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DIODE FAILURE IN BRUSHLESS SELF EXCITED SYNCHRONOUS GENERATORS

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ABSTRACT

The paper discusses the effects of diode failure on the output voltage of the brushless single phase self excited synchronous generators. Self excitation is achieved via a suitable connection of the rotor circuit. The rotor phases are connected with two diodes to ensure a good rectified current. The failure of self excitation arrangement may be occurred by either an open or short circuit diode. Shorting one diode tends to cut off the generating voltage. However, the open circuit diode has a serious effect on the load which leads to generate a heavy distorted voltage waveform and an increase in its peak value. Therefore, a protective electronic circuit is designed and built to eliminate the effect of excitation capacitor on the generated voltage under this condition.

Theoretical model which describe such failure is proposed. An acceptable correlation between measured and calculated results has been obtained.

1. INTRODUCTION

Special types of single phase alternators driven by high speed diesel engines such as the brushless self excited synchronous generators in service for many years ago. This type of generators has a wide range of applications, specially in isolated areas. Due to the simplicity in construction and numerous fields of applications, many researchs have been concerned with this type of alternators. Different designs with static excitation techniques have been proposed

[1-3,5,6]. The no load ,load and transient characteristics of nonsalient and salient pole brushless generators have been studied since 1971 [4]. The output voltage waveform has also been tested and analyzed in [7].

The previous studies concentrated only on self excitation techniques and performance calculations rather than any failure effects. This may be attributed to the earliest limited applications of this type of generators as it has a wide range of applications for lighting the farms. Recently, such types of generators are employed in essential services in hospitals, and as transportable sets for services on civil engineering [2]. Subsequently, failure in the static excitation represents a very dangerous mode that requires a careful consideration.

This paper examines theoretically and experimentally the effects of diode failure on the performance of single phase self excited synchronous generators. Such failure is represented by either an open or short circuit on the diode connection. The later case have no any effects on the load, since the generator fails to generate a terminal voltage. If, however, one diode is opened the terminal peak voltage increases and a heavy distorted voltage waveform is generated. So, a protective electronic circuit was built to avoid the effects of this failure . The results show the effectiveness of the proposed circuit and the correlation between measured and calculated performance.

2. BASIC PRINCIPLES

The basic principles of the single phase self excited synchronous alternators can be explained on the light of Fig.1. A three phase slip ring induction machine can be used. Two stator phases are connected in series across the load while, the third phase is short circuited with the excitation capacitor. The rotor phases are connected with two diodes as shown in Fig. 1.

Operation of self excited generators depends mainly on the residual magnetism. If the machine rotates by means of a prime mover, a small emf will induced in the stator windings. So, a current is then flow in the capacitor circuit causing more flux that link the rotor. The rotor current will be of DC type due to the use of the two diodes. The rotor phases is then acts as an excitation winding, where a sinusoidal voltage waveform will generated. The value of the generated voltage depends mainly on excitation capacitor, while its shape depends on the existence of the two diodes.

3. EXPERIMENTAL MACHINE

A three phase slip ring induction motor is used as a single phase self excited synchronous generator. It has 4 poles, 4 KW, 380/220 volt rated values. For self excitation, the rotor phases are connected as shown in Fig. 1, through two 220 volt , 15 amps. diodes. Two stator phases (B & C) are connected in series, while phase "A" is short circuited with 72 μf excitation capacitance. The values of the machine parameters are shown in the Appendix.

4. THEORETICAL REPRESENTATION

The theoretical analysis presented herein concentrate mainly on studying the effects of the rectification failure on the output voltage. Regarding Fig.1, the stator phase voltage can be calculated using the following equations:

$$
\begin{aligned}
V_{as} &= - r_a i_{as} + \rho\lambda_{as} \\
V_{bs} &= - r_a i_{bs} + \rho\lambda_{bs} \\
V_{cs} &= - r_a i_{cs} + \rho\lambda_{cs}
\end{aligned} \qquad (1)
$$

At no load $i_{bs} = i_{cs} = 0$

The flux linkage can be obtained from :

$$
\begin{aligned}
\lambda_{as} &= (L_s+L_{ms})i_{as}+L_{sr}\, i_{ar} \cos\theta + L_{sr} \cos(\theta+120)i_{br} \\
&\quad + L_{sr} \cos(\theta + 240)i_{cr} \\
\lambda_{bs} &= L_{sr} \cos(120-\theta)i_{ar}+ L_{sr} \cos\theta\, i_{br} \\
&\quad +L_{sr} \cos(120+\theta)i_{cr} \\
\lambda_{cs} &= L_{sr}[\cos(240-\theta)i_{ar} + \cos(120-\theta)i_{br} +\cos\theta\, i_{cr}]
\end{aligned} \qquad (2)
$$

