論 文
33～1～1

電力變換器를 가지는 同期 發電機의 特性

Characteristics of Synchronous Generator with Power Static Converter

李 承 院* · 權 營 顔**
(Sung-Won-Rhee · Young-Ahn Kwon)

요 약

전력변환기를 가지는 동기발전기 시스템이 상세히 해석되고 동기기 출력특성이 디지탈시뮬레이션에 의해 계산되었다.

전력변환기는 3상변환기로서 전류구간과 인터루드 구간이 한 사이클마다 6번씩 반복하는 모델로 고려되었다.

동기발전기는 정확한 특성을 구하기 위해 실축모델로서 고려되었다.

전체시스템의 비선형 미방에 대한 수치해석 기법으로는 룽게-쿠타 기법이 사용되었다.

Abstract

The system of synchronous generator with power static converter are analyzed in detail and the output characteristics of generator are computed by digital simulation. The power static converter is considered as 3-phase converter in which the interlude interval and the commutation interval repeats itself six times per cycle. The synchronous generator is considered as a direct-phase quantities model for a more exact study of the performance. As the numerical method for nonlinear differential equations of the system, the Runge-Kutta method is used.

List of Symbols

e = voltage
i = current
ψ = flux
Z = impedance
L = inductance
R = resistance

with subscripts

a, b, c	a-, b-, c-phase
1, 2, 3, 4, 5, 6	thyrister
d, q	d-, q-axis
α, β	α-, β-axis
o	zero-sequence
f	field

ω = synchronous speed
θ = rotor angle with respect to a-phase axis
δ = displacement angle
α = controlled angle
u = commutation angle
I = d.c load current
i = commutation current
L_s, L_m, M_s = inductance coefficients of the armature
M_f = mutual inductance between armature and field

*正 會 員 : 서울大 工大 電氣工學科 教授·工博
**正 會 會 : 서울大 大學院 電氣工學科 博士課程
接受日字 : 1983年 8月10日

1. Introduction

The development and use of power converter from 50 years or more ago had a large effect on power systems and drive systems. Power static converters fed by synchronous generators are commonly used in a.c. exciter systems and in h.v.d.c transmission systems.[1],[2] Recentry, the drive systems controlled by thyristors are used in all industries.[3] However, such a application causes harmonics in the a.c. power system due to the nonlinearity of converter.[4] In most systems, harmonic filters are used to reduce harmonics.[5],[6] The filters cost very high in some cases and they complicate systems.

This paper considers that no filter circuits are connected to the synchronous generator-power static converter system. The impedance of synchronous generator feeding power static converter has an important influence on the operation of the power static converter. As the reactance presented by synchronous generator influences the commutation of converter elements, it also effects output characteristics of generator. In this paper, the system of synchronous generator with power static converter are analyzed in detail and the output characteristics of generator are computed by digital simulation.

2. Mathematical Model

The overall system that is analyzed in this paper, is a system in which synchronous generator is connected to the power static converter with no filter circuits, Fig 1.

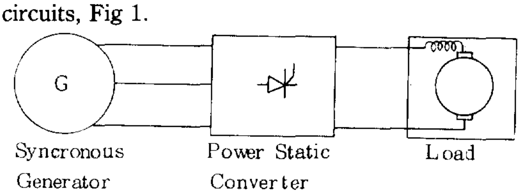


Fig. 1. Overall system

2.1 Mathematical Model of Power Static Converter

Methods of converter dynamic simulation have been proposed on tensor techniques.[7],[8] It has been shown that tensor methods result in more flexible simulation.

