DIGITAL SIMULATION OF A VARIABLE SPEED SHAFT DRIVEN ALTERNATOR WITH VOLTAGE AND FREQUENCY CONTROL

By

M. M. I. El-SHAMOTY

Department of Electrical Engineering, El-Mansoura University, El-Mansoura, Egypt.

ABSTRACT :

Nowadays, an electrical system abroad-ship can be built of a shaft driven alternator which supplies AC loads with constant voltage and frequency through a D link. The stability of such a system depends on the choosing of its parameters and operat. conditions. The aim of this paper is to investigate the effect on the alternator perfo. nce. of the smoothing-reactor, compensator damping-resistance as well as of the initial slip of synchronization process.
For this purpose, the paper presents a digital simulation which applies the time varying effective value for fast prediction of the quasi-steady state behaviour of the system. This behaviour is due to the generated oscillations with small slip in the suggested system which is assumed to be isolated from the utility network.

0.0 LIST OF SYMBOLS :

E := time varying effective value TVEV of AC excitation phase voltage, in volt.
E_p := TVEV of compensator internal phase voltage, in volt.

V := TVEV of AC terminal phase voltage, in volt.
V_D := TVEV of DC voltage behind smoothing reactor, in volt.

V_{dc} := TVEV of DC voltage appears on inverter terminals, in volt.

I := TVEV of current, in ampere.
T_I := inertia torque of compensator equivalent to one phase, in N-m.

T_c := synchronous torque of compensator, defined as above.

T_{as} := asynchronous torque of compensator, defined as above.

T_d := breaking torque of compensator, defined as above.

J := inertia coefficient of compensator equivalent to one phase, in kg. m^2.
Z := synchronous impedance per phase, in ohm.
X := synchronous reactance per phase, in ohm.
X_p := compensator Potier reactance per phase, in ohm.

R := armature resistance per phase, in ohm.
P := number of pole pairs.
n_r := relative speed of shaft-alternator.

Ω_r := mechanical angular velocity of compensator rotor, in rad/sec.

Ω_s := synchronous angular velocity of compensator stator frequency, in rad/sec.
φ := power factor angle, in radian.
δ := torque angle, in radian.
α := converter delay angle, in radian.
β := inverter advance angle, in radian, and is equal to $\pi - \alpha$.
γ := commutation angle, in radian.
γ_0 := commutation angle corresponding to zero delay angle, in radian.

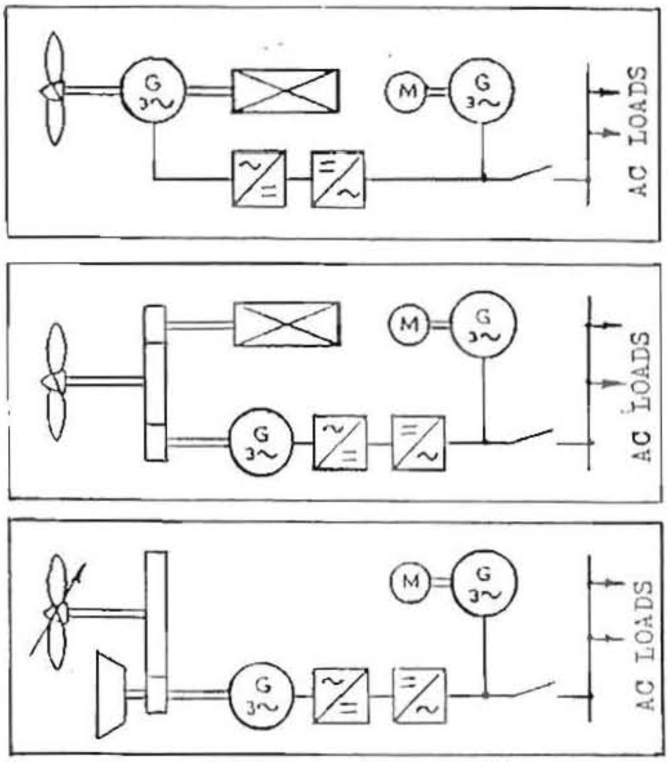


Fig. (1) : Different Types of Shaft-Alternator Coupling.

