SELF EXCITED INDUCTION GENERATOR

Topic: Steady state performance analysis of Self excited induction Generator.

Analysis to determine the frequency and magnitude of the terminal voltage developed across the stator terminals under steady state for a given set of values of load ,capacitance and speed and consequently to carry out its performance analysis i.e estimation of efficiency,power factor etc.

If an appropriate three phase capacitor bank is connected across an externally driven induction motor, an emf is induced in the windings due to the excitation provided by the capacitor.

This phenomenon is termed as " **Capacitor Self Excitation "** **.**

Motivation :

Since approximately 20% of the total electrical energy generation is done through renewable energy resources throughout the world, it becomes imperative to get equipped with the knowledge of working of induction generators .Remaining 80% of the total electrical energy generation is done through the conventional alternators.

Since isolated and distributed energy generation has gained tremendous importance over the years, it is important to have a fair knowledge on the so -called ' **Self Excited Induction generator ' or ' Separately Excited Induction generator '.**

Power Relations :

Hydro : P = pgQH

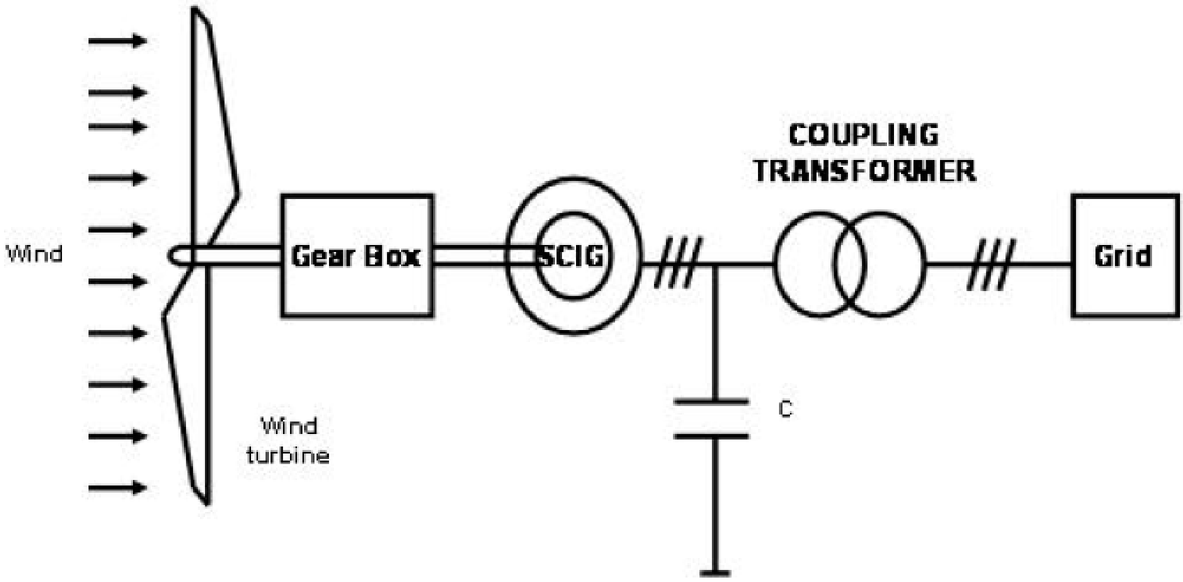
p = Water density in kg/m^3

G= Gravitational acceleration
Q= Discharge in litres/s
H= Head, m

Wind : P = pCD^2w^3

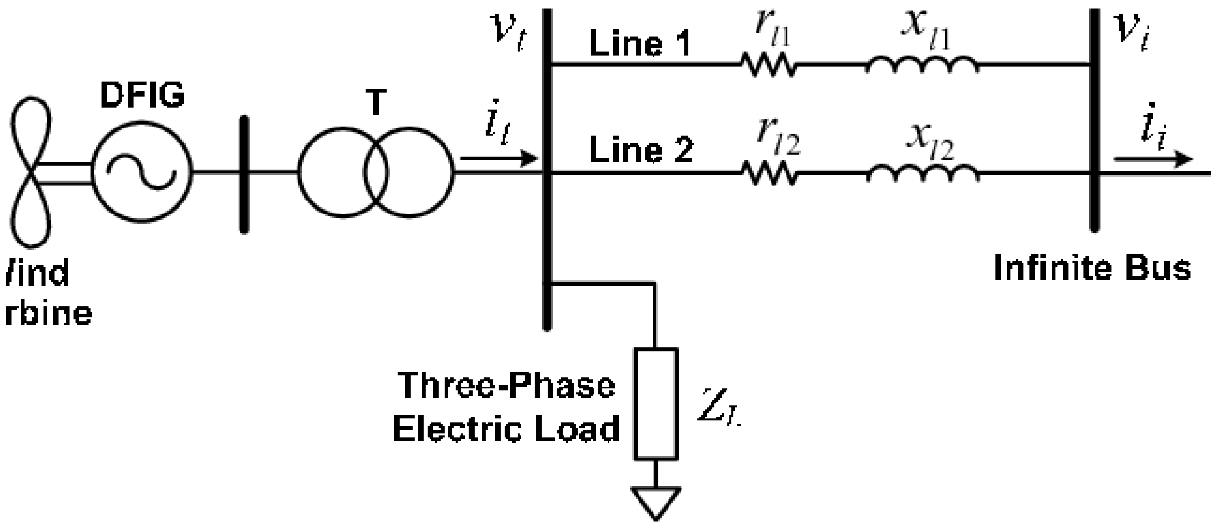
p = Air Density
C= Constant
D= Blade Area
w= wind speed

Schematic diagram of a wind system connected to the grid :



Schematic diagram of a grid connected induction generator .

Equivalent Circuit of a wind system connected to grid :



Equivalent circuit of an induction generator connected to grid through a transmission line.

Advantages of SEIG :

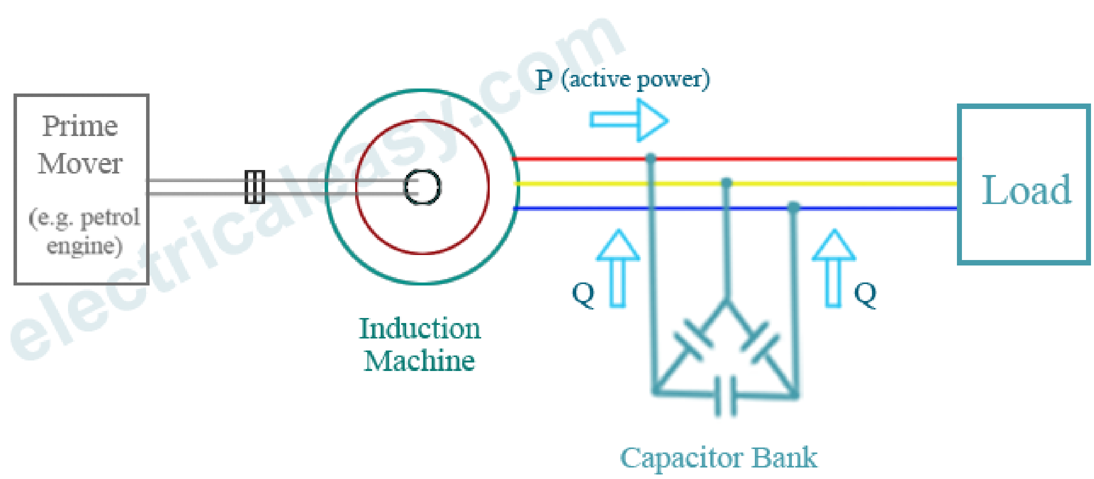
The advantages of SEIG over a conventional alternator as a source of isolated power supply are as follows :

