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Genetic Algorithm approach to find excitation capacitances for 3-phase smseig operating single phase loads

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ABSTRACT

This paper is to investigate an excitation scheme for a three-phase SEIG supplies isolated single-phase loads. It will be shown that by arranging the stator winding of the induction generator and appropriate excitation capacitances in the form of the Smith connection, good phase balance in the generator can be achieved, resulting in a high efficiency and large power output. In addition to providing the reactive power for self-excitation, the capacitances also act as phase balancers. Performance analysis is based on the method with the aid of a phasor diagram, the conditions for achieving perfect phase balance are deduced and a method to compute the capacitances required is developed.

Key Words:

Smith Connected Self Excited Induction Generator (SMSEIG), Genetic Algorithm (GA), Phase Balancing.

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INTRODUCTION

Among the various non-conventional energy sources, wind energy electric conversion systems have become more popular, since power in the order of several hundred kilowatts can be generated by a single wind turbine generator unit. In recent years, the use of the squirrel-cage induction machine has been increasing due to the widespread exploitation of renewable energy resources and the rapid developments in embedded generation in distribution systems. The squirrel-cage induction machine is cheap, rugged, does not require synchronizing equipment, speed capability, maintenance free compared to synchronous generators and has inherent protection against short circuit. Such wind turbine generator systems are classified as (i) systems supplying power directly to the grid and (ii) systems supplying power for isolated loads. The second type of system is taken up for study in this paper. The public utility networks are predominantly three-phase systems and so generally grid-connected induction generators are three-phase machines. However, there are many remote locations which are usually quite away from the load centers and in these areas; it is difficult and expensive to provide three-phase transmission and distribution networks. In such locations, if wind potential is adequate, it will be economical to provide a single-phase power network that has as wide coverage of area as possible. A need therefore arises for the use of single-phase induction generators in these systems. In this context it may be noted that nearly all commercially available single-phase induction machines are designed for motor operation, only with ratings up to 2 kW and for power ratings above 2 kW, considerations such as cost, machine size, and delivery time, all tend to favor the use of standard three-phase induction machines. So, it becomes necessary to make use three-phase machines in single-phase operation. However, the plain single-phasing mode of operation gives poor machine performance, in terms of power output (power input to the grid), power factor and phase balance [1].

II. SELF EXCITED INDUCTION GENERATORS (SEIGs)

The phenomenon of self-excitation in isolated induction machines has been known since the 1930s. The utilization of such an idea in the generation of electric power was realized after the recently energy crisis, and the growing interest in the use of other energy sources. This has been motivated by concern to reduce pollution by these of renewable energy resources such as wind, solar, tidal and small hydro potential. Preference is given to self-excited induction generators over a wide range of speeds. This type of conversion has been found particularly convenient for isolated and remote loads.

Considerable work has been done on the analysis of capacitor-excited, balanced, three-phase induction generators [2], however, the unbalanced operation of such machines has been given no attention. This mode of operation may sometimes be of great interest for various small-scale applications where balanced conditions are not necessary, such as single-phase emergency supplies, portable sources for remote construction sites and isolated line repeaters. In case of the failure of one or two capacitors in a machine with balanced excitation, the drop in power output will not be very great if the remaining capacitor is used for excitation - a matter which does not affect unbalanced loads.

In the stand-alone operation of such Self-Excited Induction Generators (SEIGs), the terminal voltage and frequency vary with the prime-mover speed, excitation capacitance and load impedance. Furthermore, owing to saturation, the equivalent magnetizing reactance and the core loss resistance vary with the operating point [3].

Low-power generators (say up to 10 kW) invariably feed a single-phase supply system. Since it has been found that a normal single-phase induction motor cannot be effectively used as an SEIG, a specially designed two-winding single phase SEIG has been used. Since this requires modified manufacturing procedures, and hence is expensive, the alternative of using a three-phase induction generator as an SEIG to feed single-phase load appears attractive. This requires a suitable balancing system to achieve balanced winding currents and to obtain maximum output with minimum losses.

Three-phase induction generators operating on a single-phase grid is an extreme case of unbalanced operation, and hence, some form of phase balancing need to be provided to ensure proper machine operation. [4]used an artificial third line, created using a capacitance and an inductance of equal reactance's, for supplying the induction generator whose power factor has been corrected to unity. The disadvantage of such a method is that, in the event that the supply is removed, severe over voltages will be produced as a result of series resonance between the capacitance and inductance.