The terminal voltage can also be calculated from :

$$
V_L = \rho\lambda_{bs} - \rho\lambda_{cs} \qquad (3)
$$

The rotor phase voltages can be deduced using the following equation :

$$
\begin{aligned}
V_{ar} &= 0 = r_r\, i_{ar} + \rho\lambda_{ar} \\
V_{br} &= 0 = r_r\, i_{br} + \rho\lambda_{br} \\
V_{cr} &= 0 = r_r\, i_{cr} + \rho\lambda_{cr}
\end{aligned} \qquad (4)
$$

and,

$$
\begin{aligned}
\lambda_{ar} &= (L_r+L_{mr})i_{ar} - 0.5L_{mr}i_{br} - 0.5\, L_{mr}i_{cr} \\
&\quad +L_{sr} \cos\theta\, i_{as} \\
\lambda_{br} &= -0.5L_{mr}\, i_{ar} +(L_r+L_{mr})i_{br} -0.5\, L_{mr}i_{cr} \\
&\quad +L_{sr} \cos(\theta + 120)i_{as} \\
\lambda_{cr} &= -0.5\, L_{mr}i_{ar} - 0.5\, L_{mr}i_{br} +(L_r\; L_{mr})i_{cr} \\
&\quad + L_{sr} \cos(\theta +240)i_{as}
\end{aligned} \qquad (5)
$$

The voltage equation of the excitation capacitor can be developed for each mode of operation as follows :

4.1. Mode -1 : Both Diode Conducts

This operating mode represents the normal operating conditions in which the two diodes conduct. The capacitor voltage can be represented by:

$$-\frac{1}{C}\int i_{as}\,dt + r_a i_{as} = (L_s + l_{ms})\rho i_{as} + L_{sr}\,\rho i_{ar}\cos\theta$$

$$+ L_{sr}\cos(\theta + 120)\,\rho\, i_{ar} + L_{sr}\cos(\theta + 240)\,\rho\, i_{cr} \qquad (6)$$

$$- L_{sr}\,\dot{\theta}(i_{ar}\sin\theta + i_{br}\sin(\theta + 120) + i_{cr}\sin(\theta + 240))$$

Equations 1 to 6 can be arranged to calculate, numerically, the generated terminal voltage when the two diodes are conduct.

4.2 Mode - 2 : One Diode Conduct

This mode represents the case in which one of the two diodes openned , while the other still operate satisfactory. In this case , the following equations can be written:

$$i_{cr} = 0 \quad \text{and} \quad V_{br} = V_{ar} \qquad (7)$$

The voltage across the diode conducted is :

$$V_D = - r_r\, i_{br} + \sqrt{3}\, L_{sr}\,\rho i_{as}\sin\theta - (L_r + 1.5\, L_{mr})\rho i_{br}$$

$$+ \sqrt{3}\, L_{sr}\,\dot{\theta}\, i_{as}\cos\theta \qquad (8)$$

and ;

$$(L_s + L_{ms})\rho i_{as} + \sqrt{3}\, L_{sr}\cos(\theta + 150)\rho i_{br} = r_a\, i_{as} -$$

$$\sqrt{3}\, L_{sr}\,\dot{\theta}\sin(\theta + 150)\, i_{br} + \frac{1}{C}\int i_{as}\,dt \qquad (9)$$

$$\sqrt{3}\, L_{sr}\cos(\theta + 150)\,\rho i_{as} + 2(L_r + 1.5 L_{mr})\rho i_{br} =$$

$$\sqrt{3}\, L_{sr}\,\dot{\theta}\sin(\theta + 150)\, i_{as} + 2 r_r\, i_{br} \qquad (10)$$

Equations 7 to 10 describe the generator in Mode -2 and are programmed using a digital computation to calculate variation in terminal voltage.

5. Computer Model

Based on the previous equations ,a computer program has been constructed to calculate the no load output voltage waveform. Such calculations are carried out for the previously two modes of operation.

Before embarking on any experimental measurments, the computer model is tested where the computed results are shown in Fig. 2. It has been observed that, in mode- 1, the generated voltage drops just after positive and negative peak values. However, this drop reachs to zero if one diode is only conduct. This behaviour will be explained later with the aid of the experimental measurments.

6. MEASURED RESULTS

To study the effect of diode failure on the behaviour of single phase self excited synchronous generators, the windings of a slip ring induction machine is connected as shown in Fig.1. The generator is driven using a separate excited DC motor. The no load performance is measured under normal operating conditions, where the two diodes are conduct. Also,the generator behaviour is tested if any of the two diodes is opened or short circuited. This will be discussed subsequently in the following sections.

6.1. Operation With Two Diodes Conduct

In this case, the generator terminal voltage waveform was recorded during operating Mode -1 and under no load condition. . As shown in Fig.3, the voltage waveform is approximately of sinusoidal form. There are periods of lower voltage level. This may be explained on the light of the theory of operation and the measured results shown in Fig. 4. If the machine is driven as a self excited synchronous generator, a sinusoidal voltage signal will induced at the capacitor circuit as shown in Fig. 4-a. So, an AC current is flow in such circuit with the waveform shown in Fig. 4-b. Consequently, more flux borns in the airgap and linkages the rotor circuit. A rectified current will then flow in the rotor circuit which causes the generator excitation. The voltage signals across the diodes "B" and "C" are recorded and are shown in Fig. 4-c. It may be emphasized that, the two diodes operate over a half cycle as , there is a zero voltage level between each period of diode conduction. The rotor circuit in this period does not act, and in turn the terminal voltage decreased and distorted as shown in the figure. Such result is confirmed with that obtained analytically.

