MENOUFIYA UNIVERSITY
FACULTY OF ENGINEERING
ENG. RESEARCH BULL.
Vol. 17 Part I, 1994

P.P. : 209 : 225
Received at : 23 / 3 / 1994
Accepted at : 23 / 4 / 1994

CAPACITOR CONTROLLED SELF EXCITED SERIES CONNECTED SYNCHRONOUS GENERATOR

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ABSTRACT

Three phase series connected self excited synchronous generators are considered one of the efficient electric energy resources. This is due to the fact that ,this type of generators is characterized by a constant induced voltage frequency which depends only on generator speed. However, some applications require a constant output voltage.

This paper introduces a theoretical analysis and experimental investigation for obtaining a constant terminal voltage regardless of load variations. A fixed Capacitor Thyristor Controlled Reactor technique is applied to maintain a constant output voltage. The thyristor firing angles are performed via a special control circuit which is built for this purpose. A comparative study between measured and calculated results illustrate clearly the effectiveness of the proposed technique to stabilize the output voltage.

1. INTRODUCTION

Recently, attention was paid to use different types of renewable energy resources , such as solar, tidal and wind energy. The self excited induction generator seems to be the most convenient mean to convert wind energy into electrical energy. This may be attributed to its ability to provide such conversion over a wide range of rotor speed. Subsequently, significant research work has been devoted to study the performance of self excited induction generators.

These studies show that the output frequency is dependent on generator speed, excitation capacitor and loading conditions [1- 9].

The series connected synchronous generators were suggested [10,11], to have a fixed voltage frequency. Such type of a generators offers the advantage of constant frequency which is independent of excitation capacitor and loading conditions. On the other hand, it shares with induction generator the merit of self excitation.

The steady state performance of a self excited synchronous generator has been analyzed as a parametric generator [10]. Moreover, the steady state performance is obtained depending on phasor diagram representation [11].

Most of previous studies concerning self excited synchronous generator concentrate mainly on calculating the terminal voltage as a function of capacitor value,and load current. As a result,the terminal voltage decreases with increasing the load current.

This paper presents an experimental and theoretical investigation for controlling the terminal voltage via the excitation capacitor. The terminal voltage variations as a function of load current , at different values of excitation capacitor , are examined. A fixed capacitor thyristor controlled reactor is designed and built. An electronic circuit to provide the thyristors firing signals is constructed and tested. A simulation program to predict the required capacitance under different load conditions which maintain a constant terminal voltage has been built.

The experimental results illustrate clearly the ability of proposed technique to obtain constant terminal voltage through controlling the capacitor values.

2. EXPERIMENTAL SET-UP

The experimental set-up consists of 2.2 KW, three-phase slip rings induction motor, coupled with a 2.2 KW separately excited D.C motor as a prime-mover. The induction motor operates as a three-phase self excited synchronous generator. To operate as a generator, the rotor and stator phases are connected in series , in a proper phase sequence , via three groups of excitation capacitances as shown in Fig. 1. More details about the machine parameters are given in the Appendix.

3. MATHEMATICAL REPRESENTATION

3.1. Steady State Analysis

The mathematical model developed in this section is used to calculate the steady state performance for the generator under test. The analysis is based on the phasor diagram shown in Fig. 2 . The equivalent impedance of the load and capacitor combination, Fig.1, is given by :

$$R_{Le} = \frac{R_L X_C^2}{R_L^2 + (X_L - X_C)^2} \quad , X_{Le} = \frac{X_C (R_L^2 - X_L^2 - X_L X_C)}{R_L^2 + (X_L - X_C)^2} \qquad (1)$$

where,the equivalent resistance and reactance are given by :

$$R_{eq} = R_{Le} + R_1 + R_2$$
$$X_{eq} = X_{Le} + (X_1 + X_2) \frac{F}{50} \qquad (2)$$

and the equivalent phase angle is :

$$\Phi_{eq} = \tan^{-1} \left(\frac{X_{eq}}{R_{eq}} \right) \qquad (3)$$

The magnetizing reactance may be evaluated from :

$$X_m = \frac{R_{eq}}{\sin \theta} \frac{1}{\sqrt{1+K^2+2K \cos \rho}} \frac{N_s}{N_r} \qquad (4)$$

where;

$$\theta = \sin^{-1} (K \sin \Psi) \quad , \quad \rho = \theta + \Psi \qquad (5)$$

(ψ) can be calculated using the following equation:

$$K \cos \Psi + \sqrt{(1-K^2 \sin^2 \Psi)} - 2K \sin \Psi \tan \Phi_{eq} = 0 \qquad (6)$$