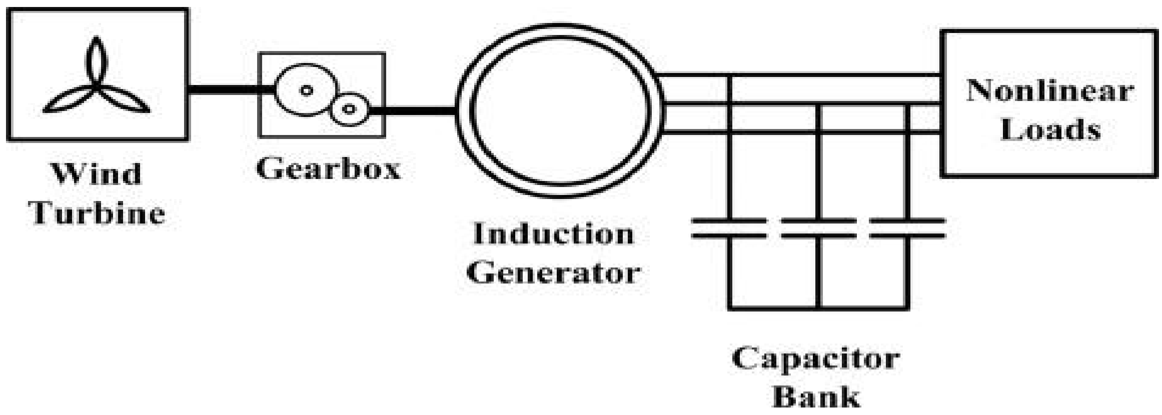
Reduced unit cost
Rugged and Brushless rotor (due to squirrel cage construction)
Absence of a separate DC Source
Ease of maintenance
Asynchronous operation

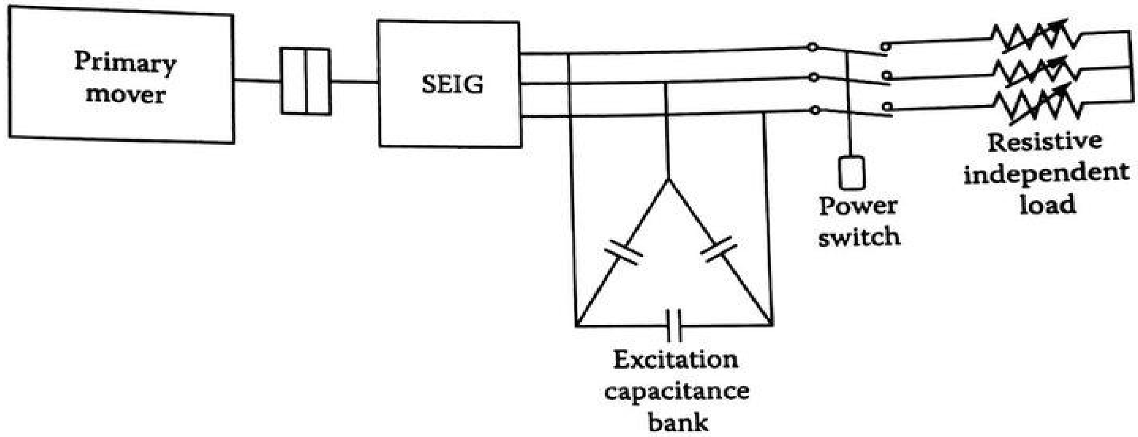
Scheme :

In this scheme what is done is that instead of connecting the stator terminals to a grid, the same is connected through a 3 phase capacitor bank to a 3 phase local load . The machine is driven with the help of a prime mover , most probably a wind turbine , hydro turbine , gas turbine etc at a certain per unit speed with the help of a gear box arrangement.

The scheme is shown below.







Phenomenon :

When a suitable capacitor C/ph is connected across a 3 ph induction machine driven at a per unit speed v , voltages and currents are induced in the stator due to self-excitation and exchange of energy between an electromagnetic machine and an electrostatic capacitor similar to resonance.

Raise of voltage and current is arrested by magnetic saturation in the machine.

Condition for self excitation :

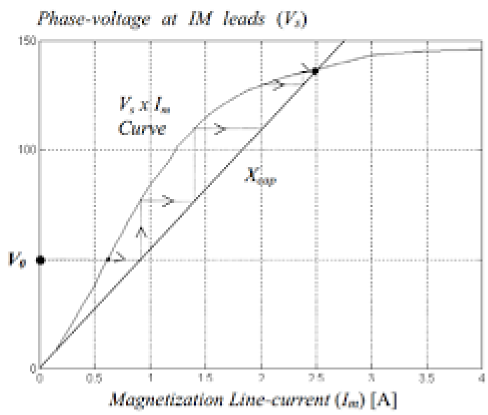
Remnant flux in the machine, or initial charge in the capacitor.
To initiate self excitation.

Qualitative explanation :

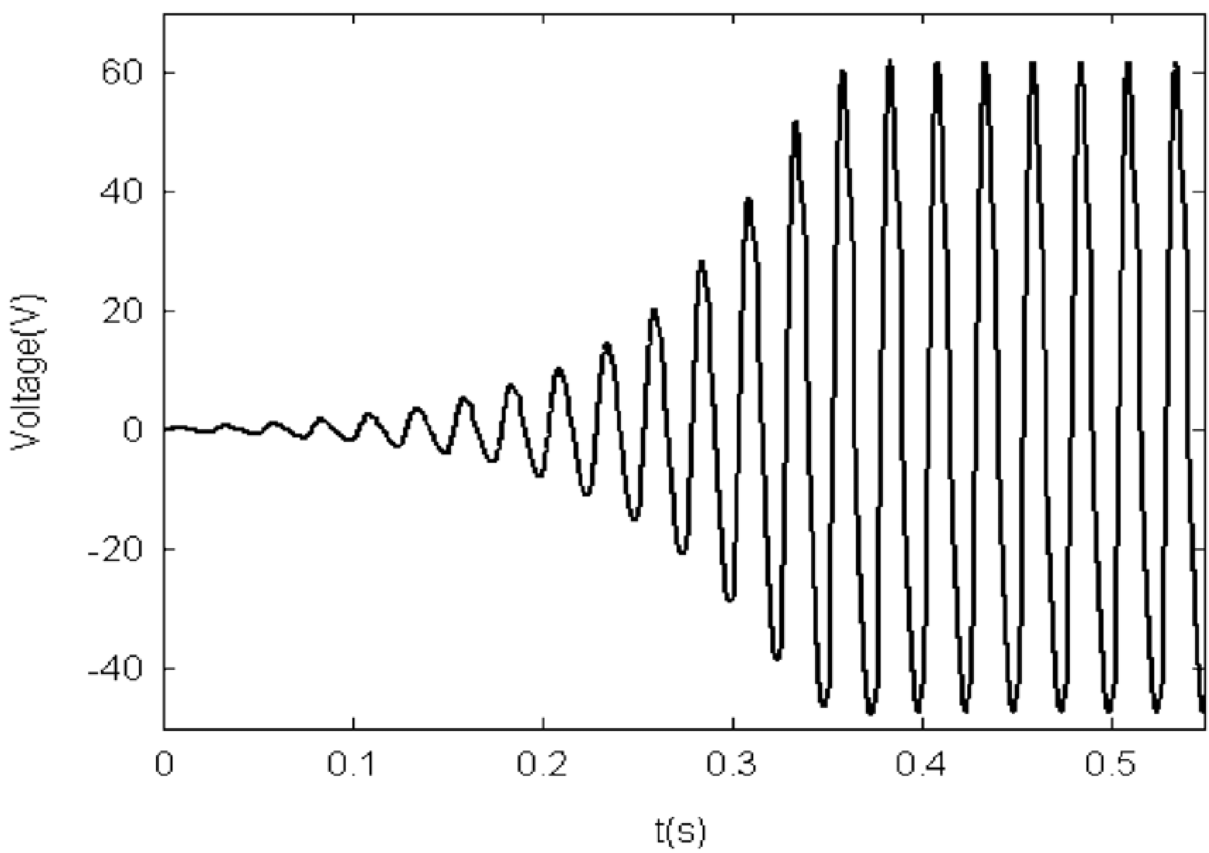
A remnant flux in the rotor induces a small balanced voltage in 3 ph stator winding.
Connected capacitor has a magnetising effect as in any ac generator.
Flux raises.
Voltage increases.
This leads to an avalanche effect.
Increase limited by saturation.