6.2. Operation With One Diode Shorted

For the present case, the generator was driven at its normal conditions, where one diode is suddenly short circuited. The terminal voltage is then recorded and the results are shown in Fig. 5-a. It is observed that, the generator fails to generate a voltage as a result of diode short circuit. This can be discussed regarding the behaviour of rotor current. As shown in Fig.5-b, the current on the reset conducting diode decays to zero due to the short circuit. So, the rotor circuit carry only an AC component which leads to the failure of the voltage generating process.

6.3 Operation With One Diode Opened

In this case, one diode is openned during operating the generator with normal condition. The rotor circuit is then has only one diode. The voltage and current of rotor circuit will be as shown in Fig. 6-a. The rotor current equals zero at the periods at which the diode non conduct. This leads to a drop in the terminal voltage at those periods. In general the peak value of this voltage is increased ,as shown in Fig.6- b & c. So, if one diode is openned , the terminal peak voltage increases and a heavy distorted waveform is generated . Therefore careful study for such a behaviour must be carried out to avoid any undesirable effects on load due to openning a diode. So, experimental analysis for the harmonic contents will be discussed in the following section.

7. HARMONIC ANALYSIS

The generated voltage waveform with an open diode, Fig. 6-c, was analyzed using a harmonic analyzer to study its harmonic contents. The spectrum of the harmonic is shown in Fig. 7. The third , fifth and seventh order of harmonics have approximately a peak value equals 80% of the fundamental. This result can not be ignored, since it has serious influence on the loads. Moreover, increasing the peak value of the terminal voltage must be avoided for all types of loads. So, a simple electronic circuit is proposed to protect loads against this conditions.

8. THE PROTECTION CIRCUIT

The main goal of this circuit is to cut off the generator terminal voltage as soon as any diode opened. This is executed via eliminating the effects of excitation capacitor.

The construction of such circuit is based on employing an operational amplifier "741" as an comparator. Also, a rectifier circuit is built and connected to rotor circuit to sence any variations due to diode failure. A reference voltage proportional to normal operating condition is used. To eliminate the effect of excitation capacitor , a triac in series with surge resistance are connected across the capacitor terminals. The circuit construction is shown in Fig.8.

Operation of the proposed circuit can be explained on the light of the condition of generator operation. If the two diodes are conducted, the output of the comparator will be zero and the triac will be off. This means that, the triac has no effect on the excitation capacitor. In case of openning the diode, the comparator output will be 5 volt due to the difference between the reference voltage and the control voltage. This will turned the triac on , which ensures a short circuit path across the capacitor and turns the terminal voltage to a zero value as shown in Fig.9. One may emphasis, with aid of Fig. 9 , that when the diode fails both the generated voltage and capacitor current decay to zero. However, the current through the surge resistance starts to build up and then decays to zero. This represents a very important aspect of the designed control circuit as it prevents the over voltage across the triac. Also, it may be stated that the circuit should be on just after reaching the steady state generated voltage. Since the present type of generators has a wide range of practical applications, an indicator lamp has been connected as shown in the figure to indicate diode failure.

9. CONCLUSIONS

This paper presentd a theoretical and experimental study of the effects of diode failure on the output voltage of the brushless self excited single phase synchronous generators. Such failure can be represented by an equivalent short circuit or an open diode. The results indicate clearly the importance of eliminating the load just after opening any of the two diodes. This may ba attributed to the heavy distorted generated voltage waveform with higher peak values.

The paper also, introduced a design for a protective electronic circuit which used to cut off the terminal voltage due to openning the diode. This circuit was designed and built with a minimum requirements to satisfy the commercial and practical uses of this type of generators.

The results presented herein show an acceptable confirmation between measured and computed results and illustrate clearly the effectiveness and importance of the protective circuit introduced.

10. 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 discussion and comments.

10. LIST OF SYMBOLS

r	phase resistance
L	self inductance
L_{ms}	stator interphase mutual inductance
L_{mr}	rotor interphase mutual inductance
L_{sr}	stator/rotor maximum mutual inductance
C	excitation capacitor
V	phase voltage
i	phase current
λ	flux linkage
ρ	operator d/dt

Subscripts

s,r	stator and rotor
a,b,c	generator phases

11. APPENDIX

11.1 Machine Parameters

The employed slip ring induction motor has the following parameters :

Power	= 4	KW.
Voltage	= 380 /220	volt.
current	= 14.8 /8.6	amps.
star wound rotor	= 103	volt.
rotor current	= 12	amps.
stator resistance	= 1.1	ohms/phase.
rotor resistance	= 4.3	ohms/phase.
stator reactance	= 2.2	ohms/phase.
rotor reactance	= 3.098	ohms/phase.
L_{ms}	= 0.5342	henery.
L_{mr}	= 0.2014	henery.
C	= 72	μf.