The armature current can be calculated by knowing the air gap voltage using the following equation :

$$I_a = \frac{V_g}{X_m} \frac{1}{\sqrt{1+K^2 + 2K \cos \rho}} \qquad (7)$$

The air gap voltage is computed from the magnetization curve as a function of magnetization reactance using line segmentation technique. For the machine under investigation, the air gap voltage is given by :

$$V_g = \begin{bmatrix} 311.85 & -1.38\ X_m & & X_m \le 95.51 \\ 715.64 & -5.61\ X_m & 95.51 \le & X_m \le 100.5 \\ 1025.29 & -8.69\ X_m & 100.5 \le & X_m \end{bmatrix} \quad (8)$$

The terminal voltage and load current are given by :

$$V = I_a \sqrt{R_{Le}^2 + X_{Le}^2} \quad (9)$$

and,

$$I_L = \frac{V}{\sqrt{R_L^2 + X_L^2}} \quad (10)$$

Equations (1 - 10) were programed previously to calculate the generator steady state performance [11]. In the present case, based on the previous equations a computer simulation program has been built. This program solves the non linear equations (1 - 10) by the Turbo-Bascal language using the Runge-Kutta numerical technique to predict the required capacitance under loading conditions in order to maintain a constant terminal voltage. This is carried out using the following steps:

i) For each operating speed and a specific capacitance value, the no load voltage which is required to be kept constant at loading is determined.

ii) The load current is increased one step. This reduces the terminal voltage which requires an additional capacitance to retain the previous value.

iii) The value of capacitance is then increased gradually using half step technique. This process is continued till the terminal voltage (V) equals the no load voltage (V_o).

To make the program more practical , the excitation capacitance is divided into two banks of capacitors as shown in Fig .3. In this case (C_m) is the main capacitor by which the no load voltage is determined. While (C_e) is the additional capacitor which is used to stabilize the no load voltage during generator loading. A smooth variation of the capacitor (C_e) is required. This may not easy to be obtain using a variable capacitor only. So, a static exciter employing a Fixed Capacitor - Thyristor controlled reactor scheme "FC-TCR" [12,13] is then more efficient and practical.

3.2. Static Exciter For Voltage Control

The "FC-TCR" technique can be explained on the light of Fig. 4. Where, by controlling the switching angle of the thyristor , the conduction interval of the capacitor current is controlled. Hence, the current flow at the inductor (Lmax) is controlled and consequently the effective capacitance is varied.

Based on the "FC-TCR" technique , the simulation program has been modified considering the following equations. The relation between the switching angle (α) and the magnitude of the fundamental current (I_c) can be written as follows:

$$I_c(\alpha) = V\left[w_r C_{max} - \frac{1}{\omega_r L_{max}}\left(1 - \frac{2}{\pi}\alpha - \frac{1}{\pi}\sin 2\alpha\right)\right] \qquad (11)$$

If the relation between (C_{max}) and (L_{max}) is adjusted such that:

$$\omega_r C_{max} = \frac{1}{\omega_r L_{max}} \qquad (12)$$

Then the effective capacitance $C_e(\alpha)$ will be:

$$C_e(\alpha) = \frac{C_{max}}{\pi}(2\alpha + \sin 2\alpha) \qquad (13)$$

Equations 1 to 10 are reprogrammed with those which describe the behaviour of static exciter, (equations 11 - 13), to calculate the controlled performance under loading. The program in this case becomes more accurate to calculate the required capacitor variation with load current to maintain a constant output voltage. Calculated results are shown with those measured experimentally.

The electronic circuit which acts with the static exciter employing a Fixed Capacitor Thyristor Controlled Reactor " FC- TCR" will be discussed in the following section .

4. THE ELECTRONIC CIRCUIT

The philosophy of the proposed electronic circuit can be explained regarding Fig.4. Such circuit is designed to generate a firing signals that required to control the thyristors switching angles. Hence, the inductor current conduction interval is controlled and consequently the effective capacitance will vary. A smooth variation of the firing signals proportional with the increase in load current can yield a constant terminal voltage. Hence, operation of the electronic circuit depends on comparing the controlled voltage with a reference value.

The proposed electronic circuit shown in Fig. 5 , is designed and built from four main parts. These parts are ,a Low pass filter, a main value detector, a reference wave generator and the main firing circuit. Each of them will be discussed subsequently.

4.1. The Filter

A low pass filter is built to eliminate the harmonics resulted from the discontinuity of reactor current. The construction of the filter is shown in Fig. 5-a . It consists of three operational amplifiers "LM 741" connected with group of capacitances and resistances. The value of capacitances and resistances are determined such that the filter operates with a cut off frequency equals 30 Hz.