A phase-balancing method applicable to standard stator delta-connected symmetrical three-phase machine is the Steinmetz connection. By using a modified steinmetz connection [5] that comprised main and auxiliary load resistances and excitation capacitances, perfect phase balance could be obtained with the SEIG operating at impedance angles exceeding ($2\pi/3$) rad. The practical application of a simplified version of the above system to small micro-hydro generation schemes was also reported recently [6]. With the auxiliary load resistance removed, however, phase balance in the SEIG could be obtained only when the impedance angle of the machine was equal to ($2\pi/3$) rad.

It can be shown that, with one phase converter connected across the lagging phase; perfect phase balance can be achieved when the generator impedance angle is $(2\pi/3)$ rad. If in addition a second phase converter is connected across the leading phase, then perfect phase balance can be achieved at any speed over the practical operating range. Both phase converters are capacitive when the generator impedance angle is less than $(2\pi/3)$ rad. But for generator impedance angles above $(2\pi/3)$ rad, one of the phase converters has to be inductive. This implies that an inductance must be used at heavy loads, with the disadvantages of higher cost and extra reactive power consumption

An unconventional winding connection that enabled a three phase induction motor [7] to operate satisfactorily on a single-phase supply . This connection is usually referred to as the Smith connection which employs capacitances exclusively for achieving phase balance. In the phase balancing schemes proposed by Smith [8], capacitors were used exclusively and there was no danger of resonance effect. Depending on the generator power factor angle, however, the schemes may require a double-line-to-ground supply system, current injection transformer, or a line-to-ground path for the injected current.

This phase-balancing scheme was also known under the trade name SEMIHEX motor or high-efficiency single-phase induction motor [9]. Satisfactory operation was reported for motor ratings up to 30 kW. Published work on the Smith connection to date, however, has been confined to the motoring mode of operation and the operational aspects such as selection of capacitances for perfect balance and motor starting.

III. Smith connected motor

There are many methods used for operating a 3-phase motor from a single phase supply. A single motor driving a 3-phase generator or a rotary phase converter can supply the 3-phase voltage for one or more three phase motors. This is relatively expensive. A 3-phase induction motor can be operated from a single phase supply, leaving one terminal unexcited, with shaft load restricted to less than name plate power rating .capacitor banks have been used to generate the split phase. Ronk has been developed a method using an autotransformer and capacitor to excite a third terminal for a full load operation, but the voltages are excessive at light load. The auto transformer is heavy and expensive.

New 3-phase induction motors can easily be supplied with 6 or 12 terminals brought out for the 3 phases. With this unique connection of the terminals, and with 3 capacitors, the motor can be operated from single phase at full load with the same high efficiency which it would have had on a 3-phase supply, the winding voltages and winding currents are balanced. The motor design should not be modified in any manner. This 3-phase motor has lower cost and higher efficiency than a comparable –quality single phase motor.

With balanced currents flowing in the stator phases, a perfect rotating magnetic field is created in the motor. The air gap voltages per phase, and hence the phase voltages, will also be balanced. Balanced conditions are valid for a given set of capacitance values and speed only. When the load or speed changes, the motor will be unbalanced and a new set of capacitance values need to be used in order to balance the motor again.

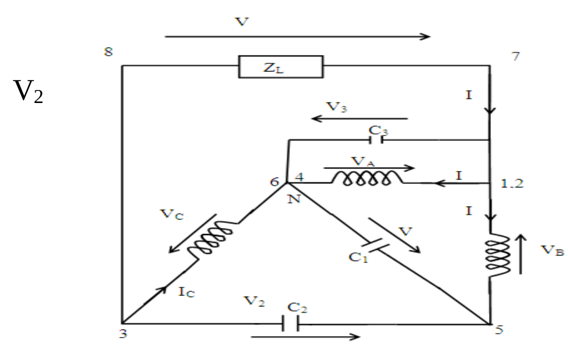

Fig 3.1 Circuit connection of three-phase induction generator supplying an isolated single-phase load.

