# Economic Delivary Of Single-Phase Power For Remote Areas Through Three-Phase Self-Excited Induction Generator

Sandeep Kumar Goel, Ajay Srivastava, Anurag Kumar Swami[#], Geeta Negi[*]
Associate Professor, Electrical Engineering Department
# Professor, Electrical Engineering Department
*Assistant Professor, Electrical Engineering Department
G.B. Pant University of Agriculture and Technology, Pantnagar-263145
INDIA

**Abstract:** This paper presents a economic technique to supply single phase power from three phase Self-Excited Induction Generator (SEIG) using series and shunt capacitances. For large single phase power requirement in hilly or remote areas it is necessary to use single phase extension instead of three-phase extension from economic point of view. Experimental method is used to find out the minimum values of series and shunt capacitance. Steady state analysis of the induction generator under different loading conditions is carried out. The result shows that under proposed scheme three phase SEIG can deliver single phase power upto 84% of its rated value. Experimental results are obtained on a 3-phase, 440 V, 1.5 kW induction machine coupled with 220 V, 12 amp, 3 kW dc motor to confirm the feasibility and effectiveness of the proposed approach.

**Keywords :** Self-excited Induction Generator, Single-phase Power, Series and Shunt Capacitor Excitation

## 1. Introduction

Electric power has a significant role and of vital importance in the developmental process of a country. Electric power must be available to each and every consumer irrespective of his location. For supplying energy to remote areas renewable energy resources or locally available energy sources may be used. Induction machines working as self excited induction generator (SEIG) could be the good choice to utilize locally available energy resources[1,2,3]. Self excitation could be done by connecting capacitors across the phases of induction machines [4,5,6].

Three phase induction generators can be used to give supply for single phase loads [7,8,9,10]. Need of operating three-phase SEIG for supplying single-phase load arises in the following situations; (i) when the cost of bringing three-phase power to the location is high because of the construction costs of the required length of three-phase extension, (ii) when large rated SEIG is needed to power single-phase loads, and (iii) when the single-phase SEIG has higher cost than the equivalent sized three-phase SEIG.

The single-phase power generation using three-phase SEIG is achieved by balanced operation of the three-phase SEIG. For this purpose the combined reactance of load compensation elements and excitation capacitances need to be varied with load. This requires a continuous variation of capacitances which is a little difficult task. To overcome this difficulty Series Shunt Capacitor Excitation Scheme could be used which gives the balanced operation with fixed capacitances over a large range of rated load.

## 2. Operation Schemes

To obtain single phase power from three phase SEIG, two operation schemes could be adopted.

### 2.1 Balanced Operation Scheme

A single-phase load is converted into balanced three-phase load by load compensation. The load compensation involves two steps: (a) load balancing and (b) power factor correction. The excitation capacitance required for exciting the SEIG at no-load, when combined with the elements of load compensation, gives a resultant variable term, which could be either inductive or capacitive, depending upon the load.

### 2.2 Partial Balanced Scheme

In the balanced operation scheme, the susceptances connected across the three-phases are to be varied continuously with load. Therefore perfect balancing is not economical. A partial balancing scheme may be used as a compromise by removing the inductive reactance portion of the excitation balancing network and fixing the capacitance of a suitable value. Induction machines are very sensitive to voltage unbalance. Even moderate values of voltage unbalance causes severe current unbalance, which increases the total copper loss. As a result, the machine must be derated. In the present work, a new excitation configuration containing two capacitors, one across a phase and the other in series of load, is proposed.

## 3. Shunt and Series Capacitance Excitation Scheme

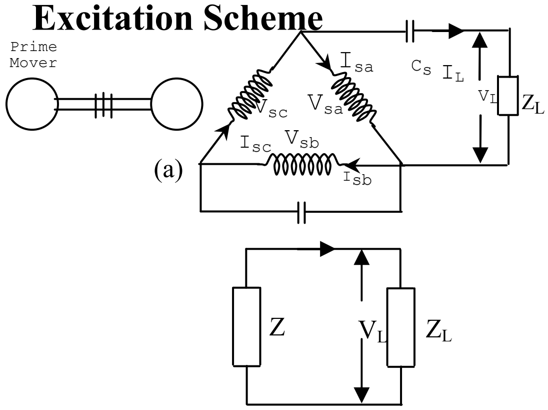



Fig. 1(a,b) Shunt and Series Excitation of Three Phase SEIG Feeding Single Phase Load