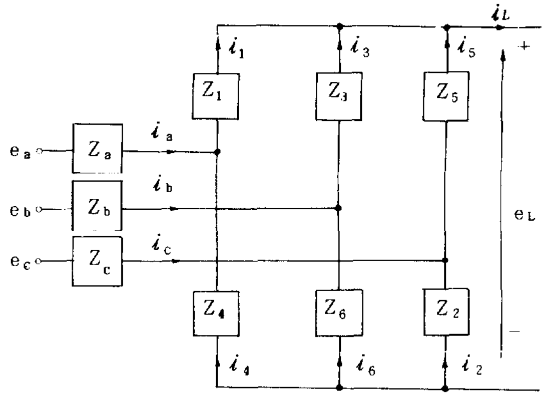


Fig. 2. Converter network

In the above 3-phase converter network, assuming that all the thyristers are conducting, the equations is a matrix form as follows.[8]

$$[E_i] = [Z_i][I_i] + [E_k] \qquad (1)$$

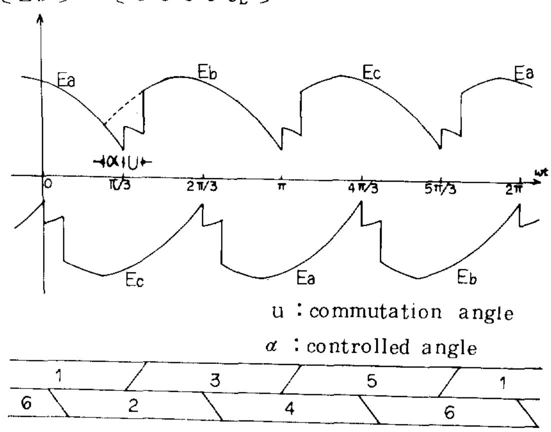
where

$$[E_i] = [e_a - e_c \quad e_b - e_c \quad e_c - e_a \quad e_c - e_b \quad 0]^t$$

$$[I_i] = [i_1 \quad i_3 \quad i_4 \quad i_6 \quad i_L]^t$$

$$[Z_i] = \begin{bmatrix} Z_a+Z_c+Z_1+Z_5 & Z_c+Z_5 & -Z_a-Z_c & -Z_c & -Z_5 \\ & Z_b+Z_c+Z_3+Z_5 & -Z_c & -Z_b-Z_c & -Z_5 \\ \text{symmetric} & & Z_a+Z_c+Z_2+Z_4 & Z_b+Z_2 & -Z_5 \\ & & & Z_b+Z_c+Z_2+Z_6 & -Z_5 \\ & & & & Z_2+Z_5 \end{bmatrix}$$

$$[E_k] = [0 \; 0 \; 0 \; 0 \; e_L]$$



mode	1	2	3	4	5	6	7	8	9	10	11	12
conducting thyristor	1 6 2	1 2	1 3 2	3 2	3 2 4	3 4	3 5 4	5 4	5 4 6	5 6	5 1 6	1 6

Fig. 3. Operation mode of 3-phase converter

In the operation of a 3-phase converter, either two or three thyristors are conducting simultaneously.[9] Therefore, twelve different modes of operation exist per cycle as shown in Fig. 3 considering ideal thyristors.[3] The interval during which two thyristors are conducting is called the interlude interval, while the interval during which three thyristors are conducting is called the commutation interval. In one cycle, interlude interval and commutation interval repeats itself six times.

In each mode, phase currents are as follows.

I : dc load current

i : commutation current

$$
\begin{array}{llll}
\text{mode } 1: & i_a = I, & i_b = -I+i & i_c = -i \\
\text{mode } 2: & i_a = I & i_b = 0 & i_c = -I \\
\text{mode } 3: & i_a = I-i & i_b = i & i_c = -I \\
\text{mode } 4: & i_a = 0 & i_b = I & i_c = -I \\
\text{mode } 5: & i_a = -i & i_b = I & i_c = -I+i \\
\text{mode } 6: & i_a = -I & i_b = I & i_c = 0 \\
\text{mode } 7: & i_a = -I & i_b = I-i & i_c = i \\
\text{mode } 8: & i_a = -I & i_b = 0 & i_c = I \\
\text{mode } 9: & i_a = -I+i & i_b = -i & i_c = I \\
\text{mode } 10: & i_a = 0 & i_b = -I & i_c = I \\
\text{mode } 11: & i_a = i & i_b = -I & i_c = I-i \\
\text{mode } 12: & i_a = I & i_b = -I & i_c = 0
\end{array}
\tag{2}
$$