4.2. The Main Value Detector

This circuit is used to convert the generator AC terminal voltage to an equivalent DC level. Three main value detector are built for the three phases. The per phase circuit is shown in Fig. 5-b. In this circuit two identical integrators are used and connected with a differential amplifier. This amplifier subtracts the integrators output signals and producing a DC voltage. The output of the main value detector is adjusted to vary from 5 volt to zero level as the load voltage decreases from no load to cut off voltage. For this purpose, a signal conditioning circuit is built.

4.3. Reference Wave Generator

The reference wave generator is designed to generate a reference voltage signal proportional to the no load voltage. The per phase schematic diagram of this generator is shown in Fig.5-c. The input of this circuit is the generator terminal voltage. The output signal is a saw tooth signal that does not change in amplitude with input variation. This is due to that,the values of the attached resistance and capacitance are predetermined so that the operational amplifiers operate under saturated conditions.

The present reference wave generator can be adjusted to control linearly the phase angle between any two angles α_1 and α_2 . In the present investigation the reference signal is adjusted at 5 volt when $\alpha = \pi/2$ and zero when $\alpha = \pi$. Also, the reference wave signal is synchronised with the generator terminal voltage.

4.4. The Thyristor firing circuit

This circuit is used to make the firing signal at the rated voltage and current required enough to turn the thyristor on. Since the gate and cathode terminals of the employed thyristor or the triac are at higher potential, the firing signals does not connected directly to the triac. Therefore, a pulse transformer is used to isolate the power circuit from the control one. In the present investigation, a triac of type "BTA 400C" is used as a power circuit. To turn the triac on an amplifier stage is built to ensure the required gate voltage and current. This has been done using Darlengton transistor of type "TIP 121" which operates at 12 volt DC. If the transistor is turned on, the triac gate signal will be 12 volt level. The per phase circuit is shown in Fig. 5-d.

Operation of the electronic circuit as a fixed capacitor thyristor controlled reactor can be explained depending on load variation. Increasing the load current will decrease the generator terminal voltage. This can be detected by the mean value detector. As a result the switching angle α increases , resulting in a decrease in the reactor current. This is equivalent to increasing the effective value of excitation capacitor. As the excitation capacitor increases, the generator terminal voltage will consequently increase. The recorded signals of the electronic circuit will be demonstrated in the following section.

5. MEASURED AND CALCULATED RESULTS

5.1. Uncontrolled External Characteristic

The external characteristics of the three phase series connected self excited synchronous generator are measured without controlling the terminal voltage. To measure these characteristic, the generator was loaded with a resistive load. The variation of load voltage with load current is then recorded at different values of excitation capacitor as shown in Fig. 6. This results indicate that, the load voltage decreases as the load current increases. Moreover, increasing the excitation capacitor results in increasing the generated voltage. Each capacitor value has a cut off voltage proportional directly with it. Also, a comparison between measured and simulated results confirm the validity of theoretical analysis to calculate the steady state performance.

5.2. Controlled External Characteristic

Stabilizing the load voltage can be achieved using the proposed electronic circuit. For experimental verification, the electronic circuit was connected and tested. The different signals generated by the electronic circuit are shown in Fig. 7. The output of the three reference wave generators are shown in Fig. 7-a . These signals are adjusted so that the firing angle varies between $\pi/2$ and π . Fig 7-b shows the control signals. The output of the generator is connected to a step down transformer (220/5 volt). The transformer output is employed to generate a synchronized reference wave signal. At intersection points between the reference wave signal and the output of the mean value detector, a firing singles are generated as shown in the figure. It is clear that the output of the mean value detector is a DC level (channel 2). It must be emphasized that the generated voltage is of sinusoidal waveform with 25 Hz at 1500 rpm as shown in Fig. 8.

The measured external characteristic with controlled electronic circuit is shown in Fig. 9. It is clear that, the proposed technique is efficient in stabilizing the terminal voltage over a wide range of loading conditions. Moreover, the variation in the capacitor value versus load current which maintain the terminal voltage constant is shown in Fig 10. This relation is useful in deducing the required incrementation of capacitance value. As shown from the figure, the analysis is exact to describe the proposed control technique.

6. CONCLUSIONS

The present paper introduced a technique to stabilize the output voltage of the three phase series connected self excited synchronous generator via a control circuit. This circuit was designed and built with minimum coasts. It has been constructed based on employing the operational amplifiers rather than the logic gates as the first is more practical and can operate at higher temperature levels. The control circuit has been tested experimentally and the results are presented.

The results recorded in this paper confirm the successful design and operation of the proposed control circuit. Also, it is clear from both measured and calculated results that , the model which describe the system with the fixed capacitor controlled reactor provide accurate prediction of capacitance variation. Therefore, the proposed technique including the electronic circuit and model description can be used in similar applications to predict the correct capacitance value which is required to maintain a constant output voltage.

7. ACKNOWLEDGMENTS

The author would like to express his gratitude to Prof. Dr. A.L.Mohamadein, vice dean , Faculty of Engineering,Alexandria University for his valuable discussions and comments.