Fig. 1 shows a circuit diagram of three-phase SEIG having connected a shunt capacitor $C_{bsh}$, having capacitive reactance $Z_{bsh}$, across line b-c and feeding a single-phase load through a series capacitor $C_{se}$ having capacitive reactance $Z_{se}$.
The terminal constraints of this circuit are:

$$V_{sa} + V_{sb} + V_{sc} = 0 \quad \ldots(1)$$
$$V_L = V_{sa} - I_L Z_{se} \quad \ldots(2)$$
$$I_L + I_{sa} - I_{sc} = 0 \quad \ldots(3)$$
$$I_{bsh} + I_{sb} - I_{sc} = 0 \quad \ldots(4)$$
$$V_{sb} = I_{bsh}.Z_{bsh} \quad \ldots(5)$$

where,

$$Y_{bsh} = j\omega C_{bsh}$$

Using symmetrical component theory, we have

$$V_{sa} = V_0 + V_+ + V_-$$
$$V_{sb} = V_0 + a^2 V_+ + aV_-$$
$$V_{sc} = V_0 + a V_+ + a^2 V_- \quad \ldots(6)$$

And

$$I_{sa} = V_0 Y_0 + V_+ Y_+ + V_- Y_-$$
$$I_{sb} = V_0 Y_0 + a^2 V_+ Y_+ + a V_- Y_-$$
$$I_{sc} = V_0 Y_0 + a V_+ Y_+ + a^2 V_- Y_- \quad \ldots(7)$$

So we can get using above equations:

$$V_0 = (V_{sa} + V_{sb} + V_{sc})/3 = 0 \quad \ldots(8)$$

Using Eq. (3) in Eq. (2) we have

$$V_L = V_{sa} + (I_{sa} - I_{sc})Z_{se} \quad \ldots(9)$$

substituting symmetrical components for the phase voltages and currents from eqns. (6) and (7), we get

$$V_L = K_1 V_+ + K_2 V_- \quad \ldots(10)$$

where

$$K_1 = 1 + (1-a)Y_+.Z_{se} \quad \ldots(11)$$

and

$$K_2 = 1 + (1-a^2)Y_-.Z_{se} \quad \ldots(12)$$

Eliminating $I_{bsh}$ from Eqns. (4) and (5) and substituting symmetrical components for the phase voltages and currents from enqn (6) and (7), we get

$$K_3 V_+ = K_4 V_- \quad \ldots(13)$$

where,

$K_3 = a^2/Z_{bsh} + (a^2-a)Y_+$ …(14)

and

$K_4 = -a/Z_{bsh} + (a^2-a)Y_-$ …(15)

Substituting $V_-$ from Eq. (13) in Eq. (10), we get

$V_L = [(K_1K_4 + K_2K_3)/K_4]V_+$ …(16)

Substituting symmetrical components for the phase currents in equn (3) from equn. (7), we have

$I_L = -K_5V_+ - K_6V_-$ …(17)

where,

$K_5 = (1-a)Y_+$ …(18)

and

$K_6 = (1-a^2)Y_-$ …(19)

Substituting $V_-$ from Eq. (13) in Eq. (17), we get

$I_L = -[(K_4K_5 + K_3K_6)/K_4]V_+$ …(20)

Dividing Eq. (16) by Eq. (20)

$V_L/I_L = - (K_1K_4 + K_2K_3)/(K_4K_5 + K_3K_6)$

or

$V_L/I_L = -Z$ …(21)

where

$Z = (K_1K_4 + K_2K_3)/(K_4K_5 + K_3K_6)$

Eq. (21) describes that, for a given values of shunt capacitance $C_{bsh}$, series capacitance $C_{se}$ and prime mover speed, the three-phase SEIG viewed from the single-phase load terminal can be represented by a single-phase circuit shown in Figure 1b.

The loop equation of Fig. 1b is written as

$(Z_L + Z) I_L = 0$ …(22)

where, $Z_L = R_L + jFX_L$ is the load impedance and F is the p.u. frequency.

Under steady state condition $I_L$ cannot be equal to zero, hence

$Z + Z_L = 0$ …(23)

Now Eq. (23) can be solved for $C_{se}$ for various values of $C_{bsh}$ and $Z_L$ by using any numerical technique.

# 4. Results and Discussion

In the results presented here, predicted characteristics are shown by solid curves and experimental results are shown by points. At first, the selections of shunt and series capacitance are investigated. Once the values of capacitor elements are chosen, the steady state performance of the system is predicted. Finally, the effect of series capacitance on the voltage regulation, current and voltage in the phase windings of the three-phase SEIG delivering safe output power are investigated.