Subscripts denote as follows :

- g - shaft-alternator
- c - synchronous compensator
- re - rectifier bridge
- in - inverter bridge
- D - DC link
- L - load receiver

1.0 INTRODUCTION :

As a consequence of increasing the cost of conventional fuel, and in order to improve the overall efficiency of electric power generation aboard-ships, propeller-shaft driven alternators are now commonly in use. In most cases, these alternators can be built directly on the propeller-shaft where the shaft-speed is high enough to limit the number of poles, as shown in Fig. (1). In cases where the shaft-speed is too low, an appropriate gearing can reduce the required pole number to an acceptable figure. In all cases , however, propeller-shafts are driven by gas turbines or diesel engines.

It is evident here that the alternator prime-mover offers a variable speed drive. Consequently, the generated e.m.f. will be mainly of variable frequency in addition to its variable value.Most of electric mains on a ship are built for AC three phase operation at constant voltage and frequency. Therefore, one of the main difficulties of supplying power of propeller-shaft driven alternators to these mains is the varying speed nature of the prime-mover.

The tremendous improvements in solid-state conversion technology make it now possible to overcome this difficulty. A DC link with an inverter connected between the variable speed alternator and the loads is a well accepted solution to supply electrical power to the loads at constant frequency and stabilized voltage [5]. Such a system, Fig. (2-a), converts the mechanical power taken from the propeller shaft into electric power with a frequency which corresponds to the shaft speed , and supplies after the conversion processes the electric power to the common bus-bars at the required frequency.
While the load requirements of active power will be supplied from the inverter, a compensator must be connected to the inverter terminals in order to supply the reactive power needed for the inverter as well as for the load. This compensator is mainly a synchronous machine in order to :

i . obtain natural commutation for the inverter through the induced e.m.f. ,
ii. operate, alternatively, as a generator to supply power to the ship's mains system in case of speeds under operating limit of the system .

It is evident that this system contains two synchronous machines which have two different applications from the usual. Each machine is connected to a non-linear conversion device; a rectifier or an inverter which is built mainly of thyristor groups. Both machines will carry currents of high order harmonics in either stators or rotors even under steady-state operation [1] . In addition to the well known effects of higher harmonics on the current-shape, it will increase the copper losses [2] . The increase in copper losses depends essentially on the delay angle of the connected conversion device. This delay angle must be considered as an important factor while designing the corresponding synchronous machine. Another factor which plays a great role in estimating the machine rating is its operational power factor. In this system the delay angle of the rectifier has a significant effect on the alternator power factor. But in case of synchronous compensator both of the inverter advance angle and the load power-factor have the major effects on the compensator power-factor and in turn, on its rating [3] .

This paper proposes guide lines for estimating the rating of the shaft-alternator and predicts its performance during the system direct synchronization [8] and the speed variation of shaft-alternator, by a simple method for formulating the mathematical model. This method is based on the time varying effective value, TVEV , and is simulated in . computer program which can be processed by Micro-computer.

..0 SYSTEM DESCRIPTION :

Figure (2) shows the schematic-diagram of the suggested system and the phasor diagrams of the included machines. Essentially, the system consists of two stages :

i . A variable-speed constant excitation alternator connected to a controlled rectifier bridge in order to deliver constant power to the DC-link under constant voltage V_{dc} .
ii. An inverter triggered with constant frequency impulses connected with controlled excitation synchronous compensator to supply the AC loads under constant frequency and voltage .