8. LIST OF SYMBOLS

V_{AR} , V_{AS}	Rotor and stator RMS phase (A) voltage.
F	Operating frequency Hz.
2P	Number of poles.
N_r, N_s	Rotor and synchronous speed (rpm).
C	Excitation capacitance μf.
R_L, X_L	Load resistance and reactance
R_{eq}, X_{eq}	Equivalent resistance and reactance for series connected stator and rotor phase windings
ϕ_{eq}	Equivalent phase angle of excitation capacitor and load combination in elect.deg
R_1, R_2	Stator and rotor phase resistance.
X_1, X_2	Stator and rotor phase reactance.
K	Turns ratio.
θ , ψ	Angles between total MMF axis and both MMF axis of stator and rotor in elect.deg
ρ	Angle between stator and rotor MMF axis
X_m	Magnetizing reactance ohms.
V_g , V	Per phase airgap and terminal voltages.
I_a , I_L	Armature and load current.
α	Switching angle of FC-TCR.
C_{max}, L_{max}	Maximum capacitance and inductance of the static exciter.

9. APPENDIX

9.1. Machine Ratings

The machine is a four poles three phase slip rings induction machine , and has the following ratings:

Power = 2.2 KW.
Voltage = 220/380 volt.
current = 6.3/3.6 amps.
Star wound rotor = 328 volt and 4.2 amps.
Stator resistance = 2.0795 ohms.
Stator reactance = 5.2794 ohms.
Rotor resistance = 1.96313 ohms.
Rotor reactance = 3.92097 ohms.
Cut off voltage = 82.32 volts
C_{max} = 180 μF.
L_{max} = 0.3242 henery.

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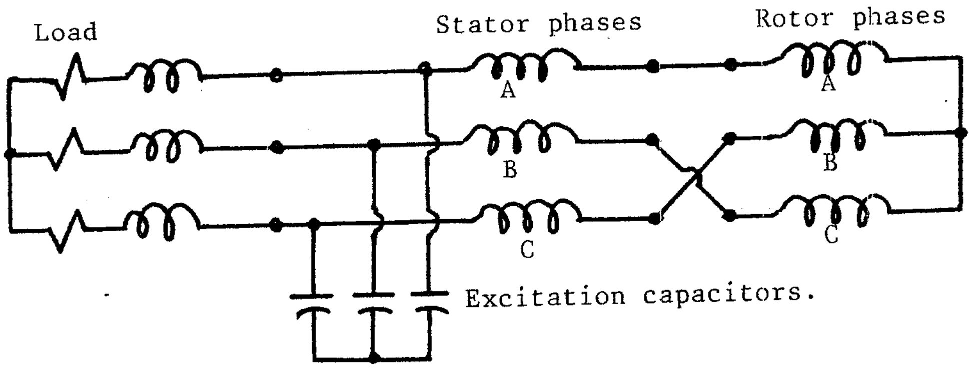


Fig. 1. Schematic diagram for the series-connected self excited synchronous generator.

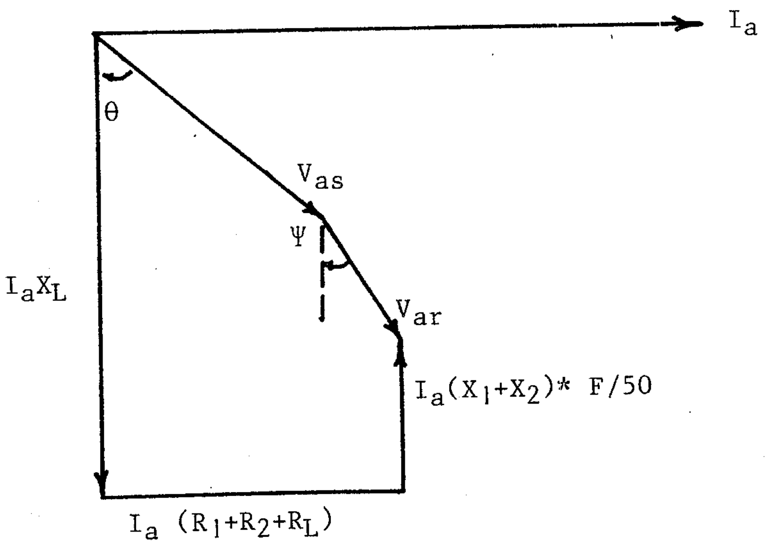


Fig. 2. Phasor diagram for self excited synchronous generator. ref.[11].

