

# ANALYSIS OF PARALLEL-OPERATED SELF-EXCITED INDUCTION GENERATORS

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**Abstract**—The paper presents an iterative solution for the problems related to steady state performance of self-excited induction generators operating in parallel. The analysis is based on voltage and current balance equations derived from an inverse-model for steady state equivalent circuit of induction machines. The non-linearity in the magnetization characteristics has been taken into account by piece-wise linearisation. The proposed method is general and can be applied for analysis of any number of parallel connected machines. Theoretical predictions and experimental results are presented to study different performance characteristics of the system.

## I. INTRODUCTION

The rapid depletion and enhanced cost of conventional fuels have given an impetus to the research on self-excited induction generators as alternative power source converting power from wind, biogas, mini and micro-hydro units etc. However, except for the case of portable emergency power supply units, it is unlikely that a single generator could meet the power demand. Also, utilization of the full potential of energy may require operation of many such units in parallel. When induction generators are connected to the power grid controlled by large rating synchronous generators, it draws the required VAR from the bus, voltage and frequency of which are determined by the dynamics of the synchronous generators. DeMello and Hannett [1] worked on several aspects of such systems and concluded favorably for a system consisting of many induction generators being operated in parallel.

Parallel operation of induction generators has the advantage of elimination of the need for synchronization and of the associated problems with hunting etc. Extensive studies have been carried out on self excited induction generators operating in stand alone mode [2]-[5], but very limited references [6]-[8] are available on the parallel operation of such units. The method of analysis in [6] is based on a simplified equivalent circuit, and as a result the developed expressions lack accuracy in certain situations, and also fail to meet the requirements to study many aspects of parallel connected generators. The methods suggested in [7]-[8] set up non-linear equations, based on conventional circuit model, and solve them by the Newton-Raphson method.

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This paper is addressed to the method(s) of investigation for certain aspects of operation of multiple self excited induction generators connected to a common bus. Such aspects are voltage regulation for given excitation capacitances, load sharing as influenced by machine parameters and speed, VAR requirements at a specified common terminal voltage etc. Different algorithms for iterative solutions of the steady state equations, under balanced operating conditions, are developed to obtain performances of such systems. Test results on an experimental setup are presented for comparison with the predictions.

## II. BASIC EQUATIONS

*A. Development of basic equations based on conventional equivalent circuit:*

The usual approach [6]-[8] to derive the equations to study the performance of parallel-operated self-excited induction generators is based on steady-state stator-referred T-equivalent circuit. In the analysis presented in this paper, it has been found that the T-model makes the equations more complicated. As actual rotor variables are not required, the inverse- $\Gamma$  model [9] may be used with advantage for the analysis.

When  $N$  number of machines operate in parallel (Fig.1), the terminal voltage (i.e. the common bus or load voltage) and frequency for all the  $N$  machines remain same, whatever may be the individual machine speeds and loading conditions. Fig.2 shows the  $i$ th generator connected to the common load. All circuit elements except the magnetizing reactances, i.e.  $X_m$ 's, are assumed to remain constant. The magnetizing reactances change with speed and load, and the changes are accounted using the rms saturation characteristics of the machines. With reference to Fig.2, the following voltage equation expressed in terms of complexors, can be written for the  $i$ th machine.

$$\frac{V_t}{F} = -Z_{si} I_{si} \quad \text{for } i = 1, 2, \dots, N \quad (1)$$

where

$$Z_{si} = \left[ \frac{R_{si}}{F} + jX_{\sigma i} \right] + \left[ ja_i X_{mi} \left| a_i^2 \left( \frac{R_{ri}}{F - v_i} \right) \right. \right]$$

in which

$$a_i = \frac{X_{mi}}{X_{mi} + X_{lri}}$$

$$X_{\sigma i} = X_{lsi} + a_i X_{lri}$$

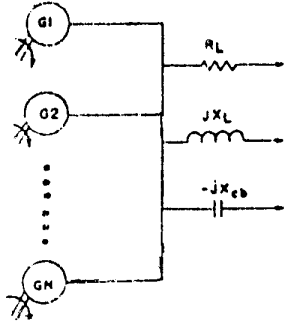
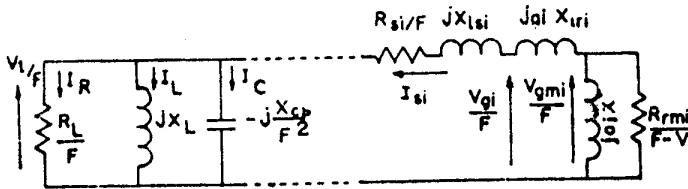


Fig.1 Induction generators connected in parallel.