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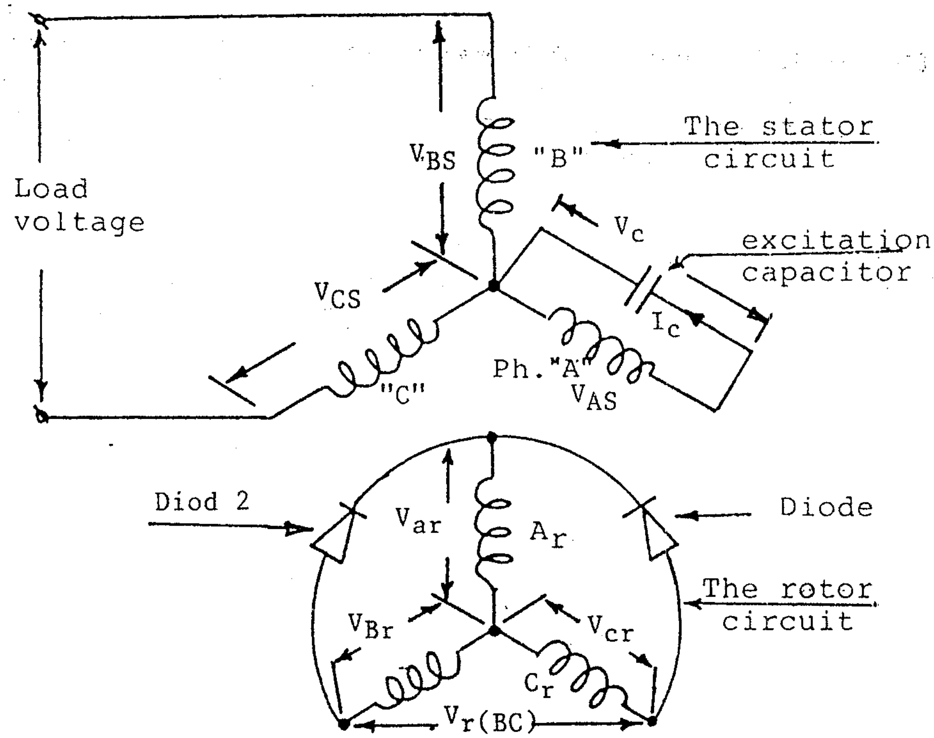
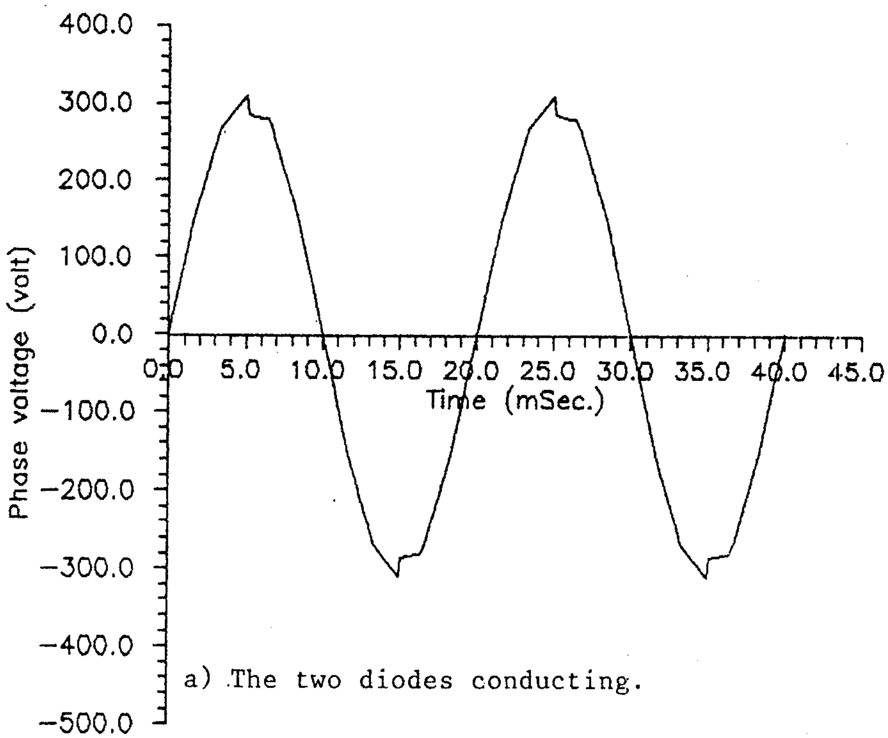


Fig. 1. Schematic diagram of single-phase self excited generator.



a) The two diodes conducting.