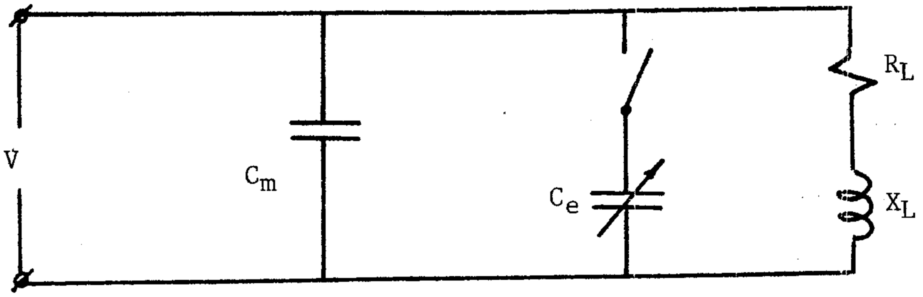


Fig.3. Representation of main excitation capacitor with two bank of capacitors.

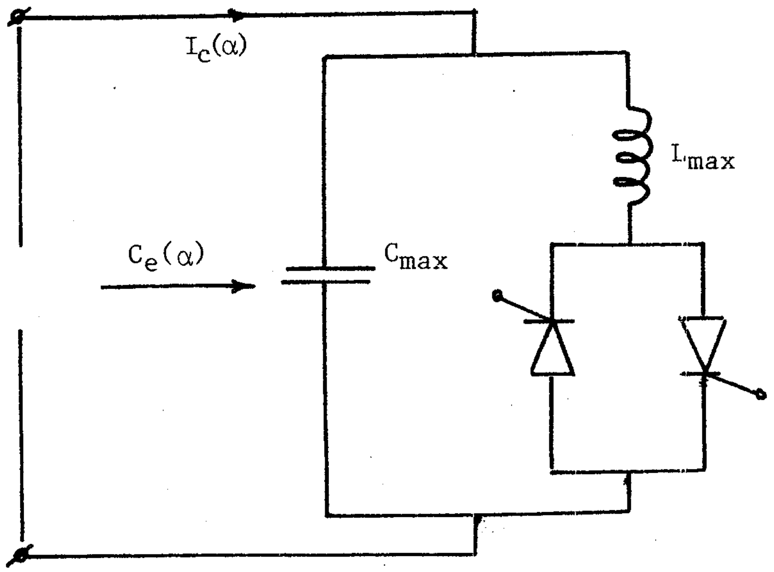


Fig.4. Basic circuit of FC-TCR.

