

Parallel Operation of Self-Excited Induction Generators

Abdallah H. Al-Bahrani and Nazar H. Malik
Electrical Engineering Department, College of Engineering
King Saud University, Riyadh, Saudi Arabia

(Received 13/4/1992; accepted for publication 22/7/1992)

Abstract. This paper discusses steady state analysis and performance characteristics of three-phase self excited induction generators operating in parallel and supplying a balanced load. It is shown that induction machines with similar or different parameters and speeds can be operated in parallel and their steady state performance characteristics can be accurately predicted using the proposed method. The performance characteristics of such machines are influenced by the excitation capacitance, load resistance as well as speeds and parameters of the individual machines. Typical cases have been investigated for a number of test machines operating in parallel. Predictions of the proposed method have been verified experimentally.

List of Symbols

WRM, SCM	=	Wound Rotor Machine and Squirrel Cage Machine.
V_t, f, n	=	Bus voltage, frequency and number of machines.
C, X_c	=	Excitation capacitance and its reactance.
R_{s_i}, R_{r_i}	=	Machine i stator and rotor reactances.
$X_{s_i}, X_{r_i}, X_{m_i}$	=	Machine i stator, rotor and magnetizing reactances.
$I_{s_i}, I_{r_i}, I_{m_i}, V_{g_i}, P_i, v_i$	=	Machine i stator, rotor and magnetizing currents, air gap voltage, power and speed.
$R, X, Z, Y_L, G_L, B_L, P_L$	=	Load resistance, reactance, impedance, admittance, conductance, susceptance and power.
I_L, I_c	=	Load and excitation capacitor currents.
C_{min}, C_{max}	=	Minimum and maximum excitation capacitances.

All quantities are in per phase pu values, rotor quantities are referred to stator and all reactances are at base frequency.

Introduction

The principle of self excitation, by which an induction generator can be excited from static capacitors, is well known [1,2]. Owing to increased emphasis on renewable resources, the development of suitable isolated power generators driven by energy sources such as wind, small hydro-electric, biogas, etc. has recently assumed greater significance. A capacitor self excited induction generator has emerged as a suitable candidate of isolated power sources [3-6] because of its reduced unit cost, brushless rotor construction, absence of separate source for excitation, ruggedness, ease of maintenance and self protection against severe over loads and short circuits.

In some applications, a group of capacitor self excited induction generators may have to be operated in parallel [7]. Parallel operation of such generators has the following advantages [8]:

- Synchronization is unnecessary.
- Generators do not have to run at a common synchronous speed.
- An underground a.c. cable system could usefully provide part of the required excitation capacitance.

In addition induction machines have higher damping as compared to conventional types of synchronous machines. Consequently, in parallel operated SEIG's, hunting problems are reduced.

Methods of analysis and performance characteristics of a single self excited induction generator have been reported in the literature [9-14]. However, that is not the case for parallel self excited induction generators. Only in reference [8], a very simplified model has been used to describe the performance characteristics of such a group of generators. This paper presents a general method of analysis that determines the steady state operating characteristics of parallel self excited induction generators. The theoretical predictions obtained from the proposed model have been verified experimentally.

Method of Analysis

Consider " n " induction machines connected to a common bus to which an excitation capacitor C and load are also connected as shown in Fig. 1. Assume that these " n " machines are being driven by their prime movers at per unit speeds of v_1, v_2, \dots, v_n , respectively. If conditions for self excitation are satisfied, all machines will operate at a common terminal voltage V_t , with a common frequency, f . Figures 2 (a and b) show the per-phase steady state equivalent circuits of the excitation capacitor and load and the " i^{th} " machine respectively. In Fig. 2-b the core losses have been ignored. However, such losses may be incorporated in the analysis by adding a resistor of

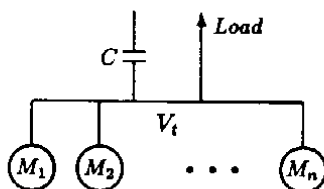
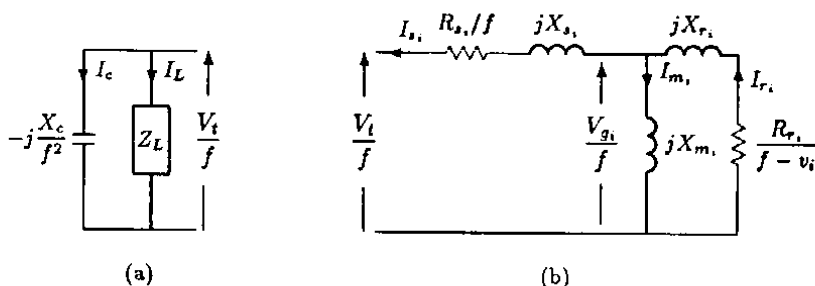


Fig. 1. Multi-induction machine system

Fig. 2. Per phase equivalent circuits of the excitation capacitor and load (a) and the i^{th} Induction machine (b).

appropriate value across either X_{mi} or the machine terminals. To represent the parallel operation of these machines, " n " such equivalent circuits (Fig. 2-b) have to be connected across the circuit of Fig. 2-a.