Fig.2 Per phase equivalent circuit (inverse- $\Gamma$  model) of the  $i$ th generator connected to common load terminals.

As the load current is the net contribution from all the machines, the following current balance equation holds at the common bus

$$\mathbf{V}_t \left( \frac{1}{R_L} - \frac{j}{FX_L} + \frac{jF}{X_{cb}} \right) = \sum_{i=1}^N \mathbf{I}_{si} \quad (2)$$

Separating out (1) and (2) into real and imaginary parts yields  $2(N+1)$  non-linear algebraic equations. With  $V_t$  as reference phasor, solutions to (1) and (2) would then give the values of  $I_1, I_2, \dots, I_N, F$  and  $X_{cb}$  provided all the machine parameters in the circuit model are known. But the values of  $X_{mi}$ 's are not known a priori and are regulated by  $F$ , machine speeds and the effective loading on the system. So additional  $N$  equations are required to determine the values of  $X_{mi}$ 's. For the current directions shown (Fig.2), airgap voltages of the individual machines are related to the terminal voltage by the following equation

$$\frac{\mathbf{V}_{gi}}{F} = \frac{\mathbf{V}_t}{F} + \mathbf{I}_{si} \left[ \frac{R_{si}}{F} + jX_{lsi} \right] \quad (3)$$

where

$$\mathbf{V}_{gi} = V_{gi} \angle \delta_i$$

The rms  $V-I$  saturation curve of each of the  $N$  machines in terms of the magnetizing reactance may be represented as

$$X_{mi} = \mathcal{F}_i \left( \frac{V_{gi}}{F} \right) \quad (4)$$

where  $\mathcal{F}_i$  indicates an explicit (implicit) non-linear relation.

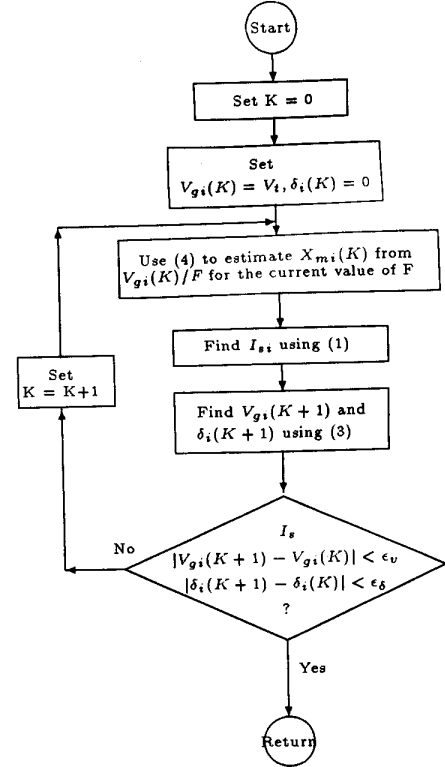


Fig.3 Flow chart of the subprogram AIRGAP.

Solutions to (1) and (2) demand a prior estimation of  $X_{mi}$ 's, whereas (3) and (4), which determine the values of  $X_{mi}$ 's, can only be solved if  $I_{si}$ 's and  $F$  are known. The interdependency of the non-linear equations indicates that a closed form solution for the machine quantities is not possible. Hence, an iterative approach is required for the solution.

In the iterative process, which involves successive improvement of the unknown variables, it is observed that the per unit frequency ( $F$ ) is the most important unknown parameter. Whatever may be the sequence of solutions of (1) through (4), an initial estimate for  $F$  and its successive improvement is a must.

For the circuit model considered, the first estimation for  $F$  in the iterative process may be obtained [6] by neglecting the stator impedance and rotor leakage reactance. The basis for these assumptions arises from (i) comparatively lower stator voltage drop and power loss and (ii) highly effective resistive rotor circuit owing to low slip value. Thus equating the generated and consumed power, the equation to calculate the initial guess for the terminal p.u. frequency

$$F(0) = \frac{\sum_{i=1}^N \frac{v_i}{R_{ri}}}{\sum_{i=1}^N \frac{1}{R_{ri}} + \frac{1}{R_L}} \quad (5)$$