Graphical explanation :

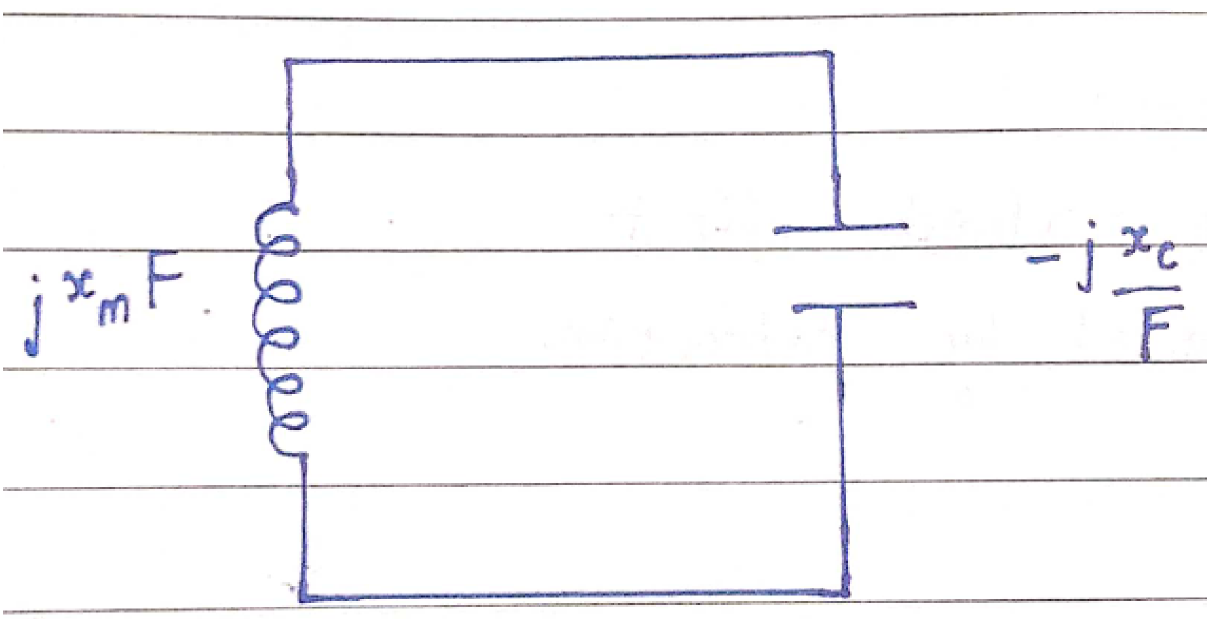
The graphical explanation shown below demonstrates how voltage build up takes place in a self excited induction generator. The process is quite similar to the process that takes place in a dc shunt generator. The magnetising characteristics of the stator magnetising reactance and the capacitor line of the connected capacitor are used to draw this diagram.



Voltage build up :



Approximate equivalent circuit :



F = per unit frequency = actual frequency/ base frequency
v = per unit speed

Approximate assumption :

F = v

Minimum capacitance :

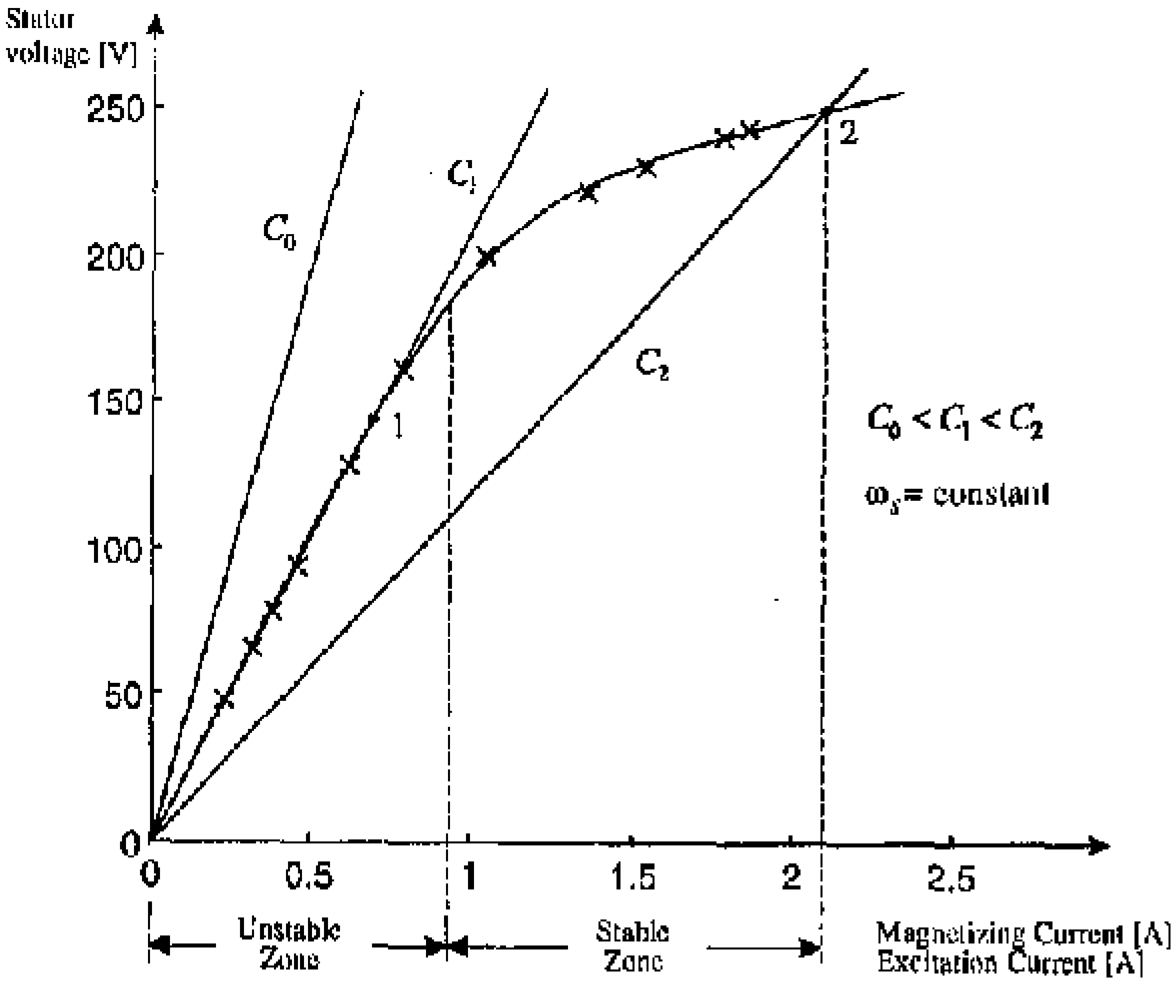
Capacitor line is tangential to the magnetising curve.