## 4.1 Selection of Shunt Capacitor

The shunt capacitor connected across the phase b-c supplies the exciting current for no-load excitation of the machine. Thus, the suitable value of shunt capacitor $C_{bsh}$ is selected first by studying the variation of no load terminal voltage with $C_{bsh}$.

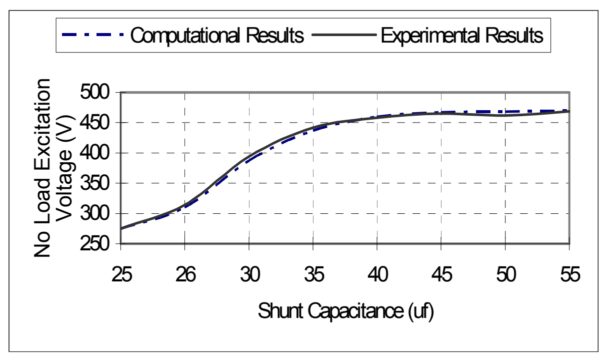



Fig. 2 Variation of no load excitation voltage with shunt capacitor in shunt and series method of excitation

Fig. (2) shows the variation of no-load terminal voltage with $C_{bsh}$ when the machine is driven to a speed of 1.05 p.u. The terminal voltage increases with $C_{bsh}$ and the rate of the increment in the voltage is reduced at higher voltage levels where the machine enters higher level of saturation.

The value of $C_{bsh}$ that gives the no-load terminal voltage of 1.0 p.u. is selected as shunt capacitance and it is 35 μf.

## 4.2 Selection of Series Capacitor

At no-load condition, there is no current through $C_{se}$ and only $C_{bsh}$ is effective in the circuit. But both $C_{bsh}$ and $C_{se}$ are effective when load is being supplied. Thus, the operating constraints such as full load voltage regulation, voltage unbalance factor, and power output capacity of the machine are taken into account for selecting the optimum value of the capacitance $C_{se}$.

The effect of $C_{se}$ on the machine terminal voltage, voltage and current unbalance factors when machine is operating at rated load condition are depicted in Figs. (3a,b,c,d).

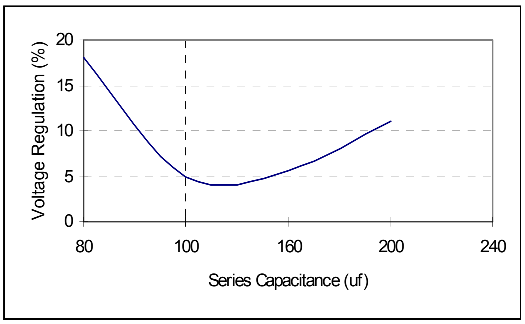



Fig. 3a Effect on voltage regulation with Variation in series capacitance

It is observed that the voltage regulation, voltage and current unbalanced factors are very sensitive to the capacitance value of series capacitor $C_{se}$. Fig. (3a) shows that the voltage regulation, which is defined as the percentage change in the load voltage as the generator delivers power from zero to rated value, is minimum for the $C_{se}$ value of 120 μf. The voltage regulation should be restricted in permissible limits, say ±6%. The voltage and current unbalanced factors, defined by ratio of negative sequence component to its positive sequence component, are minimum for the value of $C_{se}$ between 110 μf to 120 μf. Since the current unbalanced factor is the indication of negative sequence component flowing in the machine, the higher value of current unbalance causes more copper loss in the machine. Hence, the series capacitance should be selected in the range of 110 μf to 120 μf with view to limit the temperature rise of the machine.

The results depicted in Figs. (3a,b,c,d) show that there is no significant change in winding currents for the values of $C_{se}$ above 120 μf and the machine terminal voltage rises above 1.06 p.u., the permissible limit, for the value of $C_{se}$ below 120 μf. Therefore, the value of the series capacitor is selected as 120 μf in view of the minimum voltage regulation and minimum loss factor.