The performance of such " n " machines can be calculated provided that X_{mi} ($i = 1, 2, \dots, n$) and f are known. To obtain the values of these parameters, the following method is proposed.

The nodal equation at the bus is:

$$\left(j \frac{f^2}{X_c} + Y_L \sum_{i=1}^n Y_i \right) \frac{V_t}{f} = 0 \quad (1)$$

where Y_L and Y_i are given in the appendix. Under self excitation, $(V_t/f) \neq 0$, which implies that the real and imaginary parts of the total admittance at the bus must be independently equal to zero, *i.e.*

$$G_L + \sum_{i=1}^n G_i = 0 \quad (2)$$

and

$$\frac{f^2}{X_c} + B_L + \sum_{i=1}^n B_i = 0 \quad (3)$$

where G_L and B_L are the real and imaginary parts of Y_L and G_i and B_i are those of Y_i . Their corresponding expressions are given in the appendix.

In order to ensure that all machines have the same terminal voltage, the following conditions must be satisfied:

$$|Z_i| |I_{s_i}| - |Z_k| |I_{s_k}| = 0 \quad (4)$$

for $i = 1, 2, \dots, n-1$, and $k = i + 1$. The magnitude of the stator current for machine "i" can be related to the machine magnetizing reactance X_{m_i} provided the relationship between $(|V_{g_i}|/f)$ and X_{m_i} is known. Such a relationship can be measured experimentally as discussed elsewhere [10]. Generally, the variation of $(|V_{g_i}|/f)$ with X_{m_i} over the practical region of operation can be approximated by linear segments with expressions of the type:

$$|V_{g_i}|/f = a_i + b_i X_{m_i} \quad (5)$$

Hence

$$|I_{s_i}| = \frac{|V_{g_i}|/f}{|Z_{mr_i}|} = \frac{a_i + b_i X_{m_i}}{|Z_{mr_i}|} \quad (6)$$

Therefore, Eq. 4 can be expressed as:

$$\frac{|Z_i|}{|Z_{mr_i}|} (a_i + b_i X_{m_i}) - \frac{|Z_k|}{|Z_{mr_k}|} (a_k + b_k X_{m_k}) = 0 \quad (7)$$

for $i = 1, 2, \dots, n-1$, and $k = i + 1$. Expressions for $|Z_i|$ and $|Z_{mr_i}|$ are given in the appendix.

Equations 2, 3 and 7 are $(n + 1)$ equations in $(n + 1)$ unknowns ($X_{m_1}, X_{m_2}, X_{m_n}, f$) which can be solved numerically for given values of X_c , load impedance, machines parameters and speeds. Newton Raphson method was used to solve these equations. Once the values of X_{m_i} 's and f are known, the air-gap voltages of the individual machines can be readily calculated. Consequently, the complete performance characteristics of all machines can be evaluated.

It is well known that for an isolated induction generator to sustain self excitation, the terminal capacitance must be such that $C_{min} \leq C \leq C_{max}$ [9]. These extreme values of C are obtained when $X_m = X_{max}$ (X_{max} is the maximum per unit magnetizing reactance). For parallel operation of induction generators, the allowable values of C must also be within a certain range. The extreme values of C i.e. C_{min} and C_{max} , in this case, depend upon parameters and speeds of the individual machines as well as load impedance.

For given values of X_{m_i} and v_i ($i = 1, 2, \dots, n$), equations 2 and 3 can be solved numerically to find X_c (and hence $C = 1/(\omega X_c)$) as well as f . Thus, the value of C which corresponds to $X_{m_i} = X_{max}$, for $i = 1, 2, \dots, n$, will be either C_{max} or C_{min} depending upon the initial values used in the iterative numerical solution of Eqs. 2 and 3. With Newton Raphson method, the initial value of f may be selected to be the average of the generators speed, i.e.

$$f = \frac{1}{n} \sum_{i=1}^n v_i \quad (8)$$

and, from Eq. (3), the initial value of X_c can be calculated as:

$$X_c = \frac{-f^2}{\left(B_L + \sum_{i=1}^n B_i \right)} \quad (9)$$

If the initial values of f and X_c are selected according to Eqs. 8 and 9 then the solution will converge to $C = C_{min}$. On the other hand, if the initial value of f is selected to be half the mean of the generators speed, i.e.

$$f = \frac{1}{2n} \sum_{i=1}^n v_i \quad (10)$$

and then used in the calculation of the initial value of X_c using Eq. 9, the solution will then converge to $C = C_{max}$. When finding these extreme values of C , it may be essential to use a decelerating factor in order to converge to the correct solution.