F = v

$vx_m = x_c/v$
$= 1/v(wC_{min})$

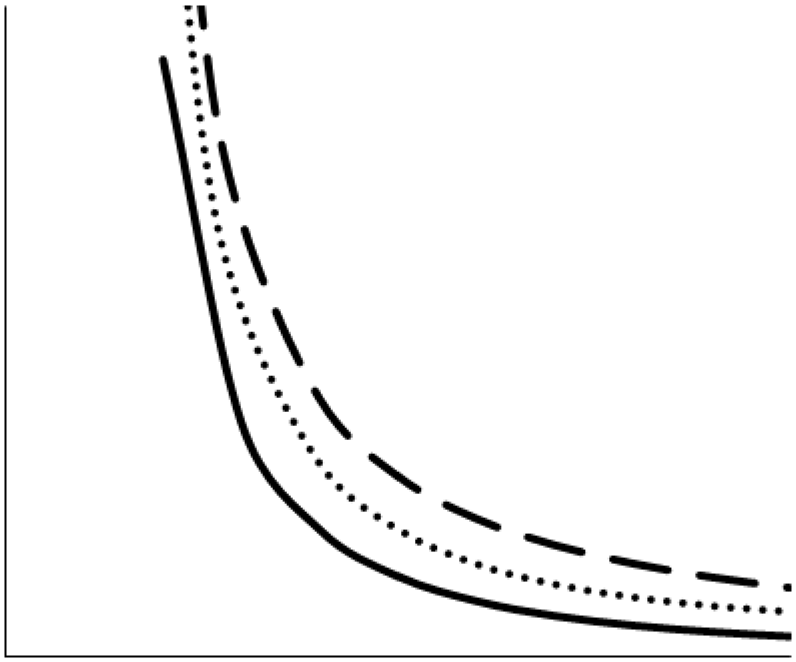
$C_{min} = 1/(wx_m)v^2$
$=1/Kv^2$

where, K= wx_m

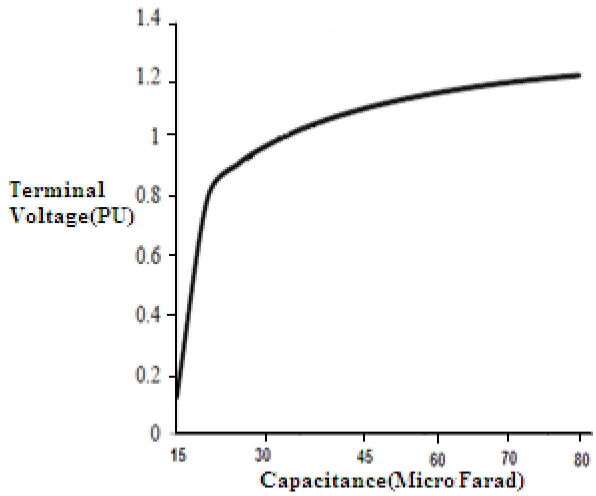


Stator voltage [V]
250
200
150
100
50
0
0
0.5
1
1.5
2
2.5
C_0
C_1
C_2
1
2
$C_0 < C_1 < C_2$
ω_s= constant
Unstable Zone
Stable Zone
Magnetizing Current [A]
Excitation Current [A]

Minimum capacitance vs speed :



Effect of capacitance :

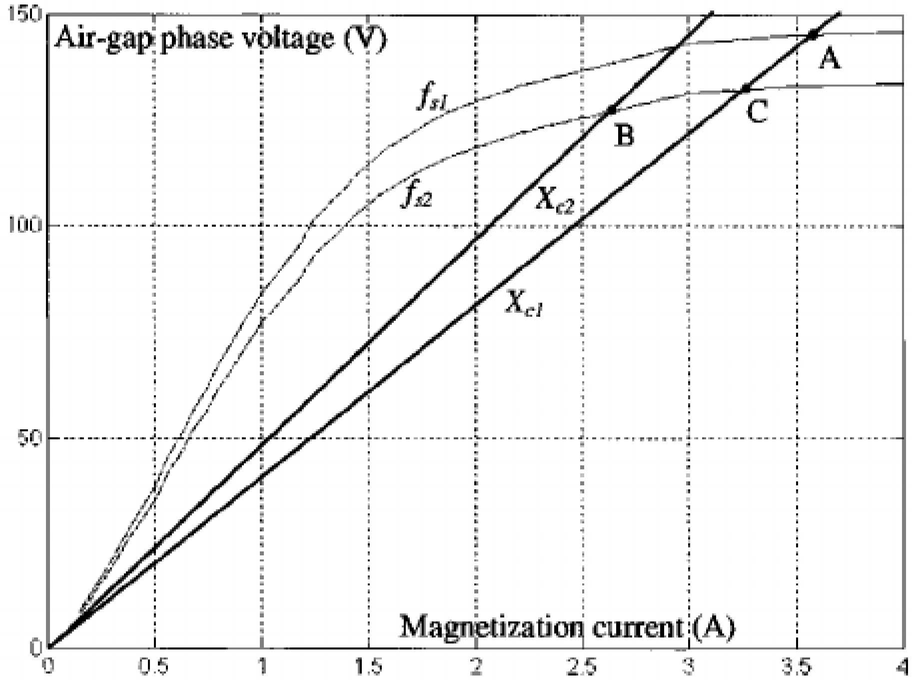


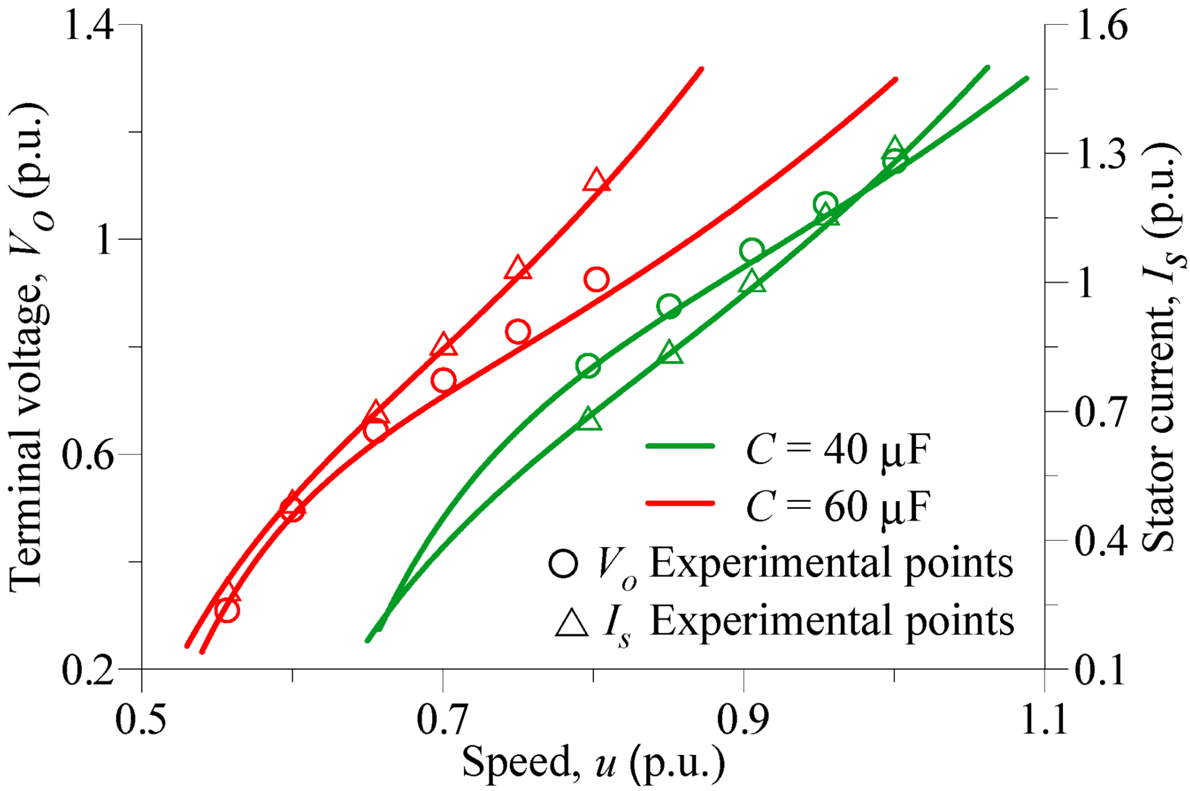
Effect of speed :

Clearly we can see that the slope of the magnetising characteristics of the stator gives us an idea about the magnetising reactance of the machine which represents the level of air gap flux in the same. We know that magnetising reactance is directly proportional to stator frequency.