Circuit Connection of an Smith Connected Self Excited Induction Generator

Fig 2.1shows the proposed excitation scheme for a three-phase induction generator that supplies an isolated single-phase load. All of the voltages and equivalent circuit parameters have been referred to the base (rated) frequency and the rotor is driven in a direction that gives a positive-sequence system if the stator phases are symmetrically connected. The "starts" of the stator phases are denoted by 1, 2, and 3 while the "finishes" are denoted by 4, 5, and 6, respectively. The motor convention has been adopted for the direction of phase currents. When viewed into terminals 1 and 3 across which the single-phase load is connected, the stator phases and the excitation capacitances are in the form of the Smith connection.

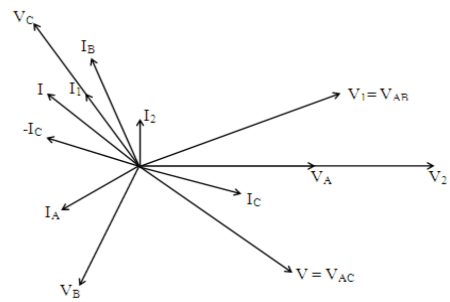

Fig 3.2 Phasor diagram balanced operation of SMSEIG.

Operating Principle of an Smith Connected Induction

For electrical power to be delivered to the load Z_L, the rotor speed must be higher than the speed of the positive sequence rotating field. The stator phase windings are designated by 1-4, 2-5and 3-6**,** respectively. It can be shown that, for generator impedances between ($2\pi/3$) rad and $5\pi/6$ rad, perfect phase balance can be achieved by using the capacitances C_1 **,**C_2 and C_3as phase converters. Fig. 3.2shows the phasor diagram of the induction generator with the Smith connection under balanced conditions, drawn using the motor convention. The capacitor currents $I_1$and I_2, driven by the voltages V_1, and V_2, provide the B phase current I_B**.** Since the voltage $V_2$is always equal to twice of A-phase voltage $V_1$the capacitor currents $I_2$and$I_3$are equal if capacitance C_3 is equal to twice the capacitance C_2**.** This will ensure that zero-sequence current is suppressed, an essential condition for achieving perfect phase balance. It can also be shown that the values of the three capacitances that yield perfect phase balance depend upon the generator positive sequence impedance angle, which in turn is a function of the rotor speed. For easy reference in the subsequent discussion, this new excitation scheme will be abbreviated as the SMSEIG.

Self-excitation in the SMSEIG takes place in a similar manner as a three-phase SEIG with symmetrical winding connection and balanced capacitances. Residual flux must be present in the rotor, and the capacitances must be sufficiently large for the terminal voltage to build up. Unlike the case of grid-connected induction generators, the frequency and magnetizing reactance of the SMSEIG are not constant but vary with the rotor speed and the load impedance.

In order to eliminate the zero-sequence current, the sum of the stator phase currents must be forced to zero. Referring to Fig 3.1, it is observed that the total current flowing into the pseudo neutral node N comprises I_A, I_C, I_1 and I_3. The B-phase current I_B consists of the capacitance currents I_1, I_2. If I_2 is made equal to I_3, the sum of the phase currents will be equal to zero, and hence, the zero-sequence current will vanish. Since the voltage V_2 is always equal to $2V_A$, the above condition is satisfied if the capacitance $C_3$is equal to twice the capacitance C_2.

Provided that the generator impedance Φ_P angle lies between ($2\pi/3$) and $5\pi/6$ rad, I_B can be synthesized with the proper magnitude and phase angle as to yield perfect phase balance in the induction generator, as illustrated in Figs. 3.2 and 3.3 . Under this condition, the induction generator operates with balanced phase currents and phase voltages and its performance is similar to a three-phase SEIG with balanced excitation capacitances and balanced load impedances. The currents I_1,I_2 and I_3 can be adjusted easily by varying the capacitances C_1,$C_2$and C_3 . Fig. 3.2 also suggests that the SMSEIG is best suited for supplying high power factor (e.g., resistive) load

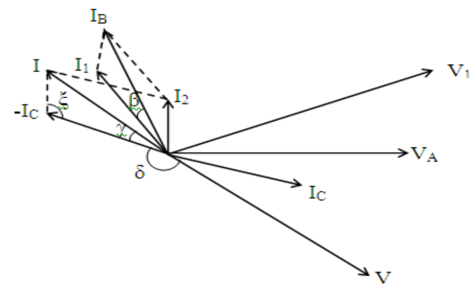

Fig3.3 Phasor diagram showing detailed angular relationships.