The electrical power generated by the shaft-alternator is characterised by both variable voltage and frequency. This voltage is rectified by means of 6-pulses, 3-phase controlled rectifier, which is connected to the DC side of the inverter through a smoothing reactor. The DC voltage applied to the inverter, V_{dc} , is held constant due to rigid, but uncontrolled, advance angle β and the constant voltage applied to the AC-side, V. The excitation of synchronous compensator is automatically controlled to keep the last voltage, V, constant. This control is ensured as long as the capacity of the synchronous compensator is enough to compensate the reactive power required by both load and inverter. The value of the advance angle β should be carefully chosen to be small enough in order to reduce the inverter reactive power but must be larger than the corresponding commutation angle, γ_{in} , to avoid inverter failure. In order to deliver constant power to the DC-link, the voltage V_{dc} is held constant by controlling the delay angle of the rectifier, α_{re} . Consequently, the voltage V_D slightly varies in proportion to the current I_D during the transient

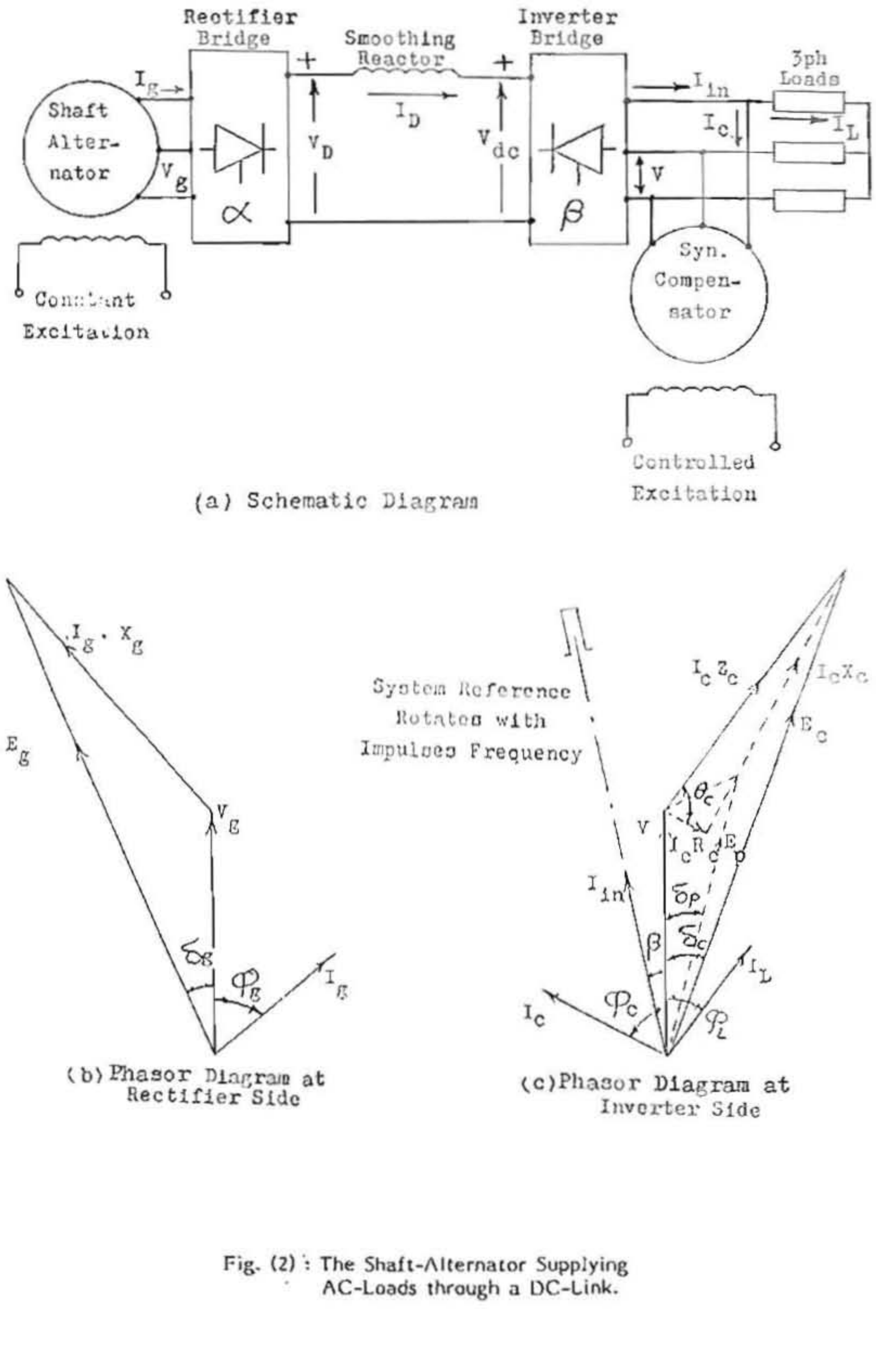
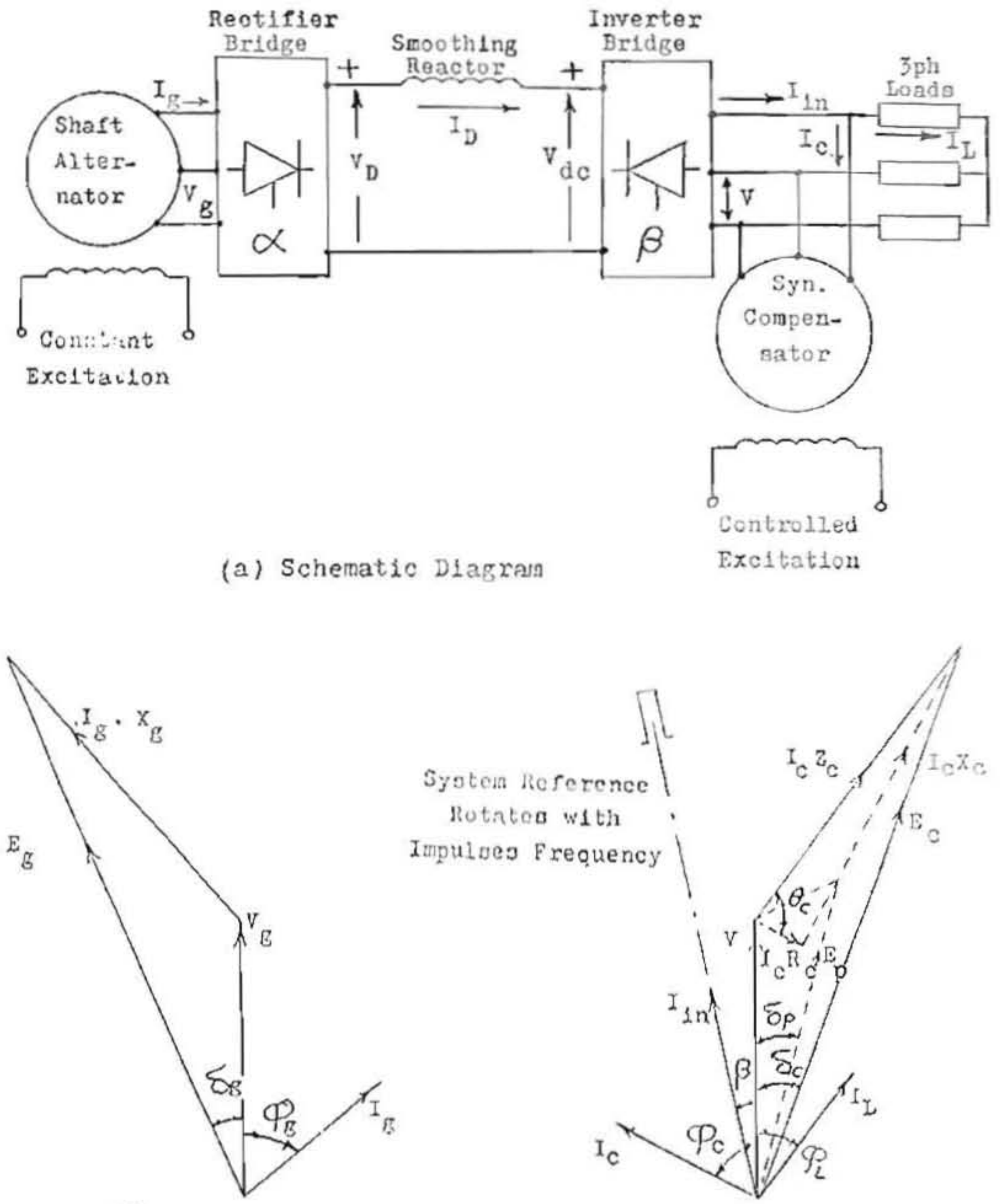