From our earlier assumption that induced stator frequency is almost equal to p. u speed , we infer that if speed increases, the slope of the O.C.C will increase. We also know that the slope of the capacitor line is inversely proportional to stator frequency (= pu speed) , hence if speed increases slope of the capacitor line will reduce and consequently we can see that the point of intersection of the two characteristics will go up in the imaginary axis and the voltage developed across stator terminals will rise as a result of the same.

In this qualitative discussion it is assumed that capacitance value is kept constant.





ANALYSIS OF CAPACITOR SELF EXCITED INDUCTION GENERATOR

Steady state analysis :

The analysis of such generators requires the knowledge of parameters of a machine to determine its performance for given capacitance, speed and load.

In the SEIG used as an isolated power source, both the terminal voltage and frequency are unknown and have to be calculated for a given speed , capacitance and load.

Newton Raphson Method :

A procedure to identify the saturated parameters and the generated frequency for a given load using the Newton Raphson Method is shown to be simple, comprehensive , efficient and well suited for MATLAB simulation.

Assumptions made in the analysis :

In the analysis , the following assumptions are made :

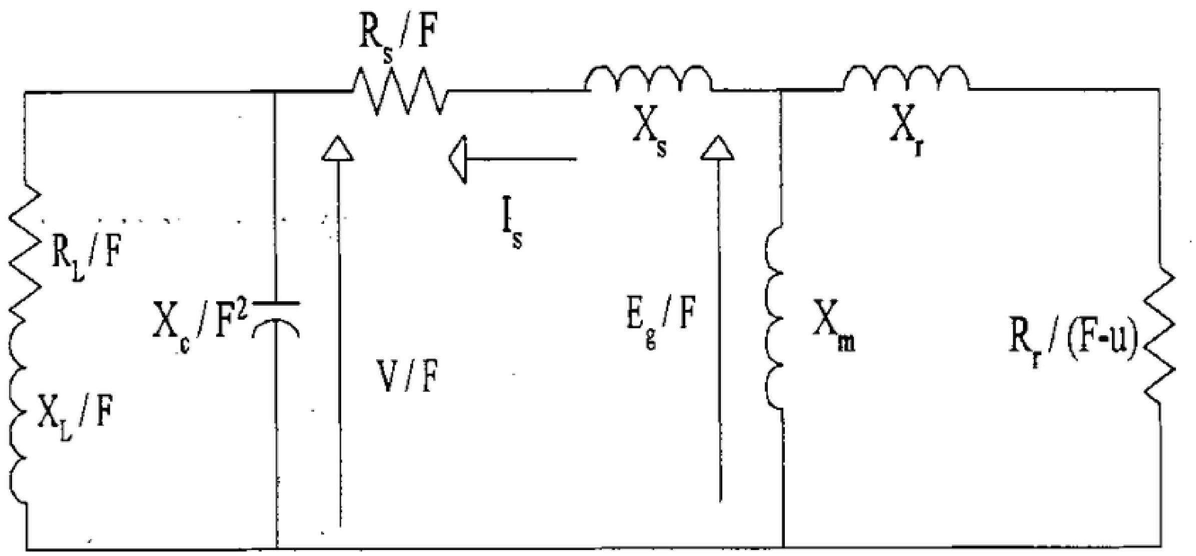
Only the magnetising reactance is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self excitation results in the saturation of the main flux. As the value of the x_m reflects the magnitude of the main flux, it is essential to consider the variation of x_m with the saturation level.

Leakage reactances of stator and rotor in per unit are taken to be equal.
This assumption is assumed to be valid in Induction Machine Analysis.

Core losses in the machine are neglected, although the analysis can be easily extended to account for core losses.

Mmf space harmonics and time harmonics in the induced voltage and current waveforms are ignored.

Equivalent circuit :



We will limit our analysis to resistive load although it can be extended to inductive load.

Equivalent circuit parameters :

R_s,R_r = Per phase stator and rotor resistance.
X_{ls},X_{lr}= Per phase stator and rotor leakage reactance.
X_m= Magnetising reactance.
X_c= Capacitance per phase.
R_l= Load resistance per phase.

All the reactances relate to base frequency F.

F,v = Per unit frequency and speed
I_s,I_r,I_l= Stator, Rotor and Load current per phase
V_l,V_g = Terminal and Air gap voltage.

Steady state analysis :

Loop equation for the current Is can be written as

$$Z_s I_s=0 \text{ ---------- } (1)$$

where,

Z_s= (-j$X_s R_l$/F^3)/(R_l/F - jX_c/F^2) + (R_s/F +jXls) + [jx_m{R_r/(F-v) + jx_{lr}}]/[{R_r/(F-v)} +{ j(x_m + x_{lr})}]

Under steady state self excitation, I_s is not 0!
Hence Z_s=0
which implies that both real and imaginary part of expression of Z_s
would be separately 0.

Substituting x_{ls}=x_{lr}=x_1

f(x_m,F)= ($C_1 x_m$+ C_2)F^3 + ($C_3 x_m$+ C_4)F^2 + ($C_5 x_m$+ C_6)F

$+ (C_7 x_m + C_8) = 0$

$g(x_m, F) = (D_1 x_m + D_2)F^2 + (D_3 x_m + D_4)F + D_5 = 0$

where ,

$C_1 = -2x_1 R_l$; $C_2 = -x_1^2 R_l$; $C_3 = 2x_1 R_l$; $C_4 = x_1^2 R_l$;
$C_5 = x_c(R_s + R_l + R_r)$; $C_6 = x_c x_1(R_s + R_r + R_l) + R_s R_r R_l$;
$C_7 = -x_c(R_s + R_l)$; $C_8 = -x_1 x_c(R_s + R_l)$

$D_1 = 2x_c x_1 + R_l(R_s + R_r)$; $D_2 = R_l x_1(R_s + R_r) + x_c^2 x_1$;
$D_3 = (R_s R_r + 2x_c x_1)$; $D_4 = -x_1(R_s R_r + 2x_c x_1)$; $D_5 = -x_c R_r(R_s + R_l)$
As the above equations are not easily solvable, some numerical technique has to be adopted to find the values of saturated magnetising reactance x_m and the output per unit frequency F for the given values of machine parameters R_l, X_c and v.

Newton Raphson method has been found to be very appropriate in solving equations.

Newton Raphson Algorithm :

$$\boldsymbol{F}\left(\boldsymbol{x}^{(i+1)}\right) = \boldsymbol{F}\left(\boldsymbol{x}^{(i)}\right) + \left|\frac{d\boldsymbol{F}}{dx}\right|^{(i)} \left(\boldsymbol{x}^{(i+1)} - \boldsymbol{x}^{(i)}\right) = 0$$

Where $x^{(i)}$= known approximation for unknowns while $x^{(i+1)}$= the next approximation

$$\boldsymbol{x}^{(i+1)} = \boldsymbol{x}^{(i)} - \boldsymbol{J}^{-1}\left(\boldsymbol{x}^{(i)}\right)\boldsymbol{F}\left(\boldsymbol{x}^{(i)}\right)$$

Here, J(x) = the Jacobian matrix defined as :

$$\left|\frac{d\boldsymbol{F}}{dx}\right|^{(i)} = \boldsymbol{J}\left(\boldsymbol{x}^{(i)}\right) = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \cdots & \frac{\partial F_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_n}{\partial x_1} & \cdots & \frac{\partial F_n}{\partial x_n} \end{bmatrix}$$

In our case the value of n is 2.