Consider the phasor diagram in Fig. 3.2 and 3.3, drawn for the special case for perfect phase balance. The current I_1 leads V_1 (or V_{AB}) by $\pi/2$ rad and hence lags V_B by $2\pi/3$ rad. The voltage V_2 (which is equal to V_{AB}-V_C), is equal to $2V_A$. The capacitor current I_2 leads V_2 by $\pi/2$ rad and hence it lags V_B by $5\pi/6$ rad. For generator impedance angles between $2\pi/3$ rad and $5\pi/6$ rad, the phase current I_B can be synthesized with the required magnitude and phase angle to give phase balance, by using suitable values of C_1 and C_2.

Under perfect phase balance conditions, the phase currents of the induction generator sum must equal to zero. This requires that the currents I_2 and I_3 to be equal, implying that C_3 must be equal to twice of C_2. With balanced currents flowing in the stator phases, a perfect rotating magnetic field is created. The air gap voltages per phase, and hence the phase voltages, will also be balanced. The generator operates as if it were supplying a balanced three-phase load , hence the efficiency is the same as that obtained when the generator operates on a balanced three-phase grid.

IV. DETERMINATION OF SEQUENCE IMPEDANCES

The positive sequence equivalent circuit of the induction machine is given in Fig. 4.1 below where reactances correspond to the base frequency (50Hz) and $X_m$is the saturated value corresponding to the forward revolving air gap flux. The negative sequence circuits would have the term (a-b) of Fig. 4.1 replaced by (a+b). For a given machine, the positive and negative sequence admittances Yp and Yn are calculated using the corresponding equivalent circuits as shown in the Figs. 4.1 and 4.2.

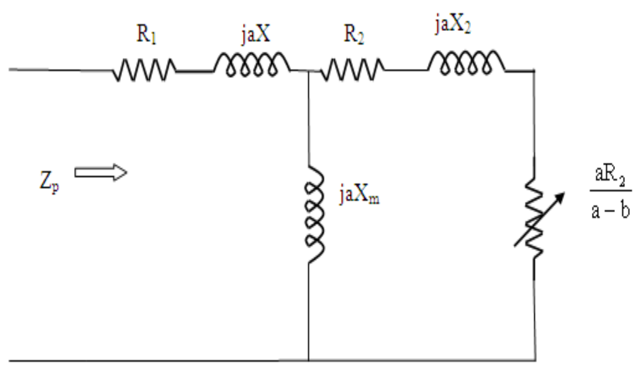

Fig 4.1 Equivalent circuit for positive sequence impedance.

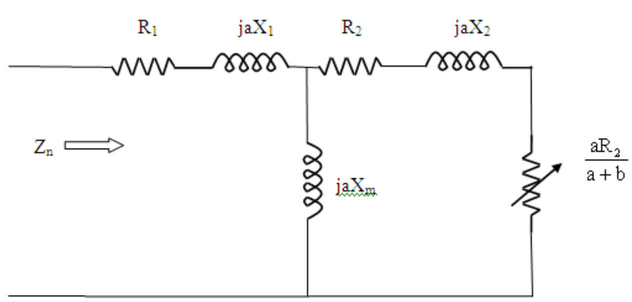

Fig 4.2 Equivalent circuit for negative sequence impedance.

Rp = real (Zp), Xp = imag (Zp),

Rn = real (Zn), Xn = imag (Zn).

The degree of phase imbalance is conveniently described by the voltage unbalance factor (VUF) which is the ratio of the negative- sequence voltage to the positive-sequence voltage.

A. Determination of machine variables

Fig. 4.3 is a passive circuit consisting of the load impedance Z_L and the equivalent Z_{in} impedance. For successful self-excitation.Of the SMSEIG, the sum of these two impedances must be equal [2] , [10].

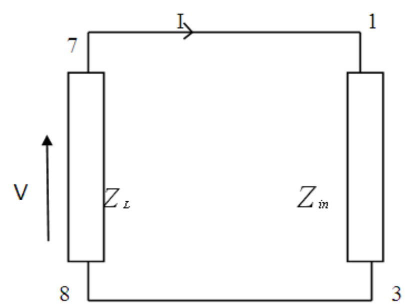

Fig 4.3 Simplified circuit of SMSEIG for determination of machine variables

$$Z_L = \frac{R_L}{a} + jX_L \qquad (4.1)$$

$$Z_L + Z_{in} = 0 \qquad (4.2)$$

It should be noted that for a given per-unit speed and a given set of excitation capacitances, is a highly nonlinear function of and, implying that (4.2) is a complex equation in these two variables. To avoid the lengthy mathematical manipulations involved, the solution of (4.2) is formulated as the following optimization problem.

$$\textbf{Minimize}(a, X_m) = \sqrt{\left(\frac{R_L}{a} + R_{in}\right)^2 + (X_L + X_{in})^2} \qquad (4.3)$$

Subject to constrains

$0 < a < b$

$0 < X_m < X_{mu}$

Where X_{mu} is the saturated value of the magnetizing reactance.