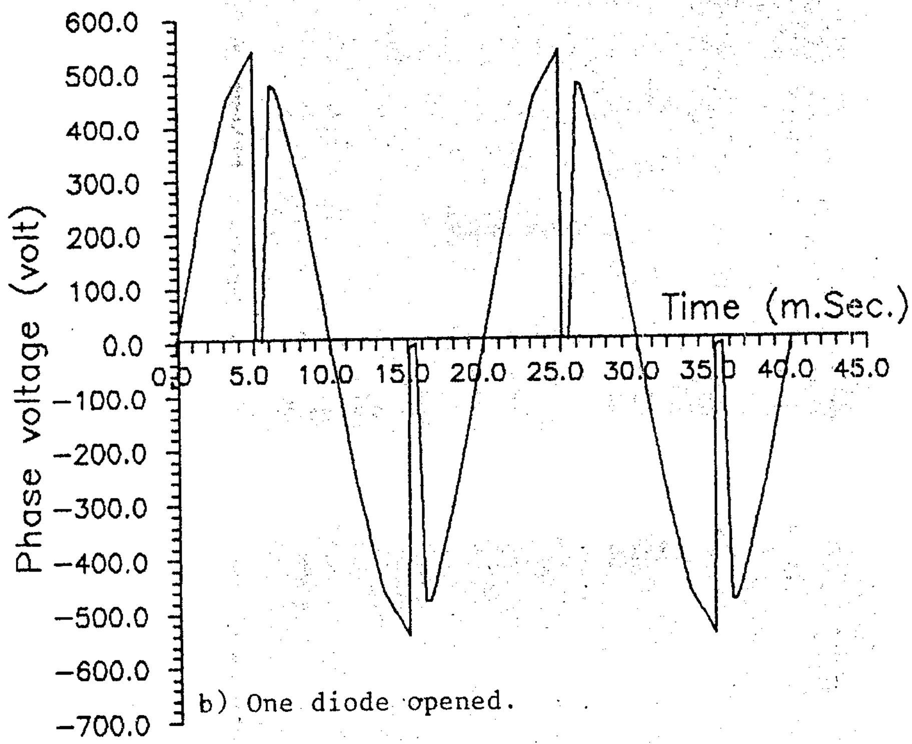


Fig.2. Calculated waveshape of the generated voltage.

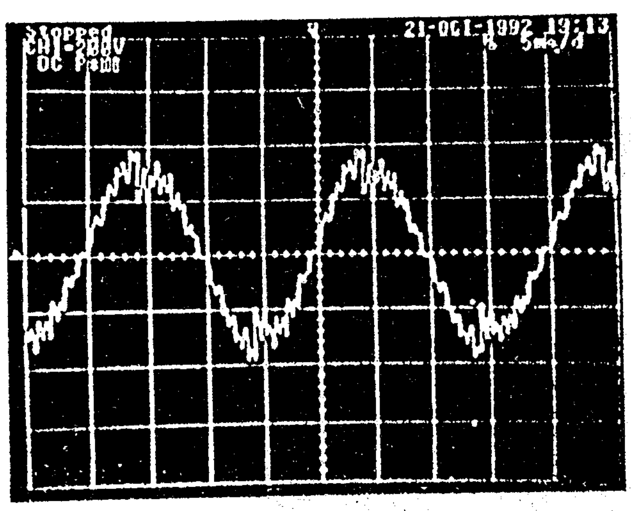
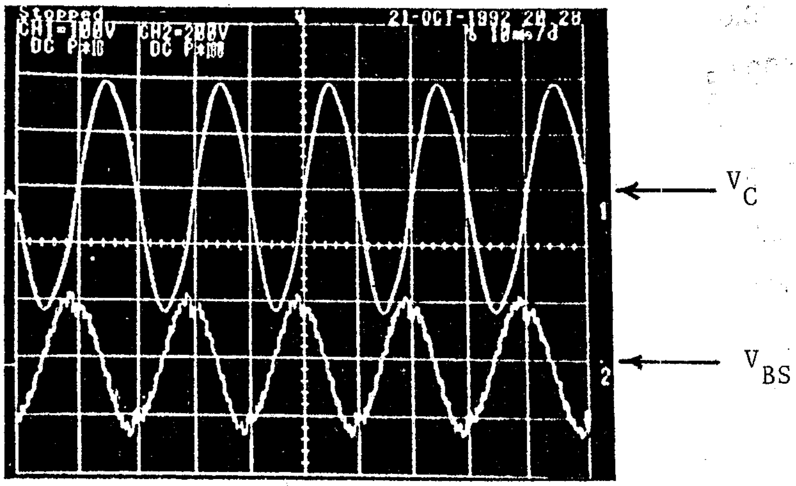
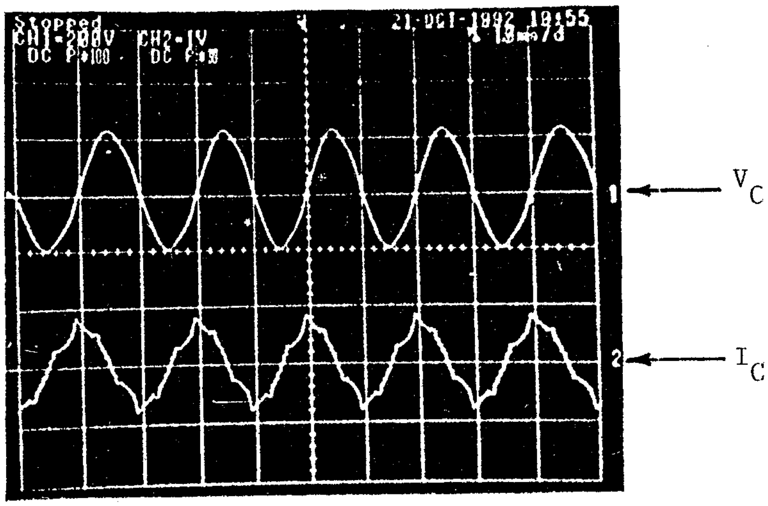