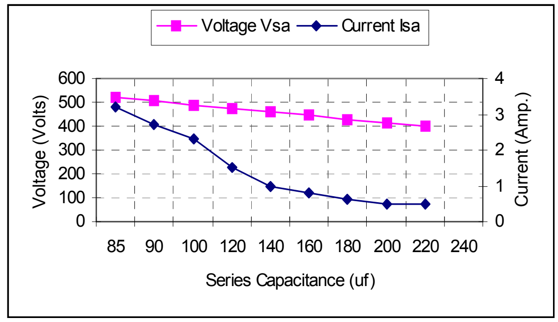



Fig. 3b Effect of series capacitance on phase voltage and current of phase A

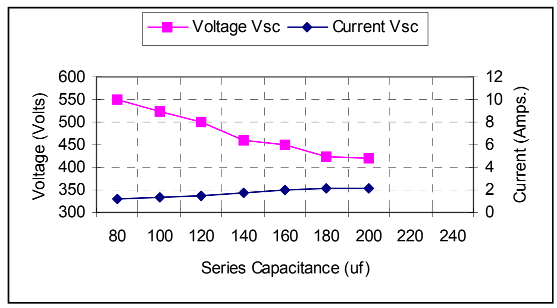
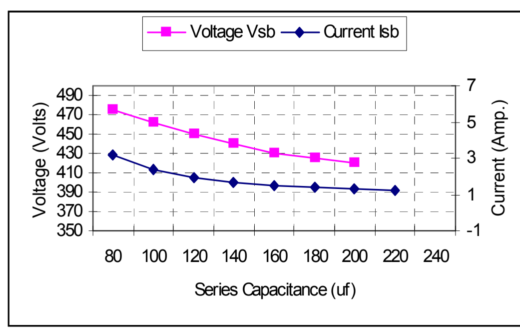



Fig. 3c Effect of series capacitance on phase voltage and current of phase B




ase

The results depicted in Figs. (3a,b,c,d) show that there is no significant change in winding currents for the values of $C_{se}$ above 120 μf and the machine terminal voltage rises above 1.06 p.u., the permissible limit, for the value of $C_{se}$ below 120 μf. Therefore, the value of the series capacitor is selected as 120 μf in view of the minimum voltage regulation and minimum loss factor.

### 4.3 Performance Characteristics

Having identified the optimum value of series capacitance, it is considered important to know how best is this selection in respect of the other relevant performance indices of the machine. One of the main criteria to be considered is that the machine should deliver the maximum safe power at the desired voltage level without exceeding the electrical and magnetic loading of the machine. The frequency of the supply should also not fall below the minimum permissible value. Fig. (4a,b,c) displays the variation of machine performance such as load terminal voltage ($V_L$), per unit frequency (F), loss factor ($f_{loss}$), voltage unbalance factor (VUF), and winding voltages and currents with power output.

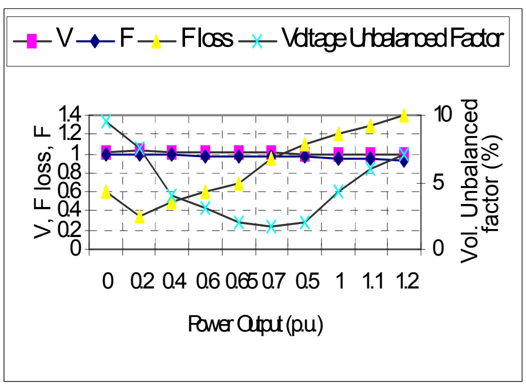



Fig. 4a Load characteristics of three-phase SEIG supplying single-phase load

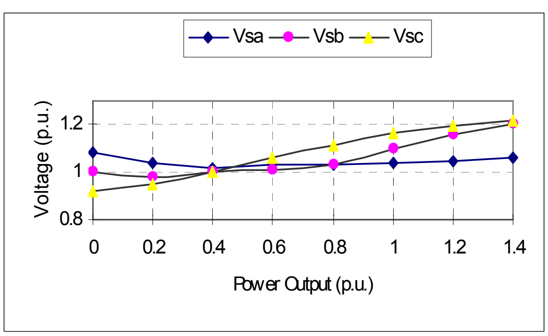



Fig. 4b Phase voltages of three-phase SEIG supplying single-phase load

It is observed from Fig. (4a) that it is possible to obtain almost a flat load characteristics with excellent voltage regulation. The load terminal voltage is 1.03 p.u. at rated power output. The loss factor initially decreases with load and then increases, reaching rated value (1 p.u.) at rated power output. The frequency of generation also changes from 1.05 p.u. to 1.01 p.u. when the generator is loaded from no load to rated power. However, at the rated power output, the current flowing through phase b and phase c winding are higher than the rated current of the machine. The unbalance condition prevailing in the system is responsible for flowing of more than rated current in the phase b and c. This condition results in localized heating of the windings thereby necessitating derating of the SEIG. Fig. (4c) shows that the machine is required to derate to 0.84 p.u. of its rated power in order to restrict the phase currents with in the rated value.