Fig. (2) : The Shaft-Alternator Supplying AC-Loads through a DC-Link.



(a) Schematic Diagram

(b) Phasor Diagram at Rectifier Side

(c) Phasor Diagram at Inverter Side

Fig. (2) : The Shaft-Alternator Supplying AC-Loads through a DC-Link.

periods. The chosen value for the firing angle at rated-speed determines the speed limits for operation under constant power. This value should be chosen carefully as to avoid the increase of higher harmonics and reactive power.

3.0 MATHEMATICAL MODEL :

As stated above, the proposed system can be sectionalized into two stages. The corresponding mathematical model is derived according to these stages. Throughout the development of model equations, the following assumptions are made [2,3,4] :

i . Magnetic saturation is neglected.
ii. Thyristors are represented by ideal switchs.
iii. Ripples in the DC-link current are neglected, and only the first harmonic is considered in all AC circuits.
iv. The dynamic equations are derived taking into account the time varying effective value.

The performance equations are derived according to the phasor diagrams given in figure (2), and on the basic-relations of power electronics [6,7] .

3.1 Performance Equations of First Stage :

Equations of the torque angle and terminal voltage of the shaft-alternator are :

$$\delta_g = \tan^{-1} [I_g.X_g.\cos\varphi_g / (V_g + I_g.X_g.\sin\varphi_g)] \qquad \ldots(1)$$

$$V_g = [E_g^2 + (I_g.X_g)^2 - 2.E_g.I_g.X_g.\sin(\varphi_g + \delta_g)]^{1/2} \qquad \ldots(2)$$

On the basis of constant power delivery and variable speed conditions, and according to the above assumptions, it can be found that :

$$E_g = n_r \cdot E_{go} \quad , \quad X_g = n_r \cdot X_{go} \qquad \ldots(3)$$

$$\cos(\varphi_g + \delta_g) = \cos(\varphi_{go} + \delta_{go}) / n_r \qquad \ldots(4)$$

Where E_{go} , X_{go} , φ_{go} and δ_{go} are determined at rated speed. With their help the corresponding values at any relative speed n_r can be obtained .

With help of the voltage behind the smoothing-reactor V_D, an expression of the shaft-alternator terminal voltage, V_g, can be given as :

$$V_g = V_D / [(3\sqrt{6}/\pi). \cos(\alpha_{re} + \gamma_{re} / 2). \cos(\gamma_{re} / 2)] \qquad \ldots(5)$$

According to the principle of constant power operation, as stated above, the voltage drop due to commutation will be the same for any delay-angle. It follows that the following relation :

$$\sin(\alpha_{re} + \gamma_{re} / 2) . \sin(\gamma_{re} / 2) = \sin^2(\gamma_o / 2) \qquad \ldots(6)$$

From equations (5) and (6) , the relations of the controlled delay-angle α_{re} and the corresponding commutation-angle γ_{re} can be found .