Results and Discussion

Test machines data

In order to test the validity of the proposed method of analysis and to investigate the performance characteristics of parallel operation of induction generators, two types of machines were used, namely, a wound rotor machine (WRM) and a squirrel cage machine (SCM). Both machines are three-phase, 380 V (line), 60 Hz, 4-pole, 1 kW. Base values of frequency, speed and impedance are 60 Hz, 1800 rpm, and 75.86 Ω respectively. The per-unit measured parameters of the two machines are given in the following table:

Machine parameters					
	R_s	R_r	X_s	X_r	X_{m0}
WRM	0.09175	0.06354	0.2112	0.2112	2.00
SCM	0.16543	0.09324	0.1060	0.1060	2.84

The measured per-unit variations of the air-gap voltages $|V_g|/f$ based on a 220 V with X_m for the two machines are shown in Fig. 3. As shown in this figure, these voltages can be approximated as follows over the practical range of interest. For the WRM,

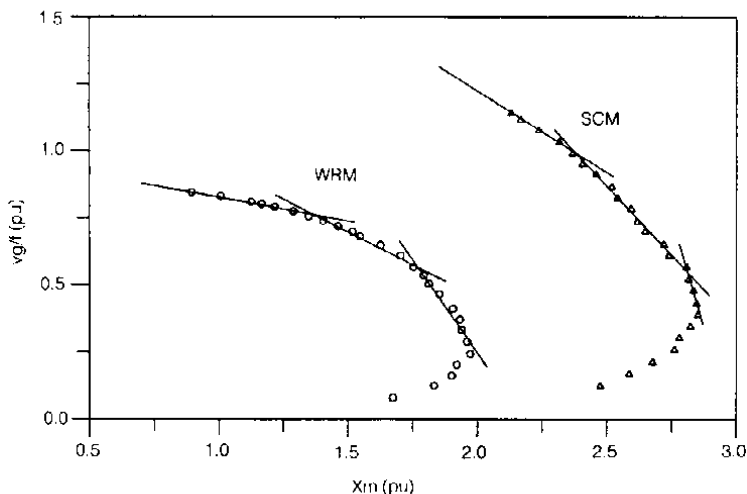


Fig. 3. Measured variations of air-gap voltages with X_m for the test machines.

$$\frac{V_g}{f} = \begin{cases} 1.0007 - 0.1741X_m & \text{for } X_m \leq 1.3666 \\ 1.4298 - 0.4881X_m & \text{for } 1.3666 \leq X_m \leq 1.7707 \\ 3.0192 - 1.3857X_m & \text{for } X_m > 1.7707 \end{cases} \quad (11)$$

and for the SCM,

$$\frac{V_g}{f} = \begin{cases} 2.4408 - 0.6080X_m & \text{for } X_m \leq 2.3839 \\ 3.4592 - 1.0352X_m & \text{for } 2.3839 \leq X_m \leq 2.8116 \\ 9.7841 - 3.2848X_m & \text{for } X_m > 2.8116 \end{cases} \quad (12)$$

Excitation requirements

In order to examine the values of C_{min} and C_{max} , Eqs. 2 and 3 were solved numerically for a number of cases. Figure 4 shows the calculated variation of C_{min} and C_{max} for two unloaded machines (WRM & SCM) and four machines (2 WRM's & 2 SCM's) at no load and under load. The machines were connected to the shaft of a d/c motor. This figure also shows the measured variation of C_{min} with v . The measured values were obtained by connecting three Y-connected capacitors of equal values,

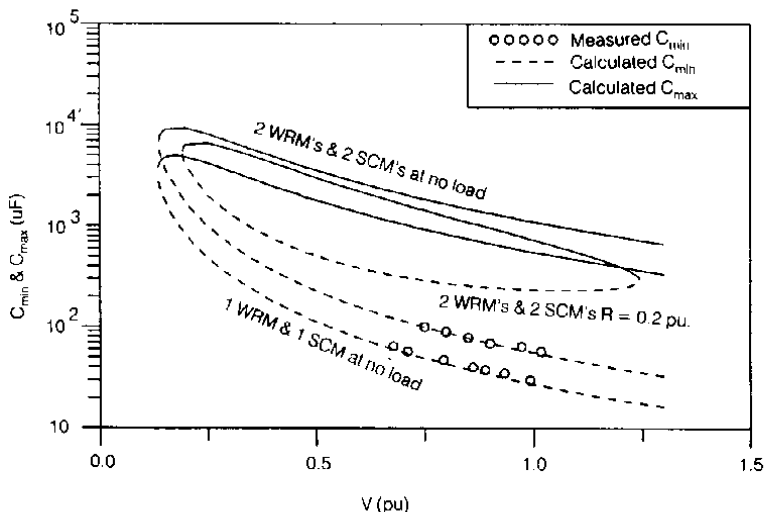


Fig.4. Variation of C_{min} and C_{max} with v and R for two and four machine systems.

across the terminals of the parallel machines. The speed of the d/c motor was gradually increased until self excitation occurred. Then, the speed was gradually reduced until the excitation was lost at a certain drop-out speed, v_d . This value of C is C_{min} at v_d . It is clear from this figure that the measured values of C_{min} agree quite well with its calculated values. Figure 4 further shows that there is a minimum value of speed below which excitation will never occur regardless of the value of C . This behavior is similar to that of a single machine as shown elsewhere [9]. This figure further shows that when the machines are loaded, the values of C_{min} is significantly increased. However, C_{max} is lower than that of the no load case. Moreover, loaded machines also have a maximum cut-off speed above which self excitation is not possible. For two WRM's and two SCM's v_{min} and v_{max} are 0.2 and 1.24 pu when $R = 0.2$ pu.