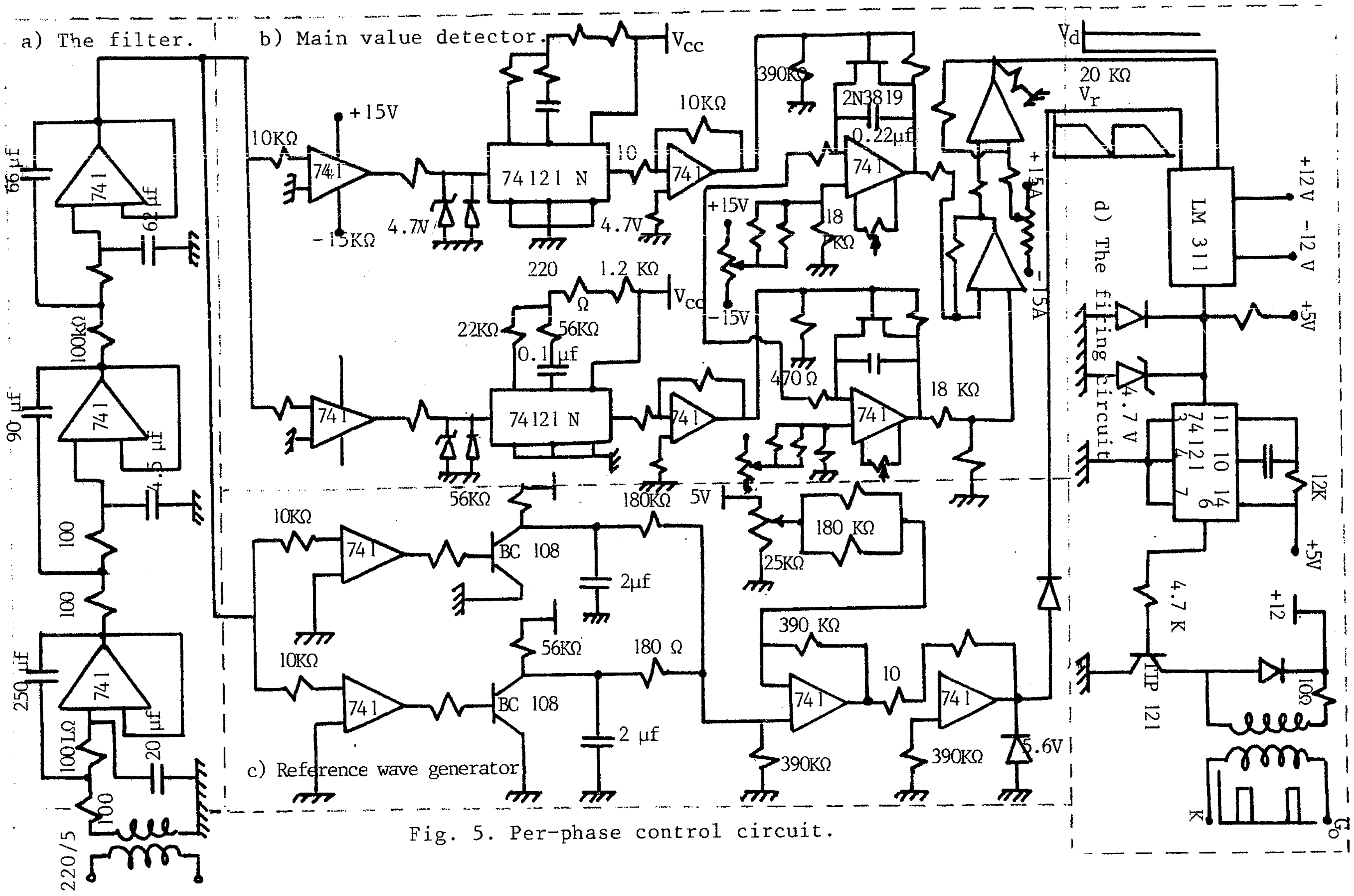


Fig. 5. Per-phase control circuit.

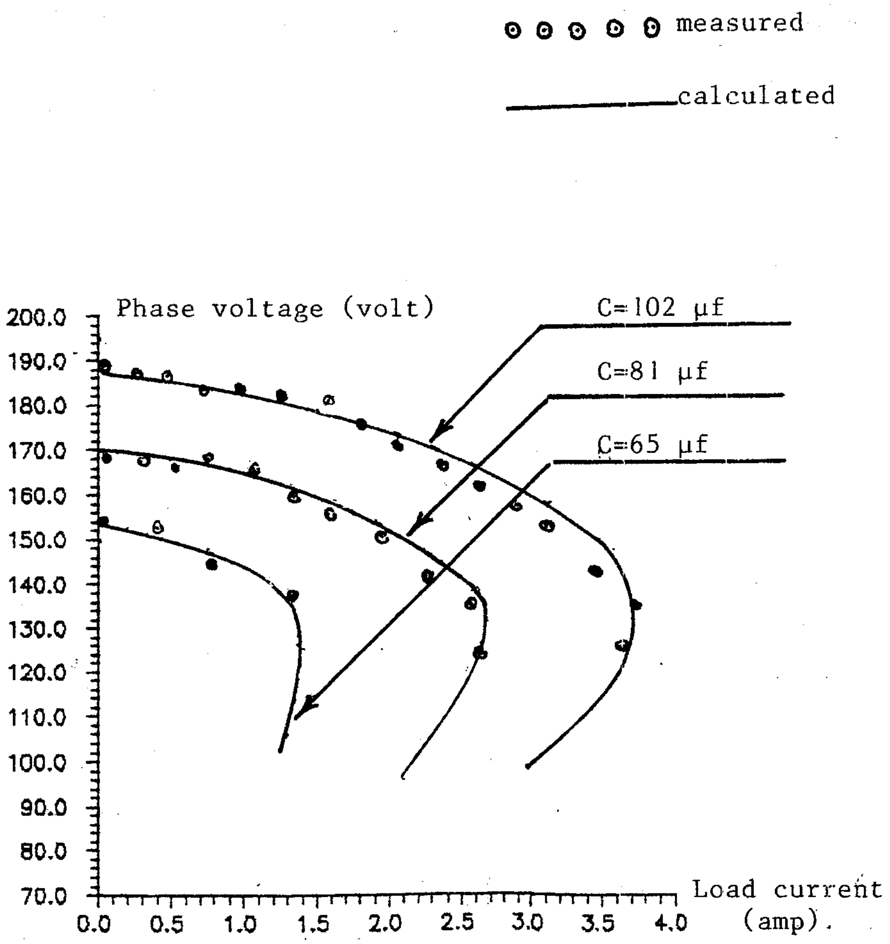
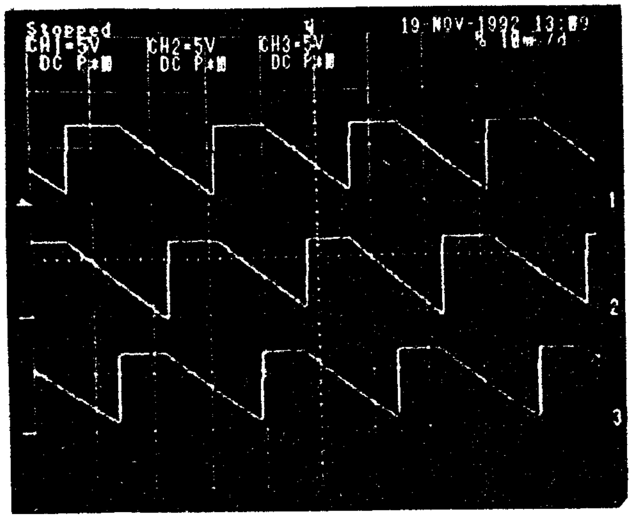