2.2 Mathematical Model of Synchronous Generator

In the analysis of an idealized synchronous generator, Fig. 4, it is assumed that the distribution of the windings and the shape of the air gap are such that the self and mutual inductances of the stator windings contain no Fourier expansion terms higher than cos 2θ, while the mutual inductances between the stator and rotor windings vary simply as $\cos\theta$.[10),11] Saturation, hysteresis, and eddy current effects are ignored.

There are several methods of predetermining the transient performance of synchronous machines.

(a) d-q-o model

Using Park's transformation, machine voltages can be expressed in terms of flux linkages as:[10]

$$
\begin{aligned}
e_d &= p\,\psi_d - \omega\psi_q - R_a\, i_d \\
e_q &= \omega\psi_d + p\,\psi_q - R_a\, i_q \\
e_o &= p\,\psi_o - R_a\, i_o \\
e_f &= p\,\psi_f + R_f\, i_f
\end{aligned}
\tag{3}
$$

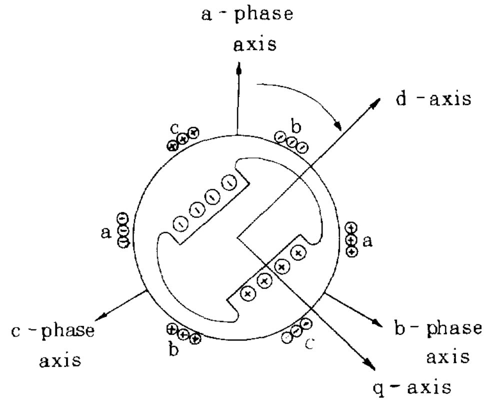


Fig. 4. Model of synchronous generator

Performance equations obtained from d-q-o model are differential equations with constant coefficients in the case of balanced load. However further transformation is necessary for the study of unbalanced load, Fig. 5, and it is difficult to use in such cases.[12]

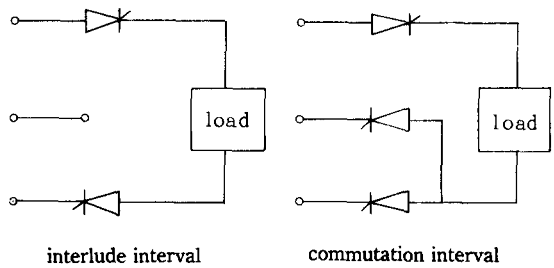


Fig. 5. Unbalanced load of 3-phase converter

(b) α-β-o model

Using a set of orthogonal reference axes α and β, the α axis being rigidly fixed to a-phase and the β axis 90° ahead in the direction of rotation, machine voltages can be expressed in terms of flux linkages as:[12]

$$
\begin{aligned}
e_\alpha &= p\psi_\alpha - R_a\, i_\alpha \\
e_\beta &= p\psi_\beta - R_a\, i_\beta \\
e_o &= p\psi_o - R_a\, i_o \\
e_f &= p\psi_f + R_f\, i_f
\end{aligned}
\tag{4}
$$

The flux linkage equations, in matrix notation, are:[12]

$$[\psi] = [L]\,[I] \tag{5}$$

where $[\psi] = [\,\psi_\alpha\ \psi_\beta\ \psi_o\ \psi_f\,]^t$

$[I] = [\,i_\alpha\ i_\beta\ i_o\ i_f\,]^t$

$$[L] = \begin{pmatrix} -L_a - M_a \mathrm{COS}\,2\theta & -M_a \mathrm{SIN}\,2\theta & 0 & M_f \mathrm{COS}\theta \\ -M_a \mathrm{SIN}\,2\theta & L_a + M_a \mathrm{COS}\,2\theta & 0 & M_f \mathrm{SIN}\theta \\ 0 & 0 & -L_o & 0 \\ -M_f \mathrm{COS}\theta & -M_f \mathrm{SIN}\theta & 0 & L_f \end{pmatrix}$$

where $L_a = (L_d + L_q)/2$, $M_a = (L_d - L_q)/2$

The performance equations obtained from α-β-o model are differential equations with variable coefficients. α-β-o model can be used in the case of unbalanced load but the advantage of simplication as obtained in d-q-o model is lost.