Performance characteristics

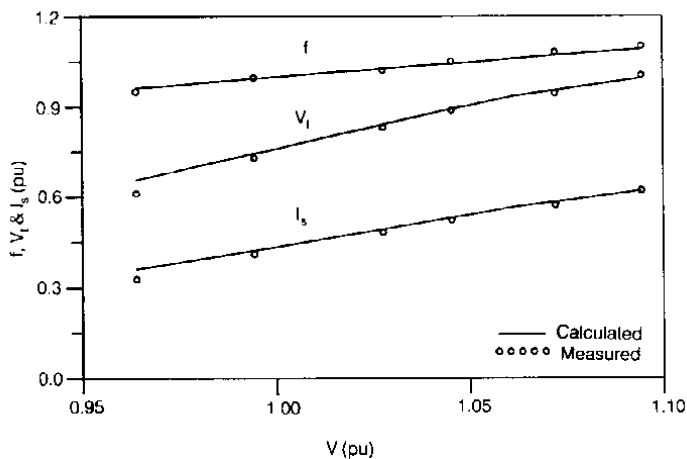
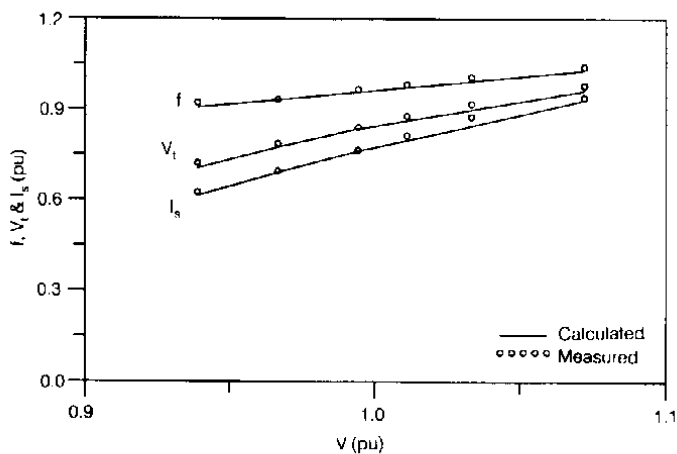
In order to investigate the performance characteristics of parallel operated induction generators, the following cases were considered:

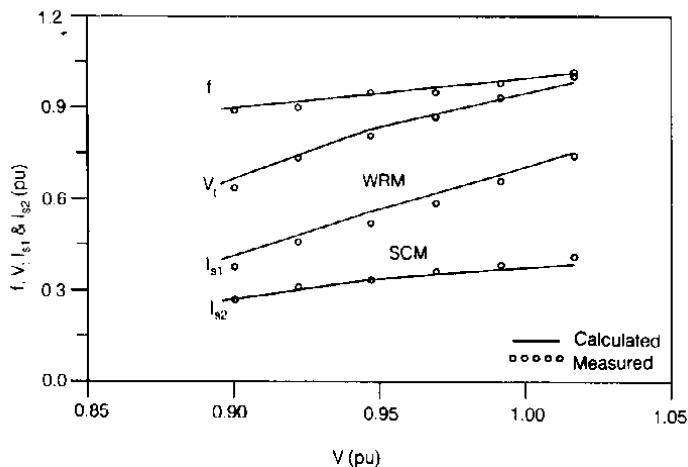
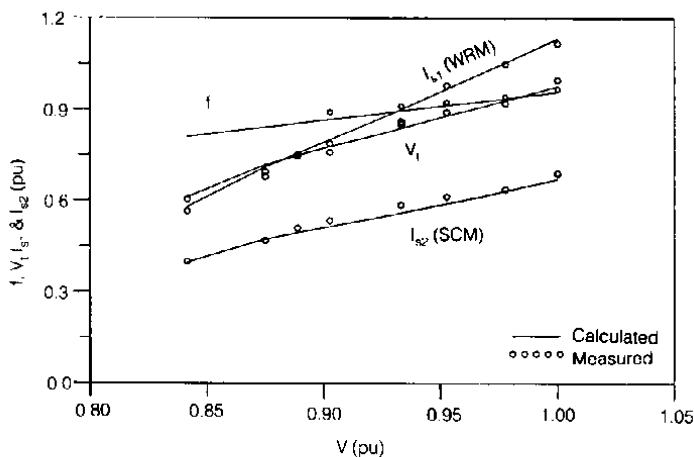
- Similar machines operating at equal speeds,
- Different machines operating at equal speeds,
- Similar machines operating at different speeds,
- Different machines operating at different speeds.