By reference to Fig.2, the exact power balance equation for  $N$  number of self-excited induction generators in parallel

is

$$\sum_{i=1}^N \frac{V_{gmi}^2 (F - v_i)}{R_{rmi} F} + \sum_{i=1}^N I_{si}^2 R_{si} + \frac{V_t^2}{R_L} = 0 \quad (6)$$

which on re-arrangement becomes

$$F = \frac{\sum_{i=1}^N \frac{V_{gmi}^2 v_i}{R_{rmi}}}{\sum_{i=1}^N \frac{V_{gmi}^2}{R_{rmi}} + \sum_{i=1}^N I_{si}^2 R_{si} + \frac{V_t^2}{R_L}} \quad (7)$$

where

$$V_{gmi} = |V_{gmi}|$$

and

$$R_{rmi} = R_{ri} \left( \frac{X_{mi}}{X_{mi} + X_{lri}} \right)^2 \quad (8)$$

 $V_{gmi}$  may be found from the following phasor relation

$$V_{gmi} = V_t + I_{si} (R_{si} + jF(X_{lsi} + \alpha_i X_{lri})) \quad (9)$$

Thus the analysis following the inverse- $\Gamma$  model has resulted in a unique expression for  $F$ , whereas the same with T-model would yield an  $N$ th order equation in  $F$ , generating  $N$  number of roots. The problems associated with the selection of proper value of  $F$  from  $N$  number of solutions in T-model justifies the formulation based on inverse- $\Gamma$  model.

### III. METHODS OF SOLUTIONS

Investigation in the present instance is broadly divided into two categories, viz. (i) operation under constant grid voltage (i.e. constant voltage operation or CVO) and (ii) operation at constant excitation capacitance (i.e. constant capacitance operation or CCO). For both categories, solution to  $F$  is the pre-requisite, hence the computational sequence to find  $F$  is discussed first.

#### A. Computation for $F$

When induction machines are behaving like generators, speeds are considered as independent variables. Thus, if  $F$  in the circuit model of Fig.2 is known, the calculations of respective power and VAR sharing become straight forward for a specific grid voltage. For a desired or declared grid voltage and load power, power sharing between generators can only be found if  $F$  is known. A direct evaluation for  $F$  is not possible because of the non-linearity of the network, hence the only alternative is to start with suitable initial guess and its further improvement through iterations. As  $F$  is a very sensitive variable, so the initial guess and the process of convergence should be formulated accordingly. The expression for  $F$  (derived from (7)) given below is used in the iteration process

$$F(M) = \frac{\sum_{i=1}^N \frac{V_{gmi}^2 (M-1)}{R_{rmi} (M-1)} v_i}{\sum_{i=1}^N \frac{V_{gmi}^2 (M-1)}{R_{rmi} (M-1)} + \sum_{i=1}^N I_{si}^2 (M-1) R_{si} + \frac{V_t^2}{R_L}} \quad (10)$$

So, for a specified  $V_t$ ,  $F$  may be improved at the  $M$ th stage from the knowledge of  $V_{gmi}$ ,  $R_{rmi}$  and  $I_{si}$  at the end

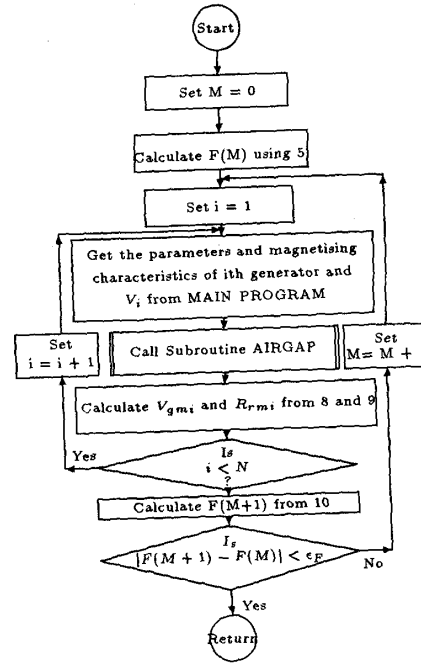


Fig.4 Flow chart of the subprogram FINDF.

of the  $(M-1)$ th iteration. The process starts with an initial estimate for  $F$  given by (5). Initially for all the machines  $V_{gi}$ 's and  $\delta_i$ 's (for  $i = 1, 2, 3 \dots N$ ) are assumed equal to  $V_t$  and zero respectively. The convergence of  $V_{gi}$ 's and  $\delta_i$ 's to their respective exact solution is achieved using (4), (1) and (3) cyclically as illustrated in the flowchart AIRGAP (Fig.3), for the considered value of  $F$ . After the convergence of  $V_{gmi}$ 's and  $R_{rmi}$ 's for all the machines is achieved,  $F$  is calculated using (10). This sequence of computation is given in flow diagram FINDF (Fig.4).