(c) direct-phase quantities model

Using direct-phase quantities, machine voltages in matrix notation can be expressed in terms of flux linkages as: [10]

$$[E] = p[\psi] - [R]\,[I] \tag{6}$$

where $[E] = [\,e_a\ e_b\ e_c\ e_f\,]^t$

$[\psi] = [\,\psi_a\ \psi_b\ \psi_c\ \psi_f\,]^t$

$[I] = [\,i_a\ i_b\ i_c\ i_f\,]^t$

$[R] = \mathrm{diag.}[\,R_a\ R_a\ R_a\ -R_f\,]$

The flux linkage equations are : [10]

$$[\psi] = [L]\,[I] \tag{7}$$

where

$$[L] = \begin{pmatrix} -L_s - L_m \mathrm{COS}\,2\theta & M_s - L_m \mathrm{COS}(2\theta - 2\pi/3) & M_s - L_m \mathrm{COS}(2\theta + 2\pi/3) & M_f \mathrm{COS}\theta \\ M_s - L_m \mathrm{COS}(2\theta - 2\pi/3) & -L_s - L_m \mathrm{COS}(2\theta + 2\pi/3) & M_s - L_m \mathrm{COS}\,2\theta & M_f \mathrm{COS}(\theta - 2\pi/3) \\ M_s - L_m \mathrm{COS}(2\theta + 2\pi/3) & M_s - L_m \mathrm{COS}\,2\theta & -L_s - L_m \mathrm{COS}(2\theta - 2\pi/3) & M_f \mathrm{COS}(\theta + 2\pi/3) \\ -M_f \mathrm{COS}\theta & -M_f \mathrm{COS}(\theta - 2\pi/3) & -M_f \mathrm{COS}(\theta + 2\pi/3) & L_f \end{pmatrix}$$

From the above equations

$$\begin{aligned}[E] &= p[L][I] - [R][I] \\ &= [I]\,p[L] + [L]\,p[I] \\ &\quad - [R][I] \end{aligned} \tag{8}$$

Performance equations obtained from direct-phase quantities model are differential equations with variable coefficients.

With the advant of modern computers, numerical methods can be employed efficiently for solving nonlinear differential equations.

In such a case, a direct 3-phase model can be used for a more exact study of synchronous machine performance. This paper uses the direct phase quantities model for a mathematical model of a synchronous generator and the procedure for simulation using numerical techniques.

3. System Equations

The rotor position at the start of the commutation interval is shown in Fig. 6.