When similar induction generators with equal speeds are operated in parallel, they share the load equally as expected. This is clearly evident from Figs. 5 (a and b) which show the calculated and measured variations of V_p , f and I_s with speed for two similar WRM's. It is clear that both machines have equal stator currents whether unloaded or loaded. Moreover, there is a good agreement between the calculated and measured values.

Similarly, when two SCM's were operated in parallel, whether loaded or unloaded, the calculated and measured values of V_p , f and I_s are also in a good agreement. Thus, if "n" similar machines with equal speeds are operated in parallel with excitation capacitance, C and load resistance, R , the performance of each machine could be evaluated by using either the method discussed in this paper or the method of analysis of a single induction generator [10] with the terminal capacitor and load resistor values selected as C/n and nR respectively.

When different machines with equal speeds are operated in parallel, their currents depend on their parameters. This is evident from Figs. 6 (a and b) which show the calculated and measured variations of V_p , f , I_{s_j} and I_{s_n} with v for a WRM and an SCM in parallel when connected to the same shaft. The highest current is delivered by the generator with the lowest rotor resistance as is evident from Fig. 6 (a and b).

(a) No-load with $C = 40 \mu\text{F}$ (b) $R = 1.3182 \text{ pu}$ and $C = 60 \mu\text{F}$ Fig. 5. Effect of speed on V_t , I_s and f for two WRM's in parallel.

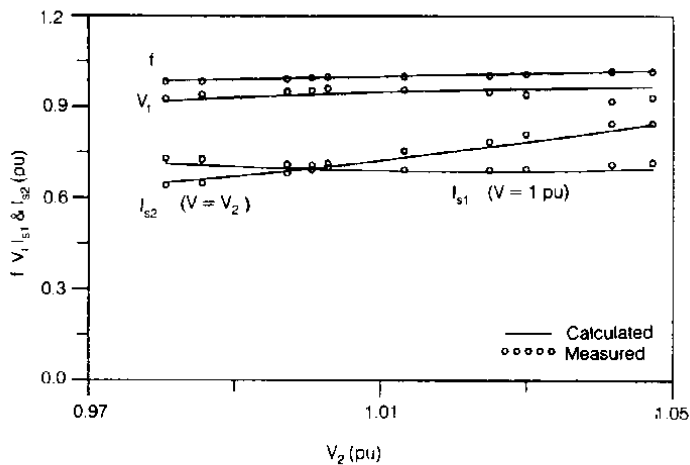
(a) No-load with $C = 40 \mu\text{F}$ (b) $R = 1.3182 \text{ pu}$ and $C = 60 \mu\text{F}$ Fig. 6. Effect of speed on V_t , I_{s1} , I_{s2} and f for parallel operation of a WRM's and an SCM.

Unlike synchronous generators, self excited induction generators can be operated in parallel even when their speeds are different. Under this condition, the power supplied by each machine could be either positive or negative depending on several factors such as speeds and parameters of the individual machines, excitation capacitance as well as load impedance. Figures 7 (a. and b.) show the calculated and measured variations of V_t , f , I_{s1} and I_{s2} when two WRM's are operated in parallel at different speeds. One machine was driven at 1 pu speed by a synchronous motor while the speed of the second machine was varied using a d/c motor as a drive. There is a good agreement between the calculated and measured values.

In parallel operation, the power supplied or taken by a given machine "i" from the common bus depends upon its speed as well as the frequency. The value of f depends on several factors such as speeds and parameters of the individual machines, excitation capacitance and load impedance, etc. In general if C is near C_{min} and the machines are not loaded, then f is approximately equal the average of the speeds of all machines. However, f drops when the machines are loaded or the value of C is increased. Consequently, the amount of power supplied or taken by each machine depends upon the various factors, mentioned above, which affect the bus frequency.

Figure 8 shows the variations of V_t , f and output powers, P_1 (SCM) and P_2 (WRM) when an SCM and a WRM were operated in parallel at different speeds. The speed of the SCM, v_1 , was fixed at 1 pu while the speed of the WRM, v_2 , was varied. The load and excitation capacitance were kept constant. It is clear that as v_2 is decreased, f decreases as well and consequently, the output powers of both machines vary. This figure clearly signifies the importance of the parameters and speeds of the individual machines in parallel operation.