#### B. Convergence of $F$

The flowchart FINDF calls the subroutine AIRGAP,  $N$  times to calculate the next value of  $F$ . As  $\delta$  is very close to zero and  $V_g$  to  $V_t$ , so the initial assumption  $V_g = V_t$  makes the convergence in AIRGAP very fast. Incidentally in the algorithm,  $F$  decreases monotonically to converge to the exact value. This makes the stator current of each of the machines to converge in a reverse way taking increasing magnitudes in the subsequent iterations. So a test of the magnitude of  $I_{si}$  in the iterative process to avoid overloading of any of the machines will not result in false termination of the program. If  $I_{si}$  is greater than a set  $I_{max}$  in the earlier stage of convergence, the exact solution of  $I_{si}$  must be higher than  $I_{max}$ .

### IV. CHARACTERIZATION OF PROBLEMS

Induction generators need an external source for lagging VAR to maintain self-excitation and supply power at a desired voltage level. The lagging VAR source could be either

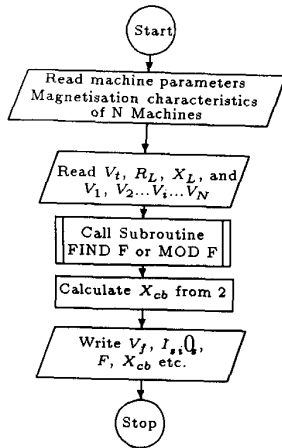


Fig.5 Flow chart to calculate capacitance requirement, F, power and current sharing in CVO mode

(i) a static VAR controller which automatically adjusts the required VAR to maintain terminal voltage at a desired level, or (ii) fixed capacitor banks connected across the machine terminals. Methods of solutions vary significantly for the two cases and hence are separately discussed here.

A. Characterization-I (Constant voltage operation i.e. CVO):

1. Capacitance requirement: This is the case when controllable static VAR source is connected to the common bus. The bus voltage is sensed and required amount of VAR is supplied to maintain the bus voltage constant at a desired level. As the VAR requirement undergoes a considerable change depending on the load and speed of the individual machines, hence an idea about the maximum leading/lagging VAR needed for the system must be known beforehand for a suitable design of static controlled VAR sources. Thus, this part involves calculation of F and the net capacitance requirement for declared values of  $V_t$ ,  $R_L$  and individual machine speeds. The flowchart is shown in Fig.5. Equating the imaginary parts in (2), capacitance requirement for a given value of F is found to be

$$C = \frac{\left[ \left( \text{Im} \sum_{i=1}^N \mathbf{I}_{si} \right) + \frac{V_t}{FX_L} \right]}{2\pi f_b F V_t} 10^6 \mu F \quad (11)$$

2. Speed range: To find the speed limit for a given load and grid voltage, speeds of all the machines are kept constant and that of the machine under consideration is varied in steps from a low to a high value, until any of the N machines attains its limiting current value.

B. Characterization-II (Constant capacitance operation i.e. CCO)

The envisaged study basically concerns the variation of grid voltage as well as the load sharing for a given value of common excitation capacitance. In this case also either the speed or the load may vary. Each iterative step is carried out in two stages to arrive at the solution. Initially for

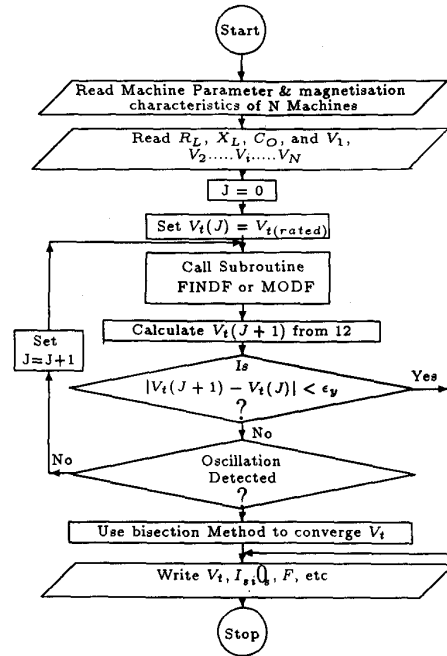


Fig.6 Flow chart to compute voltage regulation, F, power and current sharing in CCO mode.

