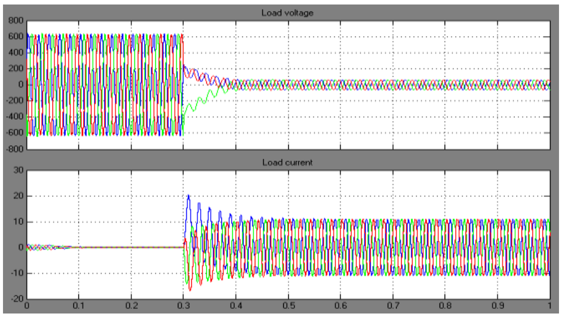
From these figures we can clearly find out that the responses of case of sudden short circuit at machine terminals, quickly voltage reach to zero value at about t =0.3sec.And after that the machine will not be recovered till the end of the operation.



(a) Generated voltage

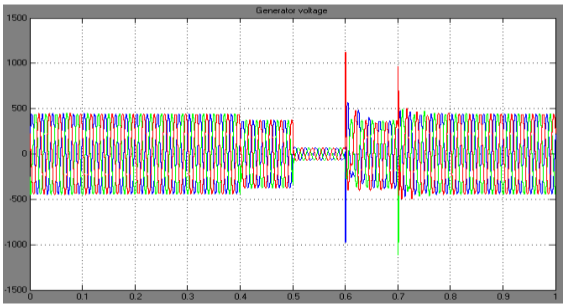


(b) Line current

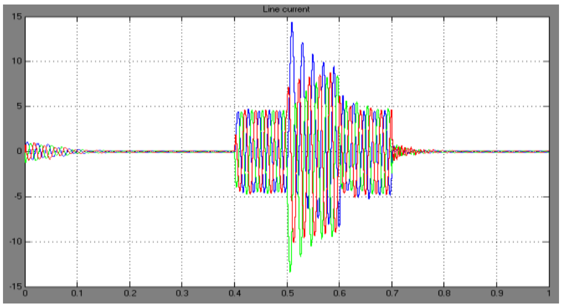


(c) Load voltage and load current

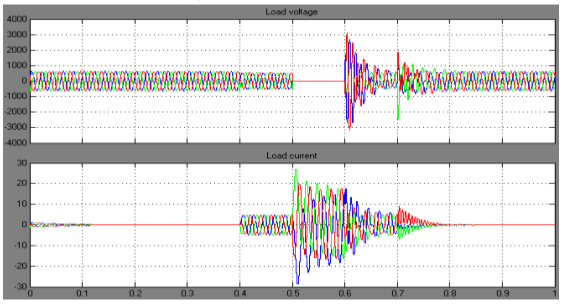
Fig.8.Response of SEIG under sudden disconnection of load



(a) Generated voltage



(b) Line current



(c) Load voltage and load current

Fig.9.Response of SEIG under sudden disconnection of load

4.6. Sudden application of load along with the short circuit at load

Fig.9. shows the transient response of the SEIG when sudden application over load and short circuit at load. This is done as soon as the voltage reaches to the voltage of 440volts and steady state value. The overload is applied at t=0.4sec to 0.7seconds and short circuit is applied at t=0.5 to 0.6sec.

In Fig. 9 (a) is the generated voltage of the induction generator, (b) is the line current of the induction generator (c) is the load voltage and load current of the induction generator.

With the application of two faults at the load on the same time the machine will under go several changes and the several fluctuations in the behavior of the machine as shown in Fig. Sometimes the machine spoil under these faults application for a long time.

5. SOLUTION FOR ALL PROBLEMS

Several methods are there to avoid the over-voltage etc...If we consider the factors as unbalanced fault, unbalanced load, unbalanced capacitor, harmonic current and power factor, the best solution is shown in Figure 10.is SEIG with the STATCOM

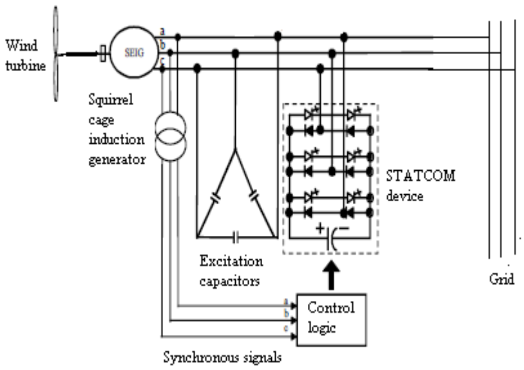


Fig.10. SEIG with STATCOM

6. CONCLUSIONS

The transient analysis of the machine we studied was analyzed to determine the effects of various conditions on the SEIG. The specific conclusions of this paper are as follows:

- The simple shunt SEIG not only has poor voltage regulation and low overload capability but it also suffers from problems related with loss of excitation, re-excitation and short circuit.
- If the short circuit occurs at the load, the machine sustains excitation and settles to a steady state condition, at higher voltage and current. The sustained fault current obviates the need to employ a separate excitation support system shunt SEIG.
- The machine can self excite even when load is already connected across it s terminals.
- Even after loss of excitation due to short circuit across the machine terminals, the machine rebuilds its voltage on the removal of fault and the builds up process is faster if the load is momentarily shorted.
- If the capacitors reactive power is equal to that absorbed by the machine, there is no change after the switch is opening.
- When one-phase fault is suddenly generated from the machine's terminals, the machine's phenomena are similar to a synchronous machine
- Self excitation occurs always when capacitive power remains connected to the generator, after its separation from the grid, provided a torque applies on the shaft. The RMS value of the voltage depends on the load condition and the capacitance, while the total power factor of the feeder line should also be considered.

Thus, excellent transient response of the system, establish the suitability y of the SEIG for a sinple, rugged and self regulated generating system connected to grid.

7. APPENDIX

- To compute the coefficients A_4 to A_0 of equation (4),the following equations are first defined:

$a=2\pi k(L_M r_1+L_1 r_1+L_2 r_1+L_M r_2+L r_2+r_L L_M+r_L L_2)$;

$b=-2\pi N^* r_L(L_M+L_2)$

$c=-8\pi^3 k(L L_M r_1+L L_2 r_1+L L_M r_2-r_L L_1 L_M-r_L L_2 L_M)$

$d=-8\pi^3 N(r_L L_1 L_M+r_L L_2 L_1+r_L L_2 L_M+L L_2 L_M)$

$e=-2\pi k r_L r_1 r_2$

$g=-4\pi^2 k(L_1 L_M+L_1 L_2+L_2 L_M+L L_M+L L_2)$

$h=4\pi^2 N(L_1 L_M+L_1 L_2+L_2 L_M+L L_M+L L_2)$

$i=r_1 r_2+r_L r_2$

$j=-16\pi^4 k(L L_1 L_M+L L_2 L_M+L L_2 L_1)$

$l=16\pi^4 N(L L_1 L_M+L L_1 L_2+L L_2 L_M)$

$m=4\pi^2 k(L r_1 r_2+r_L L_M r_1+r_L L_1 r_2+r_L L_1 r_2+r_L L_2 r_1+r_L L_m r_2)$

$p=-4\pi^2 N r_L L_M r_1;$

$A_4=cg-aj$

$A_3=dg+hc+-al-bj;$

$A_2=eg+hd+ic-ma-bl;$
$A_1=he+id-pa-bm$
$A_0=ie-bp;$

- The induction machine was three, phase3.5kW, 415V, 7.5A, 1500r.p.m, star connected stator winding. The machine was coupled to a wind turbine to provide different constant speeds. A 3-Φ variable capacitor bank or a single capacitor was connected to the machine terminals to obtain self-excited induction generator action.
  The measured machine parameters were:
  $r_1=11.78\Omega$; $r_2=3.78\Omega$; $L_1=L_2=10.88H$. $L_m=227.39H$ and capacitance $C=15\mu F$.
- The piecewise linearization of magnetization characteristic of machine is given by:

$E_1=0 \qquad X_m\geq 260$
$E_1=1632.58-6.2X_m \qquad 233.2\leq X_m\leq 260$
$E_1=1314.98-4.8X_m \qquad 214.6\leq X_m\leq 233.2$
$E_1=1183.11-4.22X_m \qquad 206\leq X_m\leq 214.6$
$E_1=1120.4-3.9.2X_m \qquad 203.5\leq X_m\leq 206$
$E_1=557.65-1.144X_m \qquad 197.3\leq X_m\leq 203.5$
$E_1=320.56-0.578X_m \qquad X_m\leq 197.3$

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