Figure 9 (a and b) show the influence of excitation capacitance, C , and load on V_t , f and machines output powers for two WRM's which were operated at fixed speeds of 1 and 0.9 pu. It is interesting to note that when the machines are at no-load, $P_1 + P_2 = 0$ for any value of C . For $C_{min} \leq C \leq 300 \mu F$, the faster machine supplies the same amount of power absorbed by the slower machine. However, for $300 \mu F \leq C \leq C_{max}$, the slower machine feeds power to the bus while the faster machine absorbs power from the bus to account for part of its losses. Thus the value of the excitation capacitor has a significant influence on load sharing of parallel induction generators. When these machines were loaded with $R = 2$ pu, it was found that for $C_{min} \leq C \leq 270 \mu F$, P_1 was positive while P_2 was negative and $P_1 + P_2 = P_L$, (P_L is load power). However, for $270 \mu F \leq C \leq C_{max}$, both P_1 and P_2 were positive. When the load was further increased to $R = 1$ pu, it was found that both P_1 and P_2 were positive over the entire range of C as shown in Fig. 9-b. Thus, besides machines speeds and excitation capacitance, the load resistance also affects the power sharing of parallel induction generators. This point is further clarified in Fig. 10 which shows the influence of load resistance on terminal voltage, frequency and power outputs of



(a) No-load

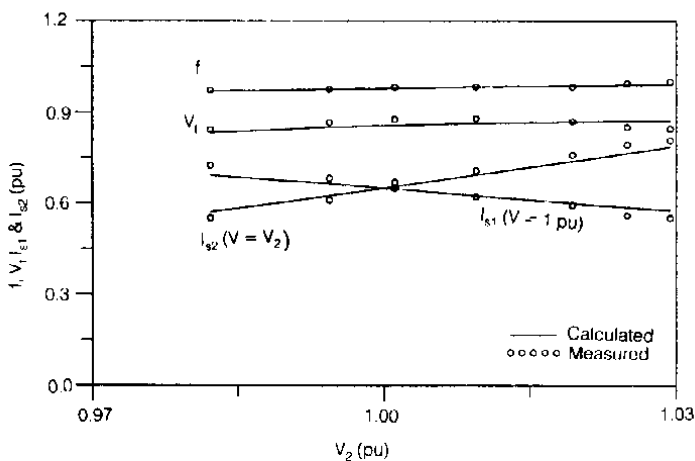
(b) $R = 2.6364$ pu

Fig. 7. Performance characteristics of two WRM's in parallel at different speeds with $C = 52 \mu\text{F}$ and $\theta_1 = 1$ pu.

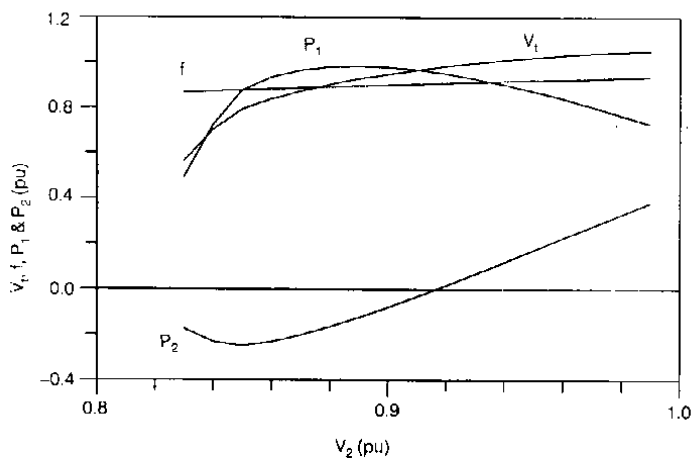


Fig. 8. Performance of an SCM (1) and a WRM (2) at different speeds with $R = \theta_1 = 1$ pu and $C = 80 \mu F$.

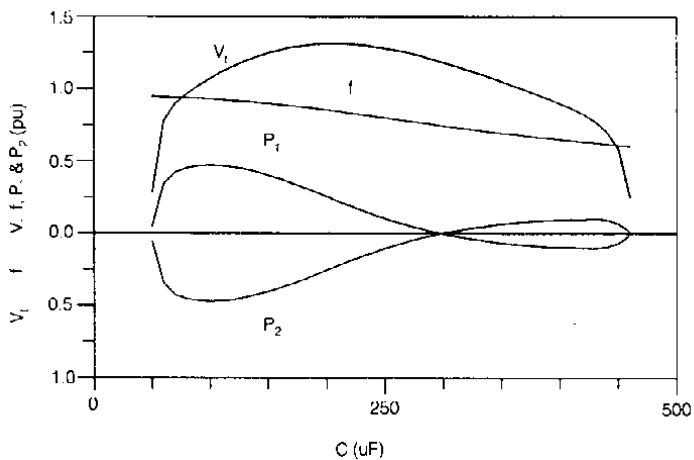


Fig. 9. (a) No-load.

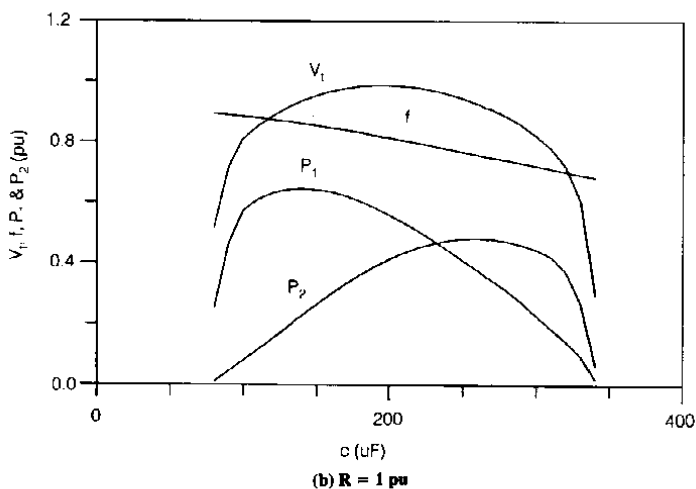


Fig. 9. Influence of load and excitation capacitance on performance of two WRM's at different speeds with $v_1 = 1$ and $v_2 = 0.9$ pu.