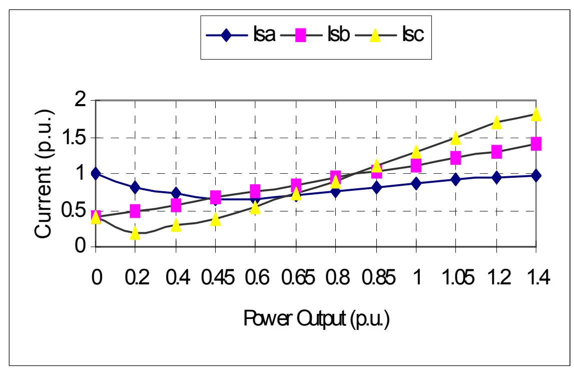



Fig. 4c Phase currents of three-phase SEIG supplying single-phase load

## 5. Summary and Conclusion

The investigation has been performed to supply single-phase power from a three-phase SEIG for remote areas. In order to get single-phase power from three-phase SEIG, partially balanced operation scheme is used.

The Shunt and Series capacitor configuration results in self voltage regulating feature of the system. Machine operates in more balanced conditions at higher loads. Selection of the capacitors for shunt and series capacitor excitation reveals that the value of the series capacitance is approximately three times the shunt capacitance. The safe power output that a three-phase SEIG can deliver to the single-phase load is approximately 84 percent of its rated capacity.

The Shunt and Series capacitor excitation has a better performance due to the following reasons.

(i) The flat load characteristics shows that the one shunt and one series capacitor configuration offers high overload capability. Hence the system is more stable at overloads.

(ii) The loss factor remains with in reasonable limits throughout its operating range, i.e. from no load to rated load conditions. Thus, this configuration is suitable for both constant and variable power output applications.

So it can be concluded that a three-phase SEIG can supply single-phase power for remote areas, if situation demanded with Shunt and Series capacitor excitation scheme.

## References


[1] P.L. Alger 1970. Induction Machines, Gorden and Breach.

[2] N. Ammasaigounden; M. Subbiah and M.R. Krishnamurthy, 1986. Wind Driven Self-excited Pole Changing Induction Generators, *IEE Proc. Electric Power Appl.* Vol. 133, Pt. B. No. 5, pp 315-321.

[3] J. Arillage and Watson, D.B. 1978. Static Power Conversion from Self-excited Induction Generator, *Proc. IEEE*. Vol. 125, No. 8, pp. 743-746.

[4] E.D. Bassett and E.M. Potter. 1945. Capacitive excitation for induction generators. *AIEE Trans.,* Vol. 54, pp. 540-545.

[5] J.L Bhattacharya, J.L. and J.L. Woodward. 1988. Excitation balancing of a self-excited induction generator for maximum output. *Proc. IEE,* Pt. C, Vol. 135, No. 2, pp 88-97.

[6] T.F. Chan. 1993. Capacitance Requirements of Self-excited Induction Generators, *IEEE Trans. on Energy Conversion,* Vol. 8, No. 2, pp. 304-311.

[7] T.F. Chan. 1996. Self-Excited Induction Generators Driven by Regulated and unregulated Turbines, *IEEE Trans. on Energy Conversion,* Vol. 11, No. 2, pp. 338-343.

[8] T.F. Chan. 1998. Performance Analysis of a Three-Phase Induction Generator Connected to a Single-phase Powder System, *IEEE Trans. on Energy Conversion,* Vol. 13, No. 3, pp. 205-213.

[9] M.O. Durham and R. Ramakumar. 1987. Power system balancers for an induction Generators, *IEEE Trans. on Industry Applications*. Vol. IA-23, No. 6, pp. 1067-1072.

[10] R.J. Harrington and F.M.M. Bassiouny. 1998. New Approach to Determine Critical Capacitance For Self-excited Induction Generators. *IEEE Trans. on Energy Conversion.* Vol. 13, No. 3, pp. 244-249.


## Nomenclature

| | | |
|---|---|---|
| $V_{sa}$, $V_{sb}$, $V_{sc}$ | – | Phase voltages of phases a,b & c |
| $I_{sa}$, $I_{sb}$, $I_{sc}$ | – | Phase currents of phases a,b & c |
| $C_s$, $C_{sh}$ | – | Series and shunt capacitances |
| $V_L$, $I_L$ | – | Load voltage and current |
| $Z_L$ | – | Load impedance |
| Y | – | Admittance |
| $V_0$, $V_+$, $V_-$ | – | Zero, positive and negative sequence voltages |
| K | – | Various constants |
| F | – | Per unit Frequency |