It is easy to show that (4.2) is satisfied when the scalar impedance function Z(a,Xm) given by (4.3) assumes a minimum value of zero. This paper presents the genetic algorithm based optimization method to solve the above minimization function.After a and X_m have been determined, the positive-sequence air-gap E_1 voltage can be obtained from the magnetization curve. The positive-sequence voltage V_P is next computed from the equivalent circuit.

B. Minimization Problem

For starting the minimization process of the objective function, an estimate for the ranges of the unknown variables is needed. In many optimization problems even to obtain such estimates suitably, certain trials may be required. However in the present problem, it is easier to give the range for the unknown variables a and X_m, because in well-designed self-excited induction generators, it is known that the slip {(a-b)/a} is small and operation of the machine is only in the saturated region of the magnetization characteristics. So, the range for a can be given as 0.8 to 0.999 times the value of b and for X_m as 25% to 100% of critical magnetizing reactance, X_{mc} . In the next Section on the predetermination of performance of a generator chosen as an example, the objective function being minimized with respect to the number of generations and finally reaching zero value is shown.

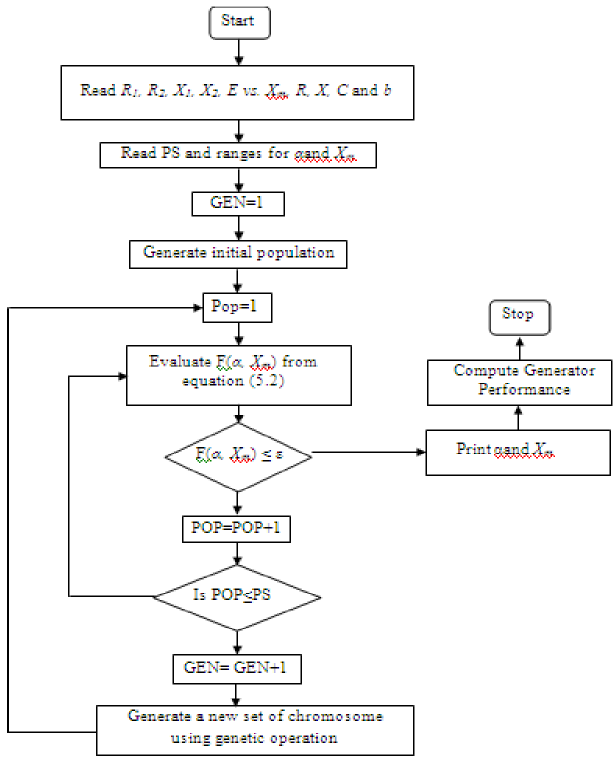

Fig 4.4 flowchart to the algorithm followed to solve GA based minimixation function.

V. CONDITIONS FOR PERFECT PHASE BALANCE

It is of interest to investigate the values of susceptances that will result in balanced operation in the three-phase induction machine. The negative-sequence voltage must vanish for the three phase, SEIG to operate with perfect phase balance.

$$(1-a^2)Y_1+2Y_2-a^2Y_p=0 \qquad (5.1)$$

Assuming that Y1 and Y2 to be pure capacitive admittances, equation may be rewritten as two simultaneous algebraic equations.

$$\frac{1}{2}\left|Y_1\right|+\left|Y_2\right|=-\frac{Y_P}{\sqrt{3}}\cos\varphi_P$$

$$\frac{3}{2}\left|Y_1\right|+\left|Y_2\right|=-\frac{Y_P}{\sqrt{3}}\sin\varphi_P$$

Where φ_P is the positive sequence impedance of the induction generator.