any assumed voltage (usually rated voltage) the subroutine FINDF gives the value of F, thus ending the first stage of iteration, then at the second stage an improvement in  $V_t$  is obtained by using the following relation, thus completing the first iterative step.

$$V_t(j+1) = F(j)X_L \left[ \frac{V_t(j)F(j)}{X_{cb}} - \left( \text{Im} \sum_{i=1}^N I_{s1} \right) \right] \quad (12)$$

where

$$X_{cb} = \frac{10^6}{2\pi f_b C_o} \quad (13)$$

Repetitive use of (12) is found either to converge  $V_t$  or oscillate between two values. Once oscillation is detected, convergence is achieved following the method of bisection.

Fig.6 shows the flowchart of the computer program developed to find  $V_t$ , F,  $I_{si}$ 's, etc. of induction generators running in parallel with constant excitation capacitor across the bus (CCO mode).

## V. CASE STUDIES

To illustrate the applications of equations for prediction of performances as well as for experimentation two laboratory type machines, whose parameters are furnished in Table-I and magnetisation characteristics in Fig.7, were used. The results of investigations are presented in three separate sections as discussed below. Base values for voltage and current are taken as 230 V and 10.9 A.

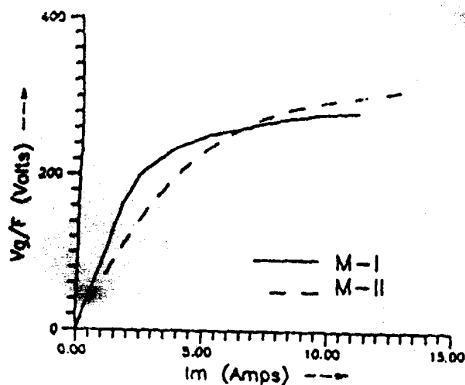


Fig.7 Magnetisation characteristics of M-I and M-II.

TABLE-1  
MACHINE RATING AND PARAMETERS

Machine Ratings:

Machine type	$V_{L-L}$	$I_L$	HP	Poles
SCM (M-I)	400 V	10.9 A	7.5	4
WRM (M-II)	400 V	11.0A	7.5	4

Equivalent Star Parameters (in ohms.):

Machine type	$R_s$	$R_r$	$X_{ls}$	$X_{lr}$
SCM (M-I)	1.23	1.105	2.756	2.756
WRM (M-II)	400 V	11.0A	7.5	4

#### A. Constant Voltage Operation (Case-I):

The VAR requirement, current distribution and power sharing for a declared terminal voltage are the objectives for this case. The calculations are based on the methods detailed in section IV A.

1) *VAR requirement:* The design of Static VAR (SVAR) sources need prior information about the maximum VAR requirement of the system. Here the VAR requirements in terms of capacitance for constant terminal voltage are found for the possible range of operation of speed and load. Fig.8 shows the individual as well as the total capacitance requirement to maintain 1 p.u. voltage across the load, when M-I and M-II are operated at 1 p.u. speed. The capacitance requirement is found to increase with the load; the rate of increase for individual machine is lower at low load and higher at high load. For an output at a declared voltage, the capacitance (VAR) requirement by parallel connected machines is more than that required by any of the machines delivering the same output at the same terminal voltage.

Situations may arise when speeds of the machines change while supplying a constant power at constant voltage. To find the range of variation of capacitance to supply a de-

sired load, speed of one machine (M-II) is changed from low to a high value, keeping the speed of the other machine (M-I) constant. The lower speed and higher speed limit being restricted by the set current limit (which has been 1.25 times the rated value in the study). Fig.9 shows the individual as well as total capacitance demand. The curves take the form of "V" and at nearly the same speeds, depending on the parameters of the machines, VAR demand is minimum. It is also noted that for individual machines, the capacitance demand is minimum when the machine is on the verge of change over from motoring to generating or vice-versa.

For the same machines running at 1 p.u. speed, Fig.10 presents capacitance variation with voltage for a few specific grid power. It is observed that at increased power demand the plot assumes the form of "V" implying that at voltages below a particular value, corresponding to minimum capacitance, the capacitance demand again increases until the excitation of the system collapses. On the other hand at low load the terminal voltage monotonically decreases with decrease in the capacitance value until the unsaturated state is reached. However, in practice, the operating points at voltages lower than that corresponding to the minimum capacitance could not be realized.