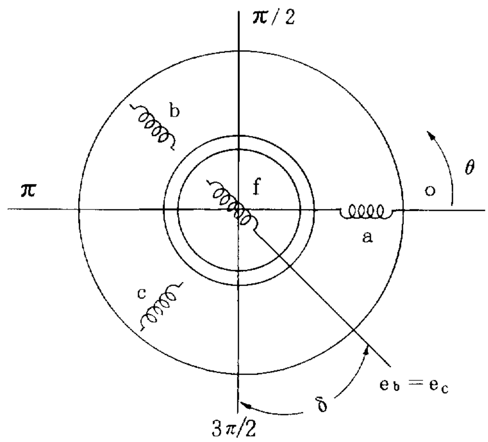


Fig. 6. Rotor position at start of commutation

If the generator is on no load, the a-phase voltage will be at its peak positive maximum at a rotor angle $\theta = 3\pi/2$. At this same angle on no load, $e_b = e_c$. However, anticipating that the armature currents influence the voltage waveforms by an armature reaction effect, it is assumed that the rotor angle at which e_b becomes equal to e_c, is dasplaced by a displacement angle δ from $\frac{3}{2}\pi$ in rotational direction. Hence the start of commutatin is delayed by an angle δ which is related to the d.c load current I. The rotor angle θ, chosen with respect to the axis of the a-phase winding is $3\pi/2 + \delta + \omega t$ corresponding to time t, Fig. 3, or is $3\pi/2 + \delta + \alpha + \omega t$ considering cotrolled angle at which the thyristor commences to conduct by injecting gate current.

In each mode, system equations are as follows from the equations (1), (2), (6), (7), and (8) considering ideal thyristors.

mode 1: $3\pi/2 + \delta + \alpha < \theta < 3\pi/2 + \delta + \alpha + u$ (9)

$$e_a = (-\sqrt{3}L_m SIN 2\theta)i' + (M_f COS\theta)i_f' + (2\sqrt{3}\omega L_m SIN(2\theta+\pi/6) - R_a)I + (-2\sqrt{3}\omega L_m COS 2\theta)i + (-\omega M_f SIN\theta)i_f$$

$$e_b = (-L_s - M_s + \sqrt{3}L_m \cos(2\theta - \pi/6))i' + (M_f COS(\theta - 2\pi/3))i_f + (-2\sqrt{3}\omega L_m \cos 2\theta + R_a)I + (-2\sqrt{3}\omega L_m SIN(2\theta - \pi/6) - R_a)i + (-\omega M_f SIN(\theta - 2\pi/3))i_f$$

$$e_c = (L_s + M_s - \sqrt{3}L_m COS(2\theta + \pi/6))i' + (M_f COS(\theta + 2\pi/3))i_f' + (-2\sqrt{3}\omega L_m SIN(2\theta - \pi/6))I + (2\sqrt{3}L_m SIN(2\theta + \pi/6) + R_a)i + (-\omega M_f SIN(\theta + 2\pi/3))i_f$$

$$e_f = (-\sqrt{3}M_f SIN\theta)i' + (L_f)i_f' + (\sqrt{3}\omega M_f SIN(\theta + \pi/6))I + (-\sqrt{3}\omega M_f COS\theta)i + (R_f)i_f$$

mode 2 : $3\pi/2 + \delta + \alpha + u < \theta < 3\pi/2 + \delta + \alpha + \pi/3$ (10)

$$e_a = (M_f COS\theta)i_f' + (2\sqrt{3}\omega L_m SIN(2\theta - \pi/6) - R_a)I + (-\omega M_f SIN\theta)i_f$$

$$e_b = (M_f COS(\theta - 2\pi/3))i_f' + (-2\sqrt{3}\omega L_m SIN(2\theta + \pi/6))I + (-\omega M_f SIN(\theta - 2\pi/3))i_f$$

$$e_c = (M_f COS(\theta + 2\pi/3))i_f' + (2\sqrt{3}\omega L_m COS 2\theta + R_a)I + (-\omega M_f SIN(\theta + 2\pi/3))i_f$$

$$e_f = (L_f)i_f' + (\sqrt{3}\omega M_f SIN(\theta - \pi/6))I + (R_f)i_f$$

The above two modes repeat six times in one cycle and the other modes are omitted.

4. Digital Simulation

The simulation involves the solution, by numerical methods, of the mathmatical model developed above. There are some techniques for solving nonlinear differetial equations.

The Runge-Kutta method was used in the present investigation for the following reasons.[13),14)]

(a) No special starting procedure is required since the method is self-starting.

(b) It permits easy change of step length.

(c) A straightforward computational procedure is repeated throughout the caculation.

(d) No modification of the computation is necessary for nonlinear equations.

(e) The method is generally more accurate than other methods.

The basic algorithm for the simulation of the mathematical model developed is as follows.

(i) From the given operating conditions, the initial currents and displacement angle are calculated approximately.