Initial values of x_{m0} and F_0 :

Newton raphson method requires the initial guess of values of the unknowns, say x_{m0} and F_0.

x_{m0} and F_0 can be chosen as

x_{m0} = x_m(unsaturated);
F_0 = v (per unit speed).

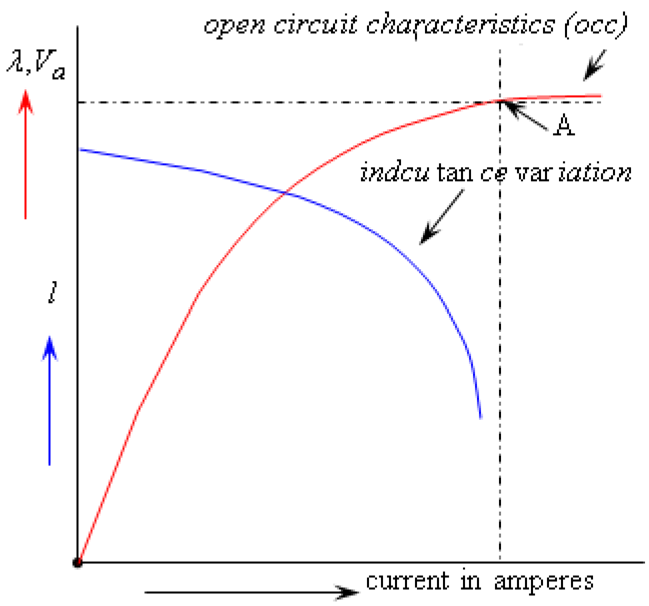
Therefore by using the newton raphson algorithm we can solve the two simultaneous nonlinear equations involving x_m and F. Thereby we will get to know about the actual frequency induced in the stator under steady state and the saturated magnetising reactance for a given values of load resistance, capacitance and per unit speed. A simple matlab algorithm can be developed incorporating the above procedure.

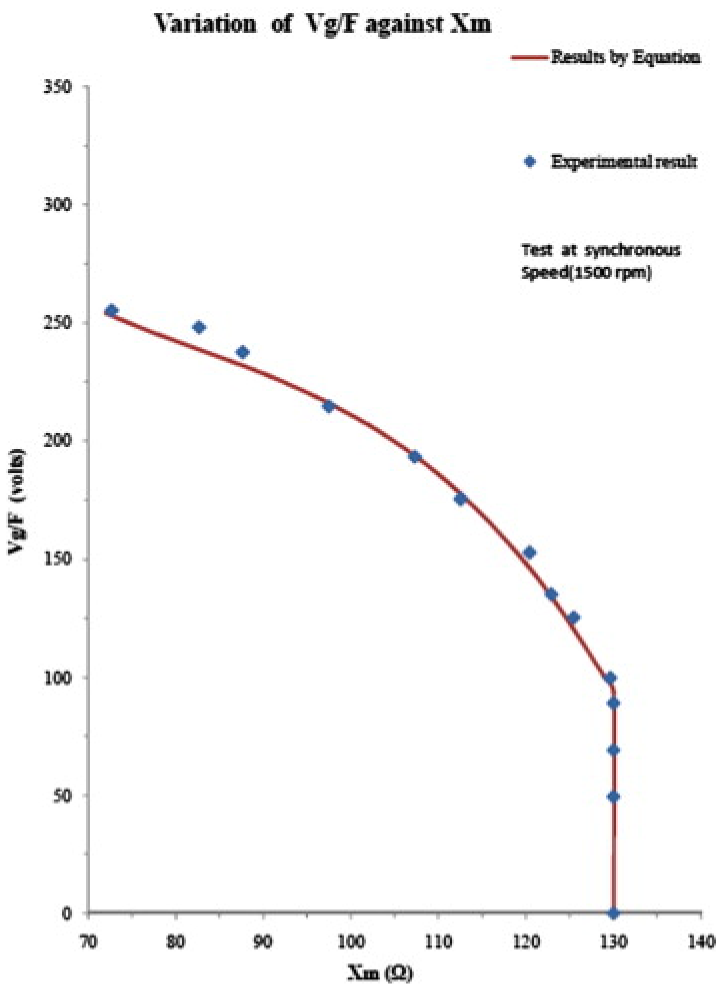
Calculation of air gap voltage V_g:

The next step is to calculate the air gap voltage V_g and the terminal voltage V_l which requires the information regarding the variation of x_m
with the quantity V_g/F.

This information can be obtained experimentally by driving the induction machine at synchronous speed corresponding to line frequency i.e F=1
and measuring x_m the magnetising reactance for different input voltages at line frequency .Basically we will have to plot the Open Circuit Characteristics of the induction machine at the synchronous speed corresponding to the line frequency F=1.

In the diagram shown below the open circuit characteristics of an induction machine have been depicted along with the inductance (magnetising reactance) variation.





In the above diagram the variation of air gap voltage V_g/F with magnetising reactance x_m has been portrayed. Now once x_m i.e the steady state saturated magnetising reactance is known after solving the above two nonlinear simultaneous equations involving x_m and F using matlab , we can proceed to calculate the air gap voltage V_g/F corresponding to the value of x_m computed using the above curve which shows the variation of V_g/F against x_m.

With the knowledge of V_g,x_m,F,x_c,v,R_l and machine parameters known, calculation of the terminal voltage V_l and the load current is straightforward using the equivalent circuit.

I_s= (V_g/F)/[R_s/F +jx_{ls}-(j$x_c R_l$)/(F$^2 R_l$-jFx_c)]

I_r= (-V_g/F)/[{R_r/(F-v)} + jx_{lr}]

I_l= (-j$x_c I_s$)/(R_lF-jx_c)

V_l= $I_l R_l$

Input power :

P_{in} = -q$I_r^{\,2} R_r$v/(F-v)

where
q= number of phases

Output power :

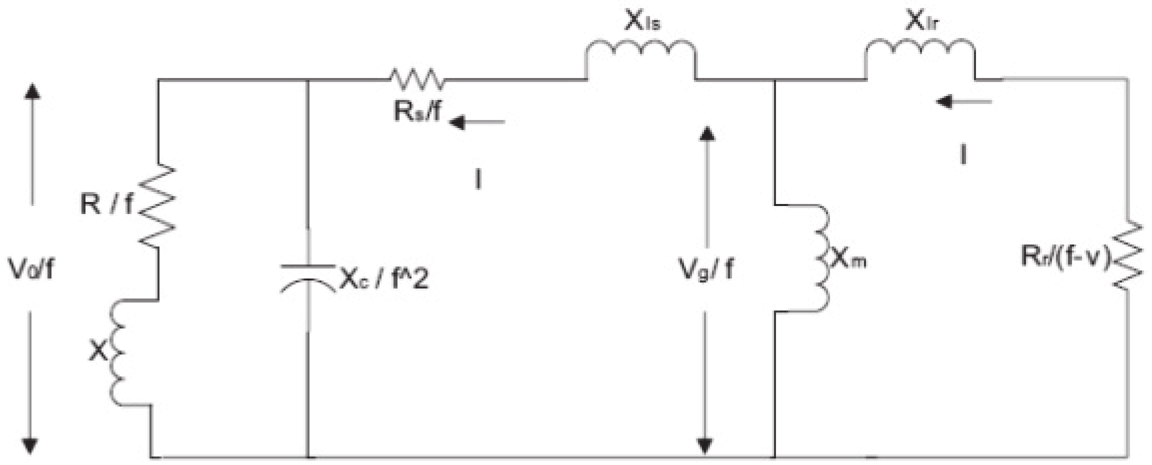
P_{out}= q$I_r^{\,2} R_l$.