2) *Load sharing:* To find the nature of current and power sharing, two machines of same rating but of different types (M-I and M-II) are run at same speeds (1 p.u.). Fig.11 shows the variation in p.u. frequency ( $F$ ), stator currents ( $I_{s1}$  and  $I_{s2}$ ) and power outputs ( $P_{o1}$  and  $P_{o2}$ ) of both the machines. Because of the differences in parameters and saturation characteristics, one machine (M-II) is found to share higher current and power than the other. M-II reaches the set maximum current before than M-I, hence the maximum power output reduces owing to the differences in parameters when two different machines of same ratings are operated in parallel compared to the parallel operation of two identical machines, with the same parameters and magnetization characteristics, running at same speeds. For the same machines Fig.12 presents situation when machine-I is driven at 1 p.u. speed and the speed of Machine-II changes from nearly 0.9 to 1.1 p.u. From the sharing of power, it is noted that one machine becomes a load on the other machine for a speed deviation by about 3%. Hence, a very close speed regulation with respect to each other is almost essential for the effective utilization of parallel connected machines having nearly identical ratings and parameters.

#### B. Constant Capacitance Operation (Case II)

This case pertains to study for constant excitation capacitance connected to the common bus. Results presented in this section follow the computational procedure(s) laid down in section IV B.

Fig.13 shows the variation in terminal voltage, p.u. bus frequency, current and power sharing with the increase of load for a common capacitance of  $44\mu\text{F}$ , when machines I and II are operated in parallel at 1 p.u. speed. As in the individual stand alone operation, here also, maximum power output is limited by the fall in terminal voltage.

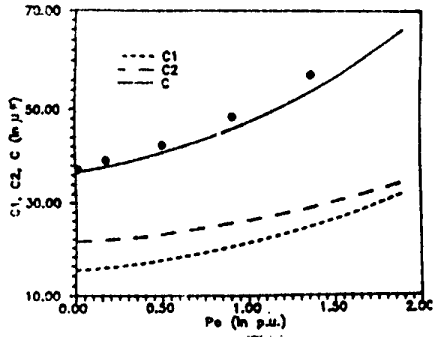


Fig.8 Capacitance requirement to maintain 1 p.u. voltage across terminals when M-I & M-II are operated in parallel.  
• experimental points

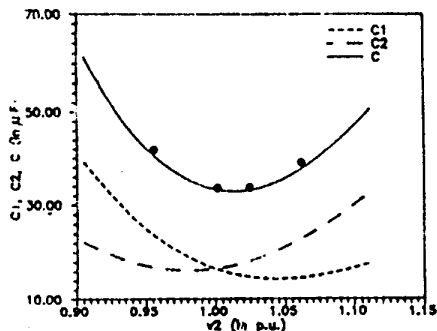


Fig.9 Capacitance requirement under variable speed condition.  
• experimental points

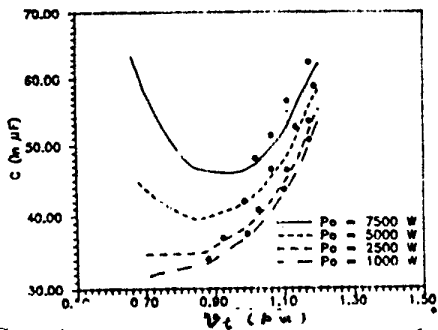


Fig.10 Capacitance requirement Vs. common bus voltage.  
• experimental points

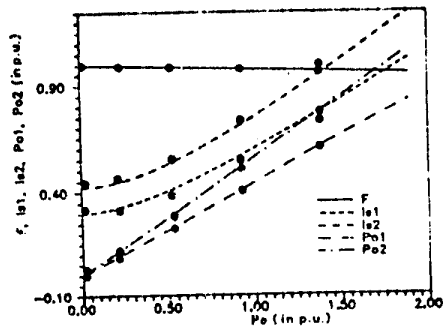


Fig.11 Variation in F, Is1, Is2, Po1, Po2.  
• experimental points

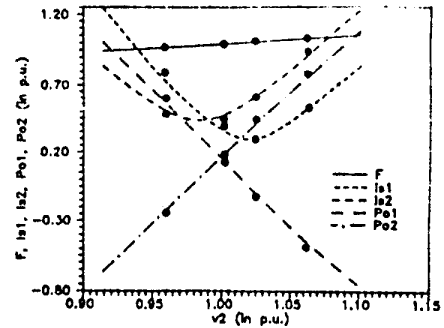


Fig.12 Variation in F, Is1, Is2, Po1, Po2 when speed of M-II is varied keeping that of M-I constant at 1 p.u.  
• experimental points