By solving above 2 equations the capacitive susceptances that result in perfect phase balance are obtained as by assuming $Y_1 = j|Y_1|$, $Y_2 = j|Y_2|$ and $Y_3 = j|Y_3|$ .the values of Y_1 and Y_2 for balanced operation are

$$|Y_1| = \frac{2}{\sqrt{3}}|Y_P|\sin(\frac{5\pi}{6} - \varphi_p) \quad (5.2)$$

$$|Y_2| = |Y_P|\sin(\varphi_p - \frac{2\pi}{3}) \quad (5.3)$$

(5.3)

$$|Y_3| = 2|Y_P|\sin(\varphi_p - \frac{2\pi}{3}) \quad (5.4)$$

(5.4)

The values of phase-converter susceptances required thus depend on Y_P and φ_P which are both functions of the rotor speed. Depending upon the generator impedance angle, one or more of the susceptances may assume negative values, implying that inductances may have to be used for perfect phase balance. When φ_P lies between $2\pi/3$ rad and $5\pi/6$ rad, Y_1, Y_2 and Y_3 all have positive values, implying that perfect phase balance can be achieved by using capacitances only. When φ_P is less than $2\pi/3$ rad, Y_1 is positive but Y_2 and Y_3 are negative hence one capacitance and two inductance are needed for perfect phase balance.

A. Excitation Capacitances for Perfect Phase Balance

It is of interest to determine, for a given load impedance and per-unit speed, the values of excitation capacitances that give perfect phase balance in the SMSEIG. Since Y_P and φ_p are functions of α and X_m, both being unknown to start with, an iterative procedure has to be used. The steps are outlined as follows:

1) Assume appropriate initial values of α and X_m.

2) For the given value of load impedance, compute the load admittance $|Y_L|$ and the operating load power factor angle.

3) Determine the corresponding generator impedance angle φ_p .

4) Compute $|Y_p|$ from (5.8), using the current values of $|Y_L|$ and φ_p .

5) Compute the capacitive admittances Y_1, Y_2 and Y_3 from (5.2) to (5.4),

6) Determine the new values of a and X_m, using the optimization method.

7) Update the values of φ_p and $|Y_L|$ using the new values of a and X_m.

8) Repeat steps 3 to 7 until the values of a in successive iterations are less than the prescribed tolerance, say 1.0exp(-6)

9) Compute the excitation capacitances C_1,C_2 and C_3 using the final values of a and X_m , hence obtaining the performance of the SMSEIG under balanced conditions.

The flowchart should be required to easily understand the above iterative process algorithm is given as follows in Fig 5.1.

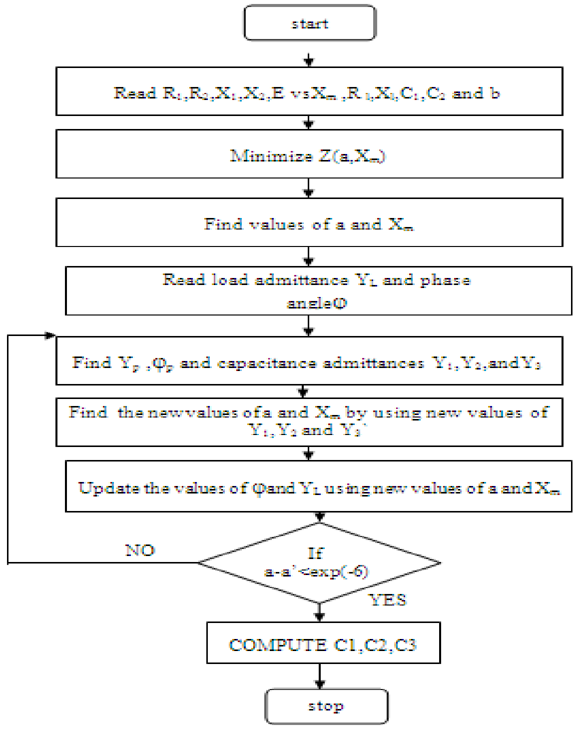

Fig 5.1 Flow chart for the iterative process to find the Excitation Capacitances for Perfect Phase Balance.

VI. Simulation Results

No load and blocked rotor tests are conducted on the machine to find out the equivalent parameter of the machine.