The above analysis can be extended for reactive loads by replacing R_l
with Z_l

Conclusion :

Therefore from the above analysis it follows that the steady state slip or the steady state induced stator frequency for a self excited induction generator does not remain constant as it happens in the case of a grid connected induction generator where the steady state stator frequency is the grid frequency itself. The stator frequency varies as we vary the load resistance , excitation capacitance and the p.u speed. In other words **“ the rotating magnetic field does not rotate with a constant angular speed , it changes as we vary the load , hence the slip of the machine changes with the load ”.** We infer this as the speed of the stator rotating field is decided by the frequency induced in the stator.

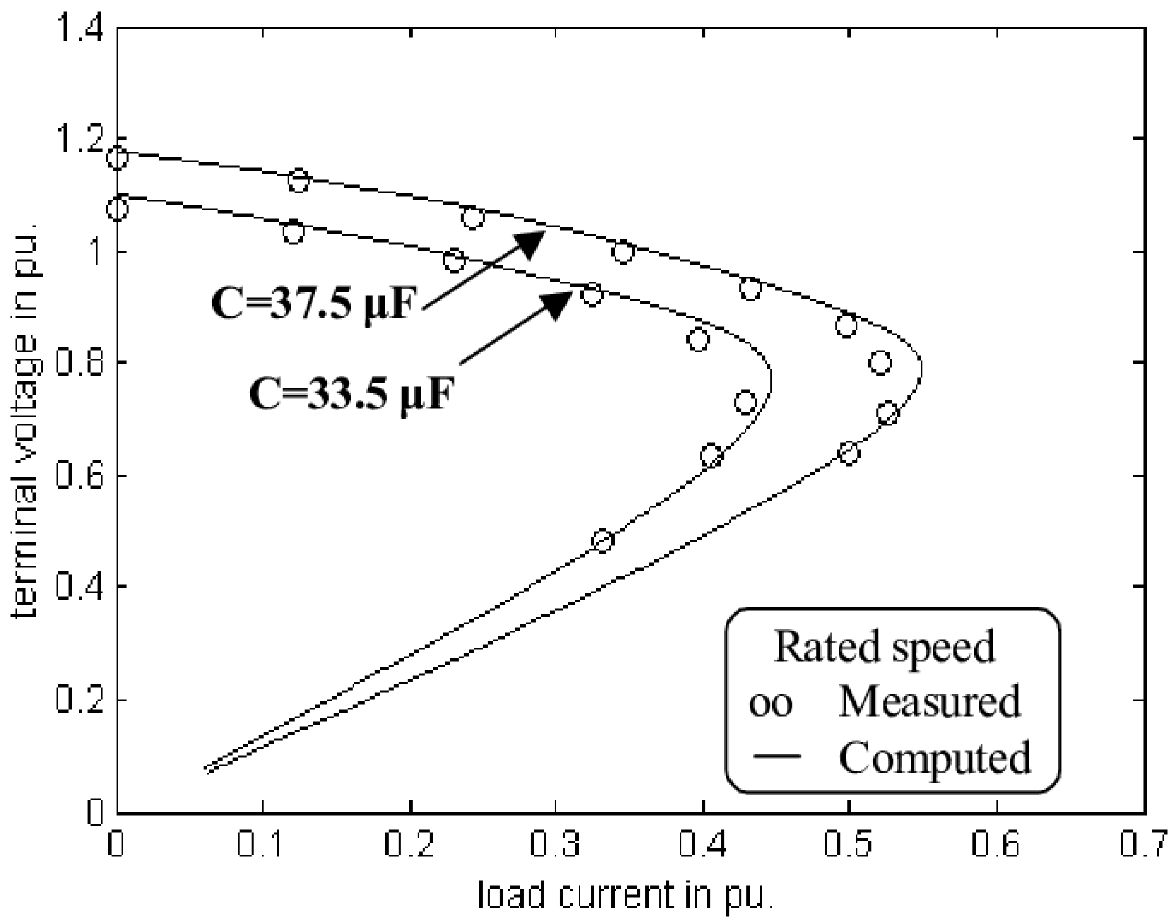
Drawbacks :



Now from the above circuit diagram , it is clear that the only source of reactive power for the whole system is the capacitor. Now when the generator is not loaded i.e there is no real power output , in that case the mechanical power fed to the machine from the turbine is negligible. Now the electrical equivalent of the mechanical power input is the power in the resistance R_r/ (F-v) i.e I_r^{2}*R_r/(F-v) . When the generator is not loaded I_r is approximately 0. And consequently there will be no reactive power losses in the stator reactance x_{ls} and rotor reactance x_{lr} .

Now when the machine will be loaded there will be electrical power output and I_r will appear . In that case what will happen is that there will be reactive power losses in the leakage reactances , but we know that the only source of reactive power in the whole system is the excitation capacitor, hence the reactive power available for magnetising the air gap of the machine will fall down. As a result the terminal voltage across the generator will reduce drastically once the machine is loaded. **It follows that the terminal voltage across the generator varies drastically from no load condition to full load condition.**

The variation of the terminal voltage with load for a typical SEIG is shown below :



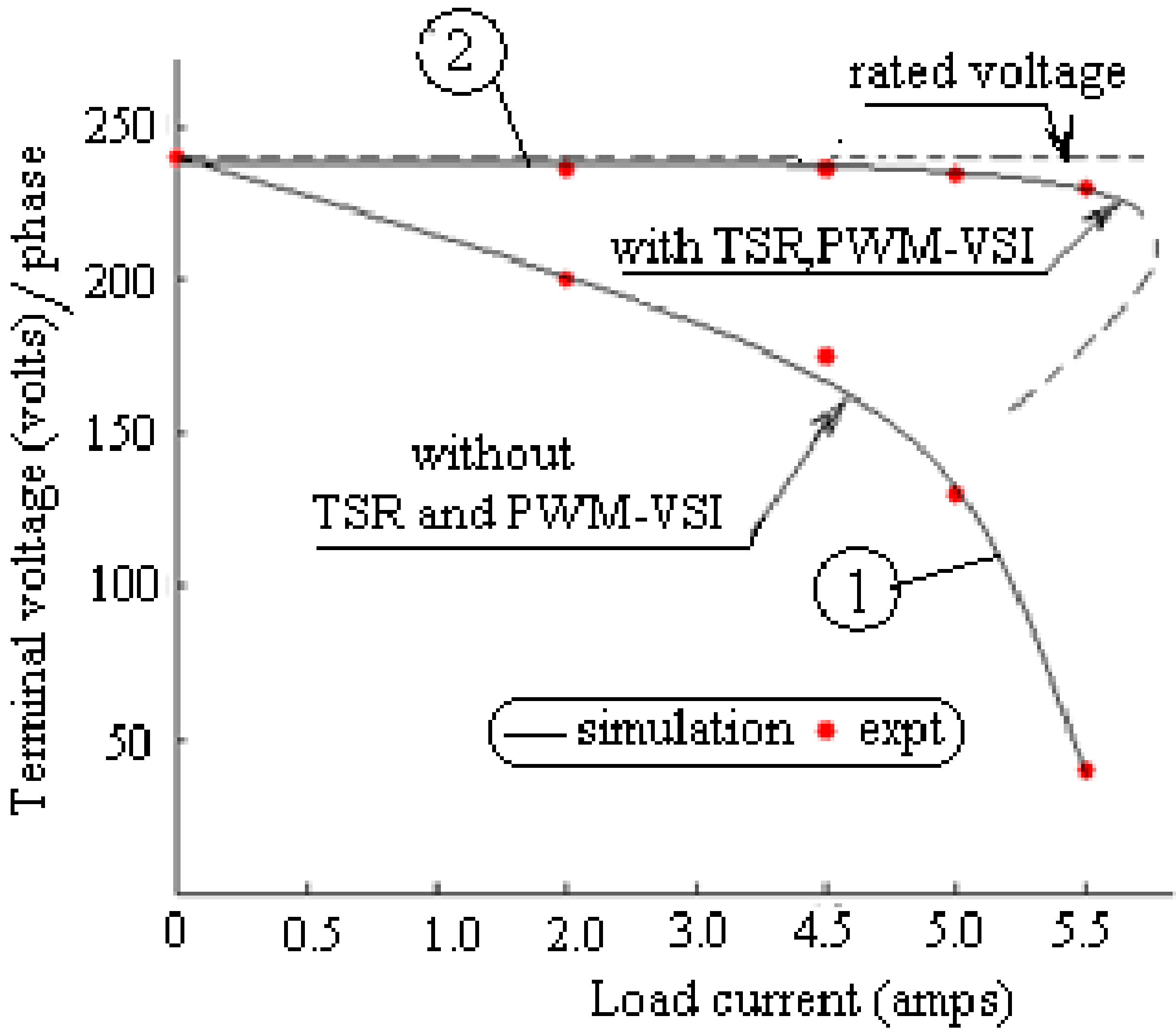


Fig. 9. Terminal voltage variation with load current of SEIG

This is the major drawback of a **Self Excited Induction Generator.**

Modern technological remedies :