Fig.6. Uncontrolled external characteristic at different values of excitation capacitor and N_r=1200 r.p.m.

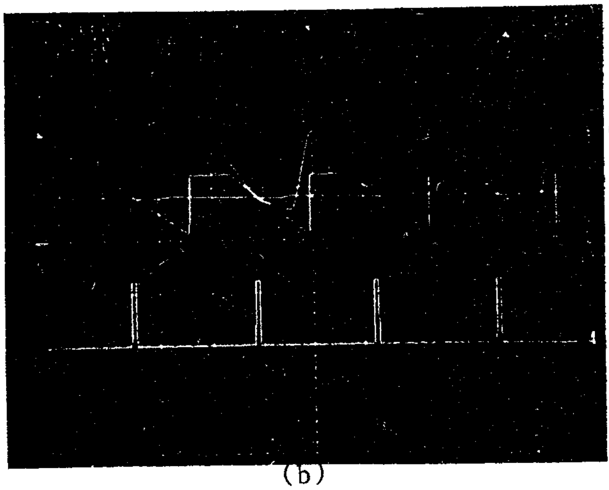


Phase A

Phase B

Phase C

(a) Reference wave generator output.



Ch.1. Filter input.

Ch.2. Mean value detector output.

Ch.3. Reference wave generator output.

Ch.4. Firing signals.

(b)

Fig. 7. Control signals.

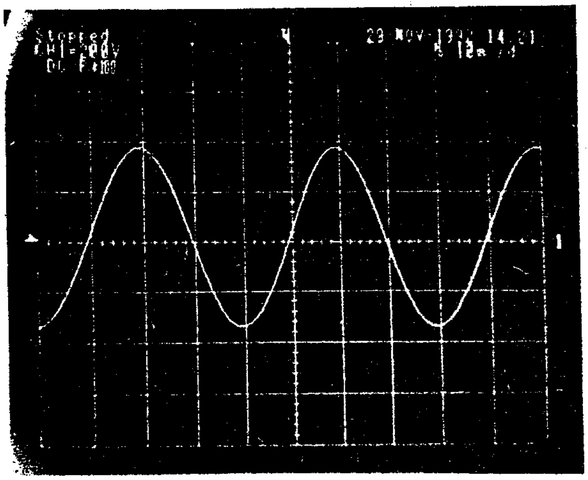


Fig.8. The phase terminal voltage.

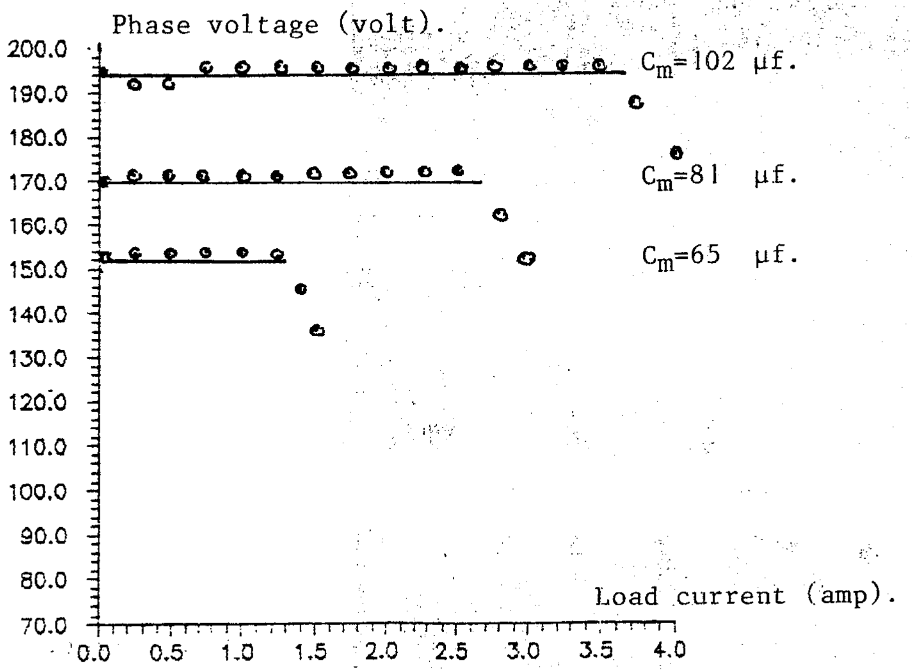


Fig.9. Controlled external characteristic at N_r=1200 r.p.m.