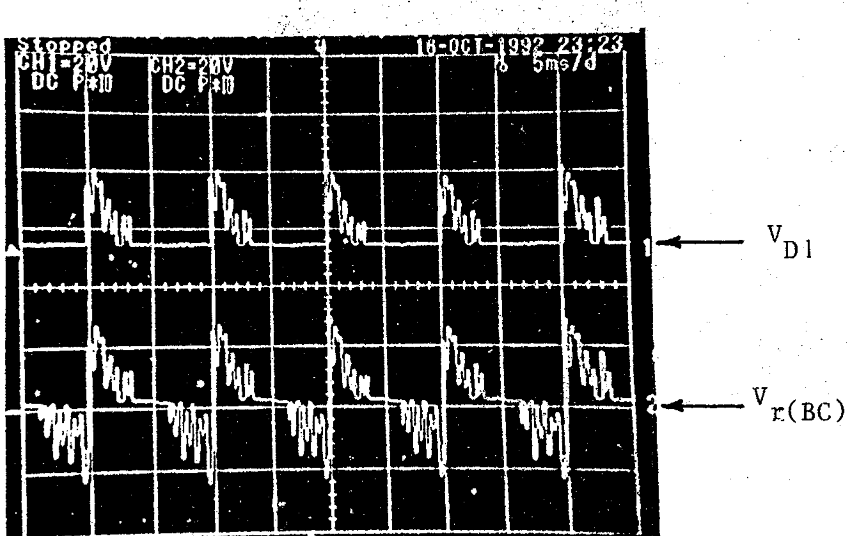
Fig.3. Waveshape of the generated voltage.



a)

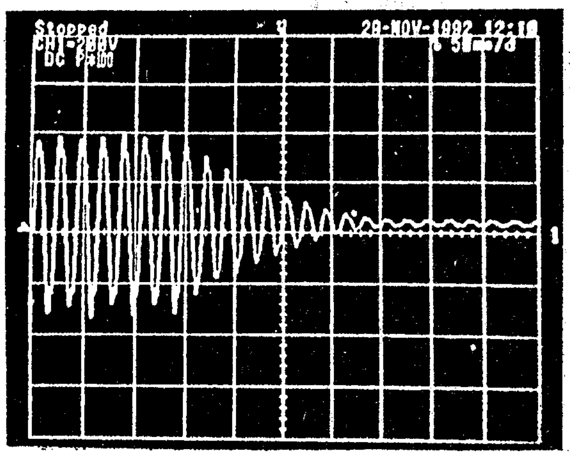


b)

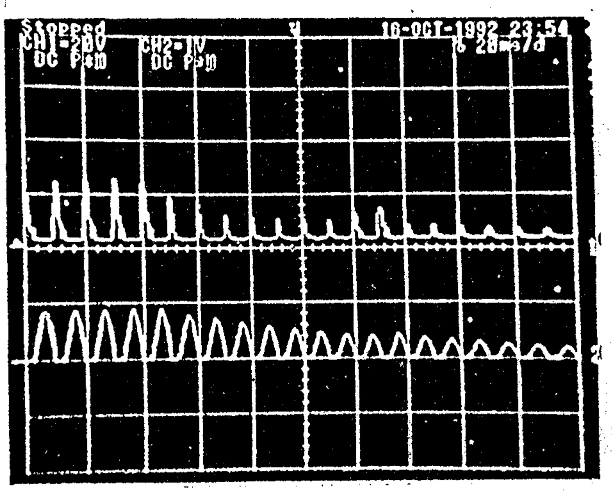


c)

Fig.4. The generator behaviour with the two diodes conducting.

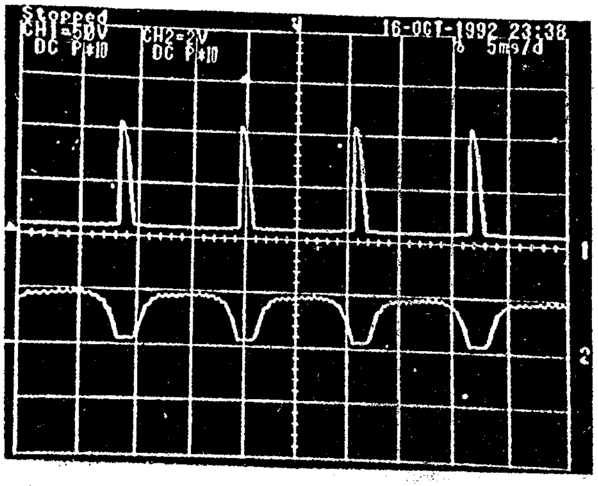


a) effect of shorting one diode on the generated voltage (D_1-shorted).