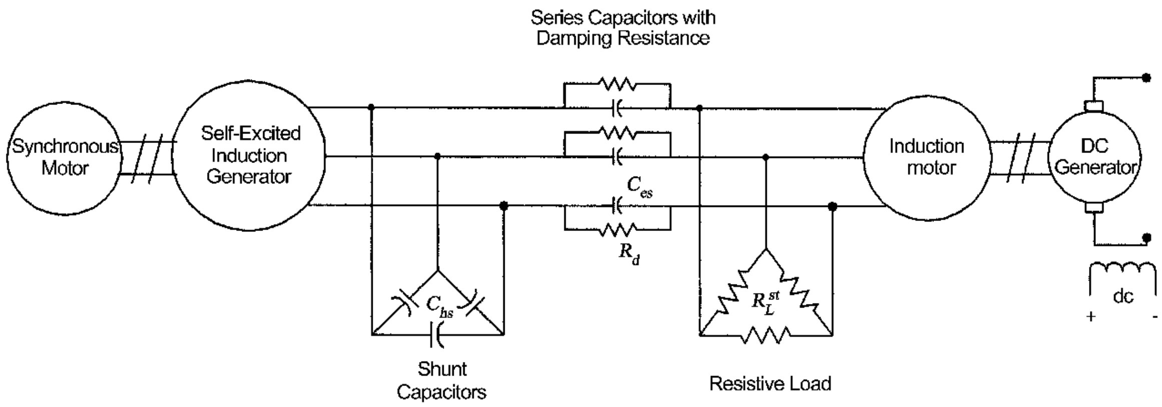
There are two possible remedies for the above problem which are as follows :

1) Synchronous condenser (Shunt compensation) :

Since we know that the terminal voltage drops from no load to full load , what we need to do is to vary the excitation capacitance, each time we vary the load so as to keep the terminal voltage at the rated value or the nominal value . But we know that it is nearly impossible to have a variable 3 phase capacitor bank so what is done nowadays is that synchronous condensers are used. We know that synchronous motors operating in overexcited condition provide leading current and in turn act as a capacitor. So nowadays we can nicely vary the field current as the load is varied to provide the required amount of reactive power to the machine so that the terminal voltage can be kept constant.

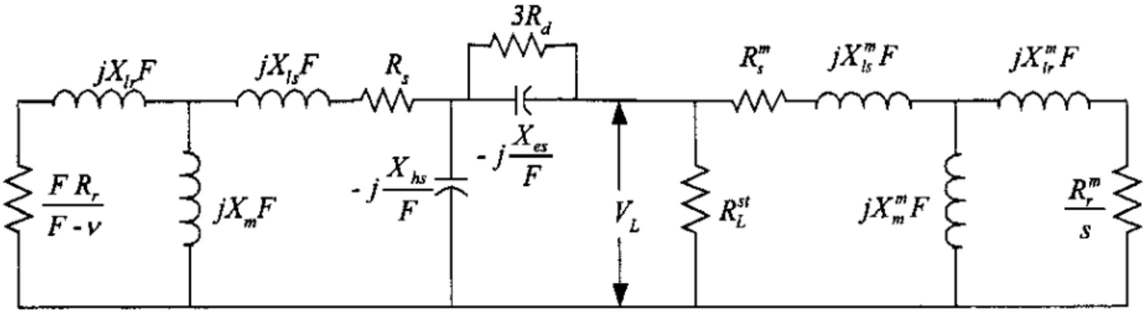
2) Series compensation :

Series compensation is another solution to this problem. In this method what is done is that series capacitors are connected in series with the load. In that case what happens is that not only the shunt capacitance provides the required reactive power but also the series capacitor provides reactive power . Since the series capacitor is connected in series with the load what happens is that the reactive power produced by the series capacitor becomes proportional to the square of the load current I_l. In this case what happens is that as the load on the machine increases , the net reactive power in the system also increases.

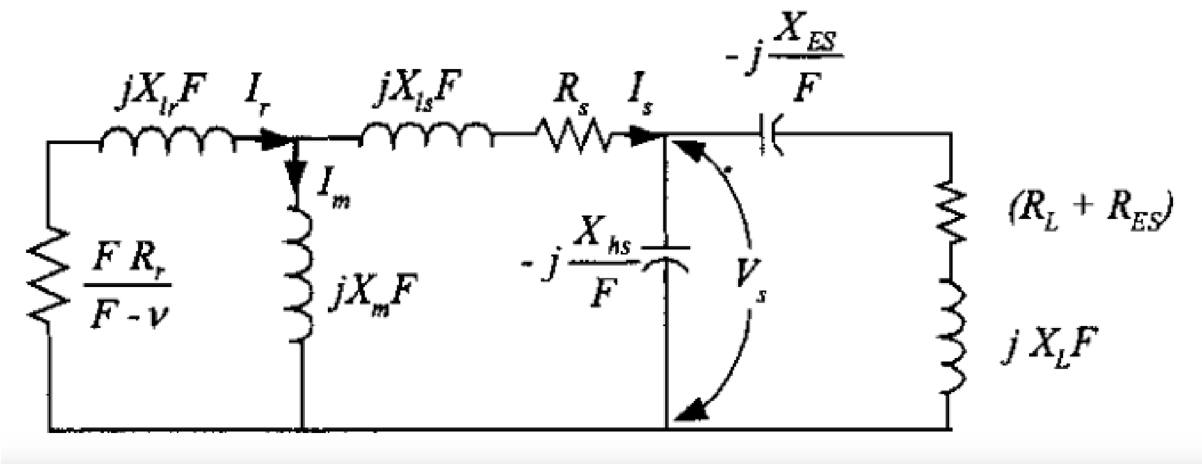


g. 1. Schematic diagram of short-shunt SEIG-IM configuration.

Equivalent circuit of a compensated SEIG feeding an RL load :



(a)



Future prospects :

Basically India is an agricultural country where majority of the total population resides in rural areas where grid availability is not there.
Grid connected induction generators are available in large numbers in urban areas generating electricity and satisfying the consumers.But then the natural question which comes to our mind is suppose we want to install a wind farm in a remote area where there is no grid. Then what is to be done? Then the only remedy is to think of an isolated generator working as an isolated power supply and satisfying the local loads.

Tamil Nadu is the greatest producer of wind energy in India, according to the National Institute of Wind Energy (NIWE) report 2020. Wind power generation capacity in India has significantly increased in recent years. As of 28 February 2021, the total installed wind power capacity was 38.789 GW , the fifth largest installed wind power capacity in the world after Denmark, Germany , Spain and Portugal.

Hence for a developing economy like India which is planning to provide electricity to such a large population , it becomes imperative that SEIGs are manufactured in abundance so that each and every individual can avail electrical power without any obliteration and shortage.

THANK YOU