(ii) The calculation in a step by step using the Runge-Kutta method starts from the initial values calculated in (i).

(iii) During the commutation interval, field current and commutation current are calculated by using the Runge-Kutta method.

(iv) The value of the angle, commutation angle, at which the commutation current attains the value of the output d.c current, is determined.

(v) The calculation for the interlude interval starts from the currents calculated in the commutation angle.

(vi) During the interlude interval, field current is calculated by using the Runge-Kutta method.

(vii) The currents at each point of angle are determined.

(viii) Field current at $t=0$ and field current at $t=\pi/3\omega$ are compared.
If they do not agree with in a specified tolerance, steps (ii) — (viii) are repeated using displacement angle calculated by new field current at $t=\pi/3\omega$

(ix) Using the above calculated value, the waveforms of the voltages and currents are obtained over a period of 2π.

(x) Other necessary values are calculated.

5. Results and Conclusions

As mentioned in the introduction, power static converters fed by synchronous generators are commonly used in ac-dc conversion systems. The purpose of this study is to analyze the system of synchronous generator with power static converter.

The system equations (9) and (10) for synchronous generator with power static converter are derived considering the direct-phase quantities model of synchronous generator, the interlude interval and commutation interval of power static converter and constant d.c load current.

The FORTRAN computer program has been applied to this system to calculate generator output characteristics. The data of synchronous generator by the per-unit are as follows.

$L_s = 0.25$　　$L_m = 0.01$

$L_f = 0.72$　　$M_f = 0.42$

$R_a = 0.00001$　　$R_f = 0.00002$

$M_s = 0.09$

The d.c load current is kept constant at 0.9 per-unit. The direct-phase quantities model is well suited for simulation on a computer and the digital solutions for different average field currents and controlled angles are computed.

Fig. 7, Fig. 8 and Fig. 9 are waveforms in average field current $\bar{I}_f = 2.0$ and controlled angle $\alpha = 0°$.

In this case the obtained displacement angle and commutation interval is 15° and 25° each.

Fig. 7 shows the c-phase voltage versus the degree. It can be noted that the large distortions of the voltage waveform occurr six times per cycle when c-phase is involved in a commutation.

Fig. 8 shows the c-phase current versus the degree. It can be noted that the current in the commutation interval is continuously changed due to the commutation reactance and the current in the interlude interval is the constant d.c load current.

Fig. 9 shows the field current versus the degree. It can be noted that the field current is not constant due to the armature current distortion and fluctuates six times per cycle because the commutation interval and interlude interval repeats itself six times per cycle.

Fig. 10, Fig. 11 and Fig. 12 are waveforms in average field current $\bar{I}_f = 3.8$ and controlled angle $\alpha = 0°$. In this case the obtained displacement angle and commutation interval is 9° and 8° each.

It can be noted that the commutation interval is shorter and voltage waveform distortion is smaller in comparison with the case of $\bar{I}_f = 2.0$ and $\alpha = 0°$.

Fig. 13, Fig. 14 and Fig. 15 are waveforms in average field current $\bar{I}_f = 1.1$ and controlled angle $\alpha = 20°$. In this case the obtained displacement angle and commutation interval is 24° and 10° each.

The waveforms of voltage and current, as shown above, include large harmonics. These harmonics cause additional core loss and copper loss in