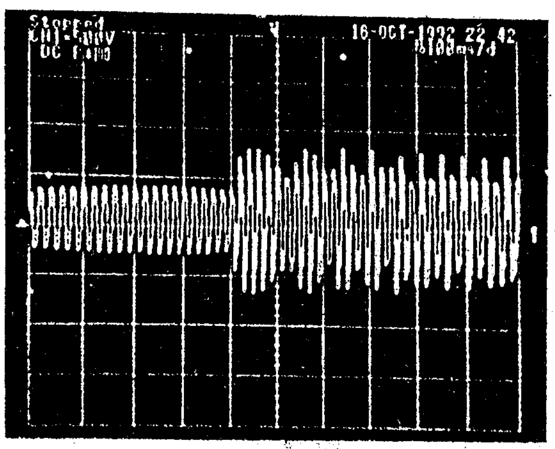


b) effect of shorting diode-1 on the behaviour of diode-2.

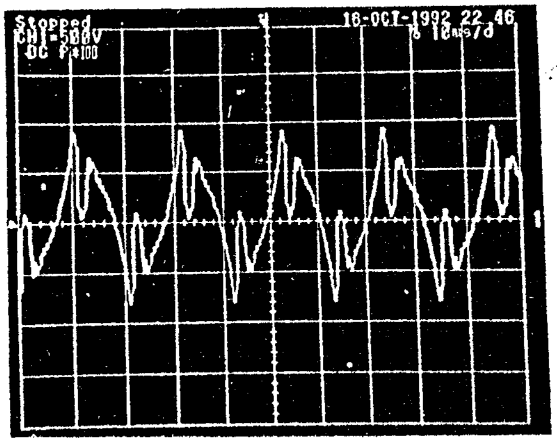
Fig.5. The generator behaviour with one diode shorted.



a) effect of opening diode-1 on the behaviour of diode-2.



b) effect of opening diode-1 on the generated voltage.



c) waveshape of the generated voltage with one diode opened.

Fig.6. The generator behaviour with one diode opened.

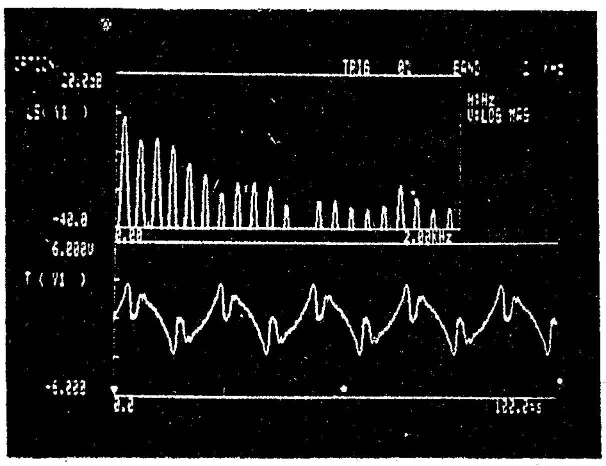


Fig.7. Harmonic spectrum of the generated voltage with one diode opened.