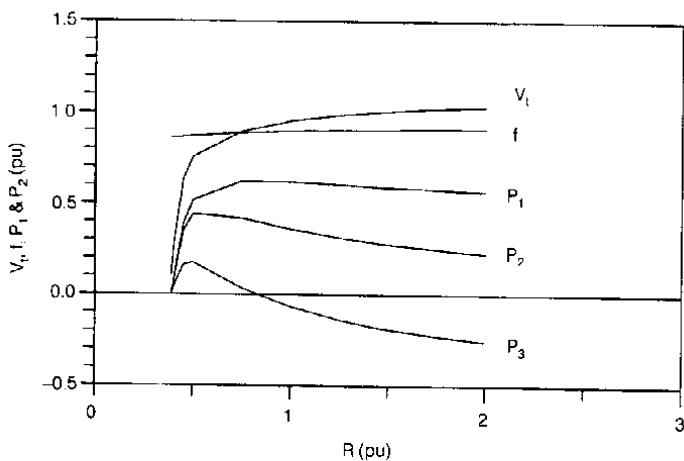


Fig. 10. Effect of load on performance on three WRM's at different speeds with $v_1 = 1$, $v_2 = 0.95$, $v_3 = 0.9$ pu and $C = 160 \mu\text{F}$.

three WRM's at fixed speeds of 1, 0.95 and 0.9 pu with $C = 160 \mu\text{F}$. It is clear from this figure that at light load, most of the power is supplied by the fastest machine. However, as the total load at the bus was increased, the slow machines started to supply more and more power. Thus for parallel operation of induction generators, the choice of machines, their speeds and excitation capacitance is very important because they control not only the terminal voltage and its frequency but also the amount of power supplied by each machine. If due care is not exercised, some machines may be acting as motors.

It is clear from the above discussion that it is possible to operate induction machines of different parameters and with different speeds in parallel. However, it is preferable to operate similar machines at the same speed. Under such conditions, the terminal voltage could be kept reasonably constant by adjusting the value of C under varying load conditions as discussed elsewhere [10]. When either different types of machines are used or when the speeds are not equal, it is still possible to control the terminal voltage by varying C . However, it may not be possible to keep the power outputs of the various machines at the desired levels.

Conclusions

This paper presents an accurate method of analysis that predicts the steady state performance characteristics of three-phase induction generators operating in parallel and feeding a balanced load. From this paper the following specific conclusions can be drawn:

1. Self excited induction generators having different speeds as well as parameters can be operated in parallel provided the excitation capacitance and speeds of the individual machines are kept within certain ranges.
2. When similar machines are operated in parallel, it is preferable to operate them at a common speed to ensure equal load sharing. However, the power supplied or absorbed by machines with different parameters and/or speeds depends upon their parameters and speeds as well as excitation capacitance and load impedance.
3. The excitation capacitance and machines speeds have strong influences on the performance characteristics of self excited induction generators operated in parallel. These parameters have to be selected carefully to avoid under or over loading of the individual machines.
4. Since parallel operation of SEIG's sets the frequency to be approximately the mean of the generators running speed, it is possible that slower machines may operate in the motoring regime.

5. Sudden removal of one generator or more of the group from service, might lead to overvoltages if the excitation capacitor is not reduced accordingly.

Appendix

The impedance for an R - L load is

$$Z_L = \frac{R}{f} + jX \quad (13)$$

and hence the corresponding load admittance is given by:

$$Y_L = G_L + jB_L = \frac{fR}{R^2 + f^2X^2} - j \frac{f^2X}{R^2 + f^2X^2} \quad (14)$$

On the other hand, if the load is capacitive, then

$$Z_L = \frac{R}{f} - j \frac{X}{f^2} \quad (15)$$

Consequently,

$$Y_L = G_L + jB_L = \frac{f^3R}{f^2R^2 + X^2} - j \frac{f^2X}{f^2R^2 + X^2} \quad (16)$$

From Fig. 2, the total impedance of the magnetizing and rotor circuit for machine "i" is given by:

$$Z_{mr_i} = R_{mr_i} + jX_{mr_i} \quad (17)$$

where

$$R_{mr_i} = \frac{(f - v_i)X_{m_i}^2 / R_{r_i}}{1 + (f - v_i)^2 (X_{r_i} + X_{m_i})^2 / R_{r_i}^2} \quad (18)$$

and

$$X_{mr_i} = X_{m_i} \frac{1 + X_{r_i} (f - v_i)^2 (X_{r_i} + X_{m_i}) / R_{r_i}^2}{1 + (f - v_i)^2 (X_{r_i} + X_{m_i})^2 / R_{r_i}^2} \quad (19)$$