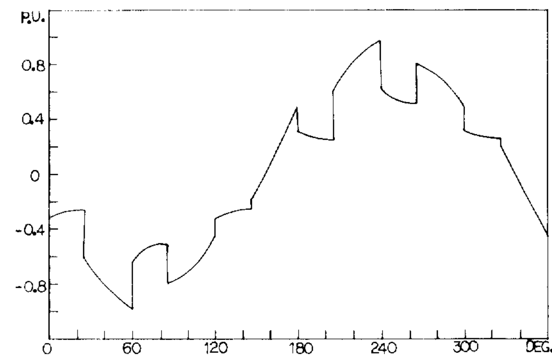


Fig. 7. Waveform of C − phase voltage

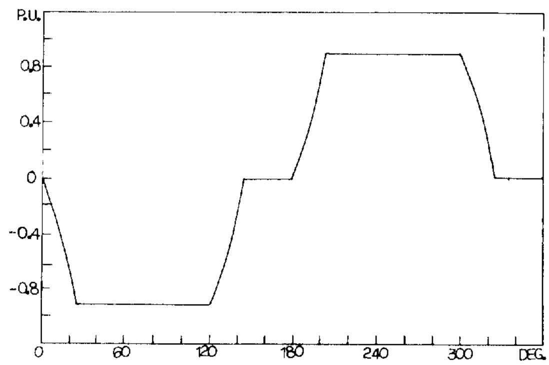


Fig. 8. Waveform of C − phase current

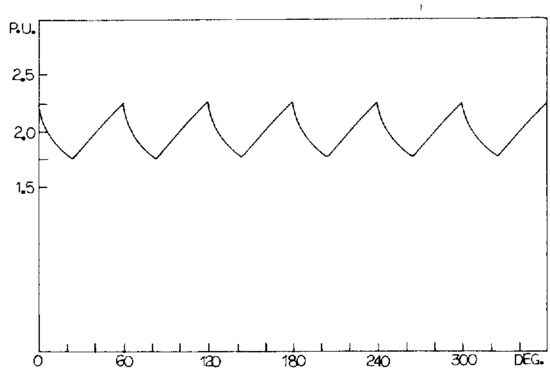


Fig. 9. Waveform of field current

machine. Therefore the harmonics must be considered for the winding distribution and the temperature rise of machine in the design of the generator connected to the power static converter and for the system design or stability.