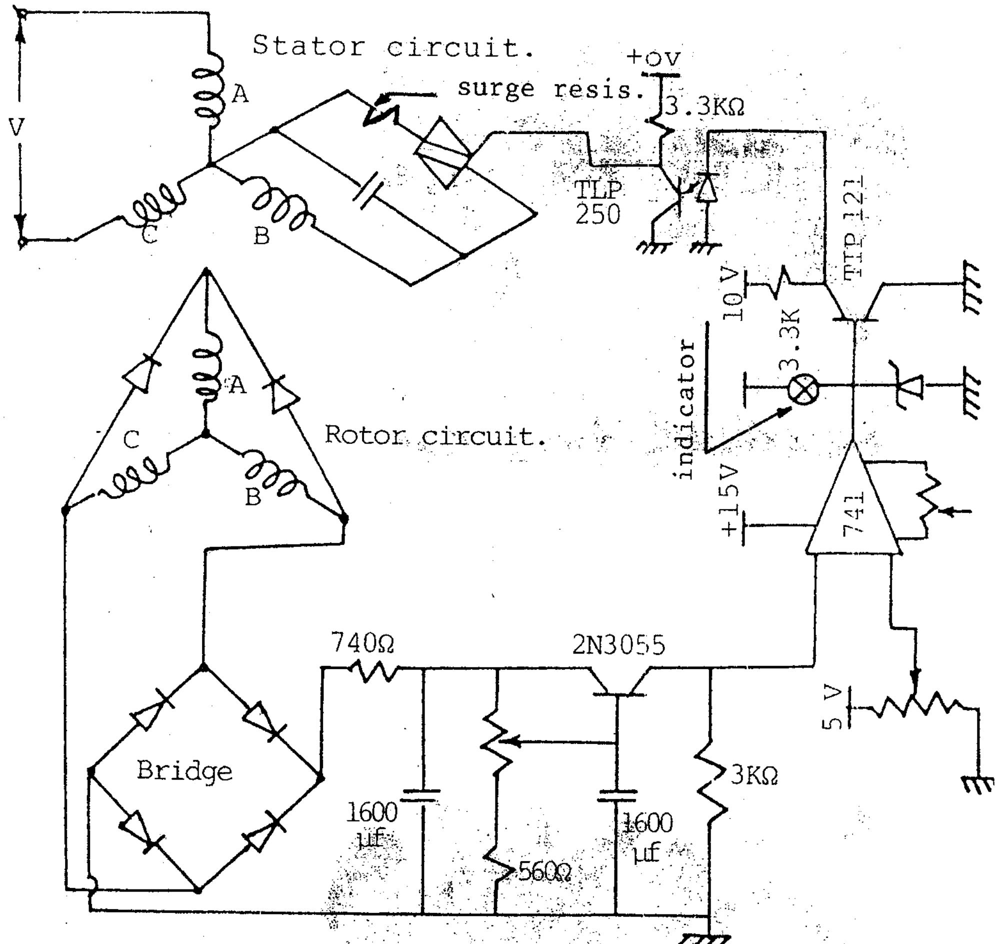


Fig. 8. The protection circuit.

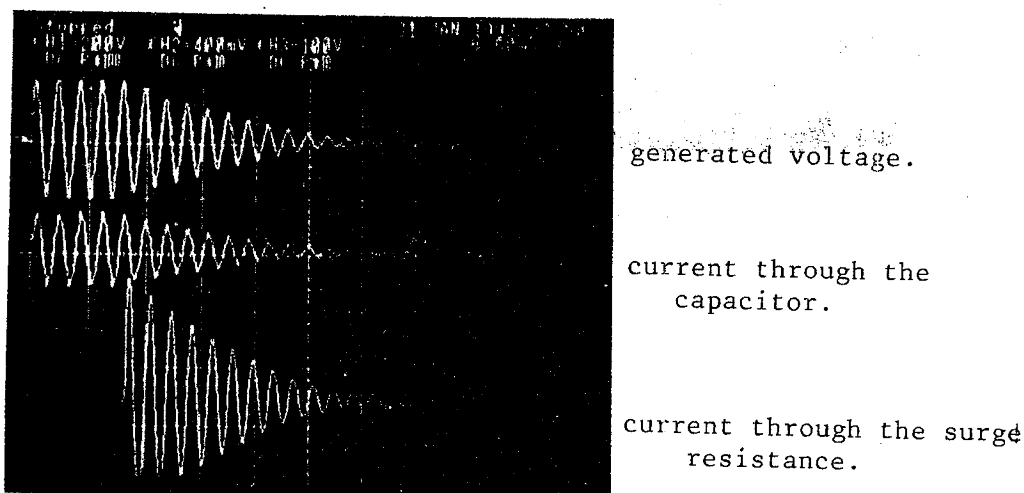


Fig.9 . Effect of the protection circuit on the behaviour of the generator.

عنوان البحـــث :

" تأثير انهيار الموحد السيليكونى فى المولدات المتزامنة ذاتية التغذية عديمة الفرش "

ملخص البحـــث :

المولدات التزامنية أحادية الوجه ذاتية التغذية من أهم مصادر انتاج القدرة الكهربية وخاصة فى المناطق المعزولة والبعيدة عن الشبكة الكهربية العامة • وتتحقق التغذيـــة الذاتية لهذة المولدات باستخدام اثنان من الموحدات السيليكونية بدائرة الدوار • وانهيار أحد هذة الموحدات له تأثير قد يكون خطيرا على الحمل المتصل بالمولـــد •

يقدم هذا البحث دراسة معملية مدعمة بالتحليلات النظرية لتأثير انهيار أحـــــد الموحدات السيليكونية على موجه الجهد المولدة • يتمثل هذا الانهيار فى أن تكـــــون دائرة الموحد مغلقة أو مفتوحـــة •

وقد تبين من هذة الدراسة انه اذا أغلقــتدائرة الموحد فان الجهد على أطـــراف الآله ينهار تماما • أما اذا حدث فتـــح فى دائرة الموحد فان موجه الجهد تتشوة وتزداد قيمتها العظمى الى مرتين ونصف تقريبا من القيمة المقننة • وبتحليل هذة الموجه وجد انها تحتوى على التوافقيات الثالثة والخامسة والسابعة بنسبة ٨٠٪ تقريبا من التوافقيـــة الأساسية وهذا يمثل خطورة على الحمل سواءا من ناحية التشوية أو من ناحية زيـــادة قيمـــة الجهـــد •

يقدم البحث ايضا دائرة حماية الكترونية مقترحة تعمل فى حالة قصر أحد الموحدات السيليكونية الموصلة مع ملفات الدوار وهذة الدائرة تعمل على توصيل مقاومة طرفى مكثف التغذية حتى يتلاشى تأثير هذا المكثف وبالتالى يحدث انهيار فى جهد الأطراف تصـــل قيمتة الى الصفر ، وقد تم اختبار كفاءة الدائرة معمليا • وحيث أن هذا المولـــــــد مستخدم حاليا وبكثرة فيمكن اضافة مصباح بيان يشير الى وجود خطأ فى دائرة الدوار•

تم عمل دراسة تحليلية نظرية لأداء الآله فى حالتى التشغيل بدون عطل وبوجود قصر على الموحد السيليكونى وقد اظهرت مقارنة النتائج توافقيا مرضيا بين النتائج المعملية والنظريـــة •