⊙ ⊙ ⊙ ⊙ measured.

——— calculated

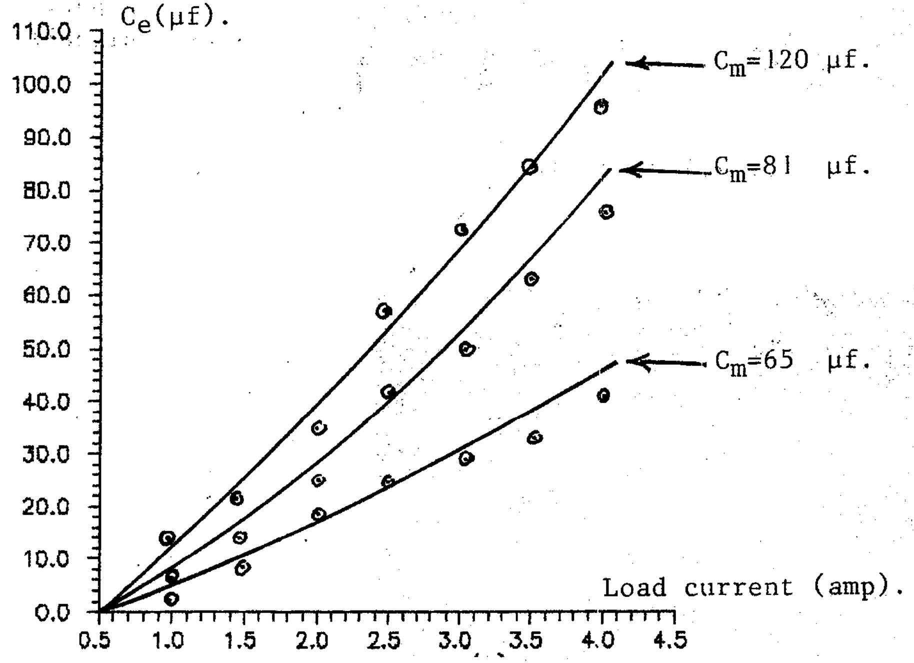


Fig.10. The profile of the additional capcitor (C_e) versus the load current at N_r=1200 r.p.m.

عنوان البحث :

" التحكم بالمثفات فى مولد توالى تزامنى ذاتى التغذية "

ملخص البحث :

تتميز مولدات التوالى المتزامنة ذاتية التغذية ثلاثيه الاوجة بانتاج جهد ذو تردد ثابت يعتمد فقط على سرعة الدوران ٠ الا ان قيمة هذا الجهد تتزايدمعقيمة المكثف وتتناقص مع تزايد تيار الحمل ٠

وللحصول على مصدر ذو جهد ثابت فيجب العمل على ثبوت جهد الخرج على مدى التحميل ٠ من الممكن الحصول على جهد ثابت من الآله بالتحكم فى مكثفات التغذية ولكن ذلك لا يعطى جهد ثابت بل يتغير مستوى الجهد مع تيار الحمل نظرا للتغير المتدرج فى قيمة المكثف ٠

فى هذا البحث أمكن تثبيت جهد الخرج باستخدام مكثفات موصلة بالتوازى مع ممانعة حثية يتم التحكم فيها باستخدام الثايرستور وبذلك يمكن تغيير السعة الفعالة تغييرا ناعما وقد تم تصميم وتنفيذ الدائرة الالكترونية اللازمة للتحكم فى زاوية اشعال الثايرستور ٠ وقد روعى عدم استخدام الدوائر المنطقية عالية الثمن أو التى تتأثر بارتفاع درجات الحرارة حتى يمكن الحصول على دائرة تحكم رخيصة الثمن وذلك لانتشار هذا النوع من المولدات ٠

تم عمل تحليل نظرى لحساب السعة المطلوبة لثبوت جهد الاطراف حيث أعطت النتائج علاقة تيار الحمل مع قيمة السعة عند جهد ثابت٠ كما تم تعديل هذا التحليل ليناسب عملية التحكم بالطريقة المقترحة حيث أوضحت النتائج اتفاقها مع النتائج المقاسة معمليا مع زيادة تيار الحمل حتى جهد القطع ٠

تم عمل مقارنة بين خصائص الحمل للمولد فى حالتى عدم التحكم فى مكثفات التغذية والتحكم فيها بالطريقة المقترحة حيث أوضحت المقارنة كفاءة الاسلوب المقترح للعمل على ثبوت جهد الخرج ٠