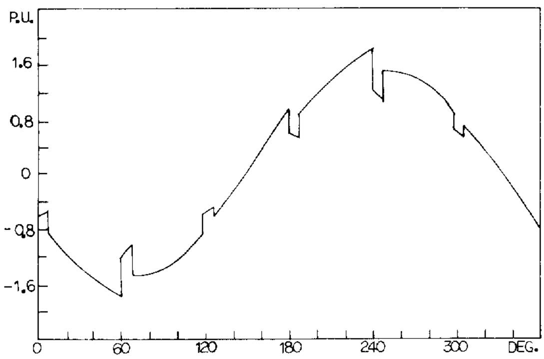


Fig. 10. Waveform of C – phase voltage

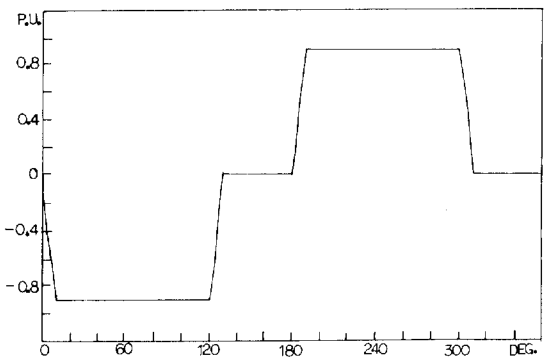


Fig. 11. Waveform of C – phase current

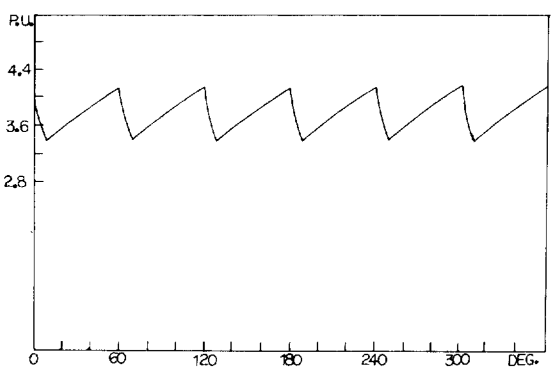


Fig. 12. Waveform of field current

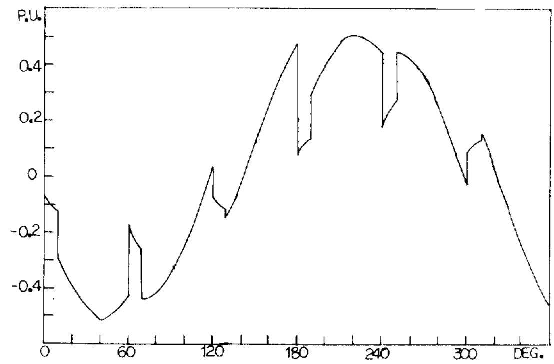


Fig. 13. Waveform of C – phase voltage

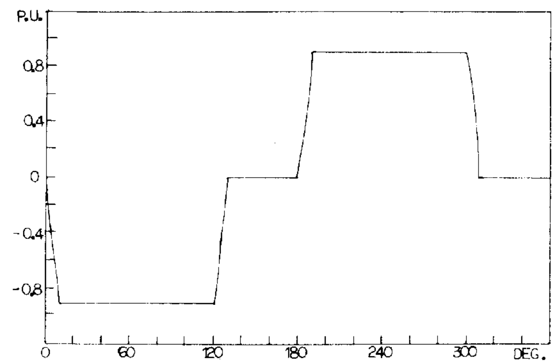


Fig. 14. Waveform of C – phase current

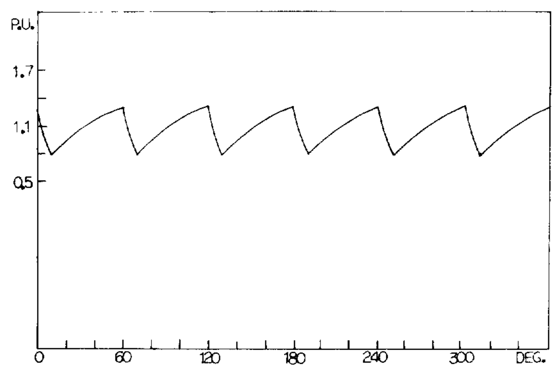


Fig. 15. Waveform of field current

References

1) V.Easton; "Excitation of large turbogenerators", Proc. IEE, vol.-111, No. 5, pp.1040-1048, 1964
2) E.W. Kimbark; "Direct current transmission", vol. 1, Wiley, 1971.
3) S.B Dewan and A. Straughen; "Power

semiconductor circuits", Wiley, 1975.

4) J. Reeve J.A. Baron and P.C.S. Krishnaya; "A general approach to harmonic current generation by HVDC converters ", IEEE, PAS-88, pp.989-994, 1969.
5) C.D. Clarke and M.J. Johanson-Brown; "The application of self-tuned harmonic filters to HVDC converters", IEE conf. pub. No. 22, pp.275-276, 1966.
6) T. Gilsig; "An interconnected a.c filter for HVDC converters", IEEE, PAS-89, pp.463-467, 1970.
7) J.S.C. Htsui and W. Shpherd; "Method of digital computation of thyristor switching circuits", Proc. IEE, vol. 118, No.8, pp.993-998, 1971.
8) S. Williams, and B.I.R. Smith; "Fast digital computation of 3-phase thyristor bridge circuits", Proc. IEE, vol.120, No.7, pp.791-795, 1973.
9) J. Schaefer; "Rectifier circuits: theory and design", Wiley, 1965.
10) E.W. Kimbark; "Power system stability; vol. III synchronous machines", Wiley, 1956.
11) C. Concordia; "Synchronous machines", Wiley, 1951.
12) H.H Hwang; "Unbalanced operation of a.c machines", IEEE, PAS-84, No. 11, pp.1054-1062, 1965.
13) S.D. Conte and C. de Boor; "Elementary numerical analysis", McGraw-Hill, 1972.
14) S.S. Kuo; "Computer application of numerical method", Addison-Wesley, 1972.