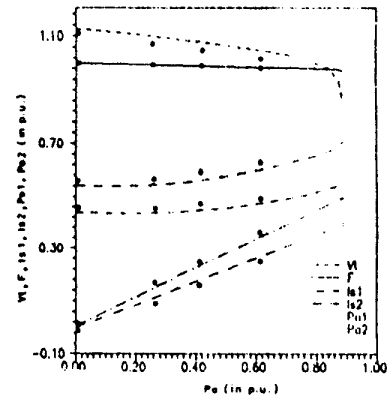


Fig.13 Variation in Vt, F, Is1, Is2, Po1, Po2 for an excitation capacitor of 44mF.  
• experimental points

Higher value of terminal capacitance is found to increase the power output limit at the cost of increased no-load terminal voltage. Fig.14 shows the common terminal voltage when M-I and M-II are operated in parallel each at 1 p.u. speed. Voltage regulation for three different capacitances viz. 36mF, 40mF and 44mF are considered for the study.

Speeds of the generator may also vary, while supplying a common load with a common excitation capacitance. Fig.15 shows regulation in voltage and terminal frequency, and sharing of current and power, when speed of M-II is varied keeping that of M-I constant at 1 p.u.

### VI. CONCLUSIONS

This paper has presented a new algorithmic method to study the steady-state performance of N number of induction generators connected in parallel. The method uses the inverse-Γ circuit model to derive a closed form expression for F from the power balance equation. The salient features of the analysis and performances are presented below:

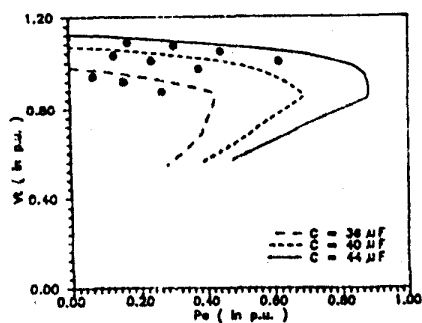


Fig.14 Voltage regulations when different capacitors are connected across the load.  
• experimental points

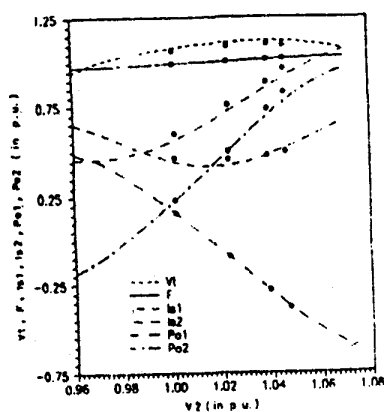


Fig.15 Variation in  $V_t$ ,  $F$ ,  $I_{s1}$ ,  $I_{s2}$ ,  $P_{o1}$ ,  $P_{o2}$  with the change in speed.  
• experimental points

- The proposed analysis is based on voltage and current balance equations. The non-linearity in magnetization characteristics has been taken into account by piece-wise linearisation technique. The iterative process starts with a justified assumption of  $F$ , which is improved by the power balance equations. Computation and convergence of  $F$  have been discussed.
- Studies have been conducted both for "constant Voltage Operation" and "Constant Capacitance Operation". Different performance characteristics viz. current and power sharing, bus frequency, capacitance requirement/voltage regulation have been found. Experimental results show excellent correlation with the performances proposed by the analysis.
- Speeds of the machines operated in parallel have a direct influence on bus frequency. Although frequency decreases with the increase in load but for a constant load, increased speeds of the machines increases the bus frequency. Also, it is expected that the machine speeds should be near to each other to avoid motoring of machines running at low speed.

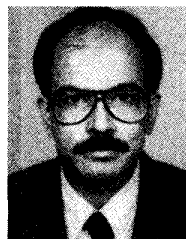
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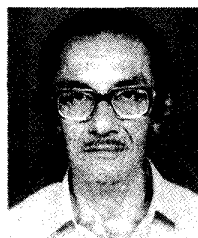
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## BIOGRAPHIES



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