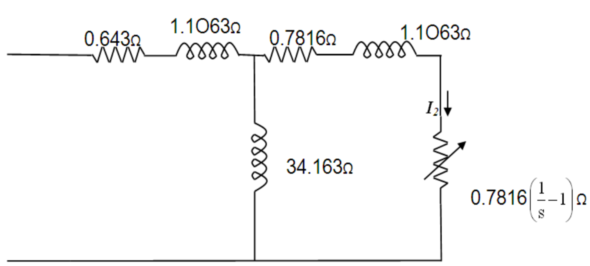

Fig.6.1 Induction machine equivalent circuit parameters

For load resistance R_L=55Ω **and per unit speed b**=0.9

We obtain per unit frequency a=0.8549

Magnetizing reactance X_m =14.4511Ω

Excitation capacitances c1=39.08uF

c2=19.54uF

c3=39.09uF

positive sequence admittance Y_p= 0.023743

negative sequence admittance Y_n=0.084890

For load resistance R_L=55Ω **and per unit speed b**=1.4

We obtain per unit frequency a=1.2653

Magnetizing reactance X_m =14.4511Ω

Excitation capacitances c1=26.4077uF

c2=13.2023uF

c3=26.2077uF

positive sequence admittance Y_p= 0.035141

negative sequence admittance Y_n=0.0510920

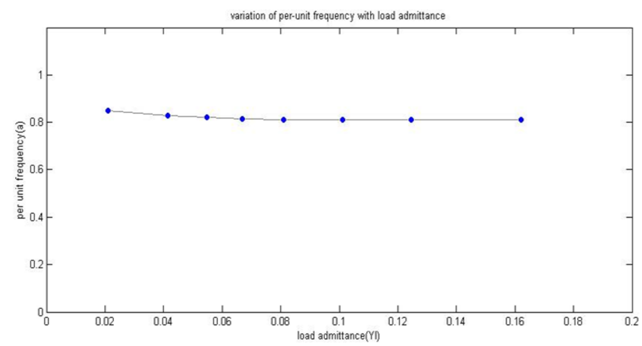

Fig 6.2 variation of per unit frequency with load admittance

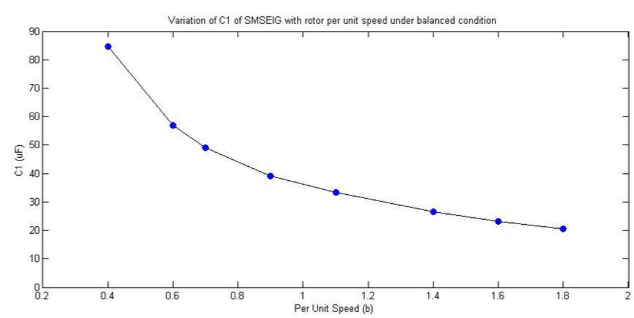

Fig 6.3 variation of c_1 with rotor per unit speed under balanced condition

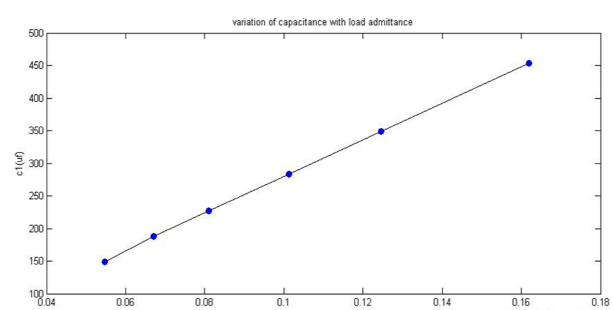

Fig 6.4 variation of capacitance with load admittance

CONCLUSION

This paper has presented the principle and analysis of a novel excitation scheme for a stand-alone three-phase induction generator that supplies single-phase loads, viz. the SMSEIG. Adopting the Smith connection with appropriate values of excitation capacitances, balanced operation of the three-phase machine can be achieved. The steady-state performance of the SMSEIG is analyzed using the method of symmetrical components in association with an optimization procedure. A method to determine the capacitances to give perfect phase balance is also presented. Although only results of the resistive load case have been reported, the analysis set forth can readily be applied to different load power factor conditions. The SMSEIG has the advantages of low cost, high efficiency, and large power output and, as such, is an economical choice when developing autonomous single-phase power systems in remote regions. The effect of capacitances on the generator performance has also been investigated.

GA based MATLAB program had used to solve the minimization function of two variables and then some equations are solved on base of Newton Raphson algorithm finally to attain the values of excitation capacitances to achieve perfect phase balance for single phasing operation.

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