Also the total terminal impedance of machine "i" is given by:

$$Z_i = R_i + jX_i \quad (20)$$

where

$$R_i = \frac{R_{s_i}}{f} + R_{mr_i} \quad (21)$$

and

$$X_i = X_{s_i} + X_{mr_i} \quad (22)$$

The corresponding machine "i" total admittance is given by:

$$Y_i = G_i + jB_i = \frac{1}{Z_i} = \frac{R_i}{R_i^2 + X_i^2} - j \frac{X_i}{R_i^2 + X_i^2} \quad (23)$$

References

- [1] Lawrence, R.R. *Principle of Alternating Current Machinery*. McGraw Hill, 1940.
- [2] Doxy, B.C. "Theory and Application of the Capacitor-Excited Induction Generator," *The Engineer*, 216 (1963), 893-897.
- [3] Watson, D.B., Arrilaga, J. and Densem, T. "Controllable d.c. Power Supply from Wind-Driven Self-Excited Induction Machines", *Proc. IEE*, 126, No. 12 (1979), 1245-1248.
- [4] Milner, I.P. and Watson, D.B. "An Autonomous Wind Energy Converter Using the Self-Excited Induction Generator for Heating Purposes", *Wind Engineering*, 6, No. 1 (1982), 19-23.
- [5] Patton, J.B. and Curtice, D. "Analysis of Utility Protection Problems Associated with Small Wind Turbine Interconnections", *IEEE Trans. on Power App. and Sys.*, PAS-101, No. 10 (1982), 3957-3966.
- [6] Raina, G. and Malik, O.P. "Wind Energy Conversion Using a Self-Excited Induction Generator", *IEEE Trans. on Power App. and Sys.*, PAS 102, No. 12 (1983), 3933-3936.
- [7] de Mello, F.P. and Hannett, L.N. "Large Scale Induction Generators for Power Systems", *IEEE Trans. on Power App. and Sys.*, PAS-100, (1981), 2610-2618.
- [8] Watson, D.B. and Milner, I.P. "Autonomous and Parallel Operation of Self-Excited Induction Generators", *Int. J. Elect. Eng. Education*, 22, (1985), 365-374.
- [9] Al-Bahrani, A.H. and Malik, N.H. "Limiting Values for Steady State Operation of Self-Excited Induction Generators." *The Arabian Journal for Science and Engineering*, 15, No.2A (April 1990), 197-201.
- [10] Malik, N.H. and Al-Bahrani, A.H. "Influence of the Terminal Capacitor on the Performance Characteristics of a Self-Excited Induction Generator," *IEE Proc. Pt C*, 137, No.2 (March 1990), 168-173.
- [11] Malik, N.H. and Haque, S.E. "Analysis and Performance of an Isolated Self Excited Induction Generator," *IEEE Trans. on Energy Conversion*, EC-1, No. 3 (1986), 134-140.

- [12] Al-Bahrani, A.H. and Malik, N.H. "Steady State Analysis and Performance Characteristics of a Three-Phase Induction Generator Self-Excited with a Single Capacitor." *IEEE Transaction on Energy Conversion*, EC-4, No. 4 (December 1990), 725-732.
- [13] Tandon, A.K.; Murthy, S.S. and Berg, G.J. "Steady State Analysis of Capacitor Self Excited Induction Generators." *IEEE Trans. on Power App. and Sys.*, PAS-103, No.3 (1984), 612-618.
- [14] Murthy, S.S.; Malik, O.P. and Tandon, A.K. "Analysis of Self Excited Induction Generator." *IEEE Proc. Pt. C.*, 129, No.6 (1982), 260-265.

الأداء المتوازي للمولدات الحثية ذوات الحث الذاتي

عبدالله حسين البحراني و نذر حسين مالك

قسم الهندسة الكهربائية، كلية الهندسة، جامعة الملك سعود، ص.ب. ٨٠٠،

الرياض ١١٤٣١، المملكة العربية السعودية

(استلم في ١٣/٤/١٩٩٢م؛ قبل للنشر في ٢٢/٧/١٩٩٢م)

ملخص البحث. تناقش هذه الورقة خواص الأداء المستقر لمولدات الحث عند توصيلها على التوازي لتغذية حمل متوازن. لقد اتضح أن مولدات الحث ذات المعالم والسرعات المتشابهة أو المختلفة يمكن تشغيلها على التوازي وحساب خصائص أداؤها المستقر بدقة حسب الطريقة المقترحة. وخواص أداء هذه المولدات يتأثر بقيمة مكثفات الحث، مقاومة الأحمال، السرعة ومعالم المولدات. ولقد بحثت حالات نمطية لعدد من مولدات الاختبار الموصلة على التوازي وقد تم تحقيق نتائج الطريقة المقترحة معملياً.