$$\alpha_{re} = \cos^{-1} [\sin^2(\gamma_o / 2) + V_D / (3\sqrt{6} . V_g / \pi)] \qquad \ldots(7)$$

$$\gamma_{re} = \cos^{-1} [\cos\alpha_{re} - 2 . \sin^2(\gamma_o / 2)] - \alpha_{re} \qquad \ldots(8)$$

3.2 Performance Equations of Second Stage :

As mentioned before, the compensator is provided with controlled excitation in order to get constant voltage V on the AC-side of the inverter. In accordance to the frequency on the same side, it is held constant due to the independent triggering frequency of the inverter. This frequency is normally taken equal to the load frequency.
Accordingly, and as a result of constant advance-angle β; either of V or I_{in} can be taken as reference in the corresponding phasor diagram, Fig (2-c) . Actually, I_{in} was taken as reference while deriving the model-equations which correspond to this stage. To get these equations, the following individual balance or equalibrium-equations are of great interest :

3.2.1. The balance equations of currents :

$$I_L \cdot \cos\varphi_L = I_{in} \cdot \cos\beta - I_c \cdot \cos\varphi_c \qquad \ldots (9)$$

$$I_c \cdot \sin\varphi_c = I_{in} \cdot \sin\beta - I_L \cdot \sin\varphi_L \qquad \ldots (10)$$

It is considered here that the sign of load angle, φ_L, is negative for lagging power-factor.

3.2.2. The equilibrium equations of voltages :

$$E_c \cdot \sin\delta_c = I_c \cdot Z_c \cdot \sin(\theta_c + \varphi_c) \qquad \ldots (11)$$

$$E_c \cdot \cos\delta_c = V - I_c \cdot Z_c \cdot \cos(\theta_c + \varphi_c) \qquad \ldots (12)$$

3.2.3. The balance equation of compensator torques :

$$T_j = \sum T = T_c + T_{as} - T_d \qquad \ldots (13)$$

in this relation :

$$T_j = J\Omega_o \cdot d(\Omega_r / \Omega_o) / dt$$

$$T_c = [V.E_c \cdot \sin(\delta_c + \alpha_z) / Z_c - (E_c / Z_c)^2 \cdot R_c] / \Omega_o$$

$$T_{as} = [E_p / (R_k \cdot \Omega_o)] \cdot (1 - \Omega_r / \Omega_o) \qquad \ldots (14)$$

$$T_d = T_{do} \cdot \Omega_r / \Omega_o$$

where,

α_z := synchronous impedance angle - $\tan^{-1}(R_c / X_c)$

T_{do} := breaking torque at synchronous speed, N-m .

3.2.4. The balance equation of compensator rotor-position :

$$\beta + \delta_c = p \cdot \int (\Omega_o - \Omega_r) \cdot dt \qquad \ldots (15)$$

With help of the above equations (9-15), the second stage mathematical model-equations can be formulated in their final form :

$$d(\Omega_r / \Omega_o) / dt = (T_c + T_{as} - T_d) / J\,\Omega_o \quad ; \qquad \ldots (16)$$

$$d(\beta + \delta_c) / dt = P\,\Omega_o \,.\, [1 - (\Omega_r / \Omega_o)] \quad ; \text{ and} \qquad \ldots (17)$$

$$I_{in} = V \,.\, [B / Z_L + (D / Z_L + 1) \,.\, \tan \delta_c] / (A + C.\ \tan \delta_c) \qquad \ldots (18)$$

where ,

$$\left.\begin{aligned} A &= R_c \,.\, \sin \beta - X_c \,.\, \cos \beta \\ B &= R_c \,.\, \sin \varphi_L + X_c \,.\, \cos \varphi_L \\ C &= R_c \,.\, \cos \beta - X_c \,.\, \sin \beta \\ D &= R_c \,.\, \cos \varphi_L - X_c \,.\, \sin \varphi_L \end{aligned}\right\} \qquad \ldots (19)$$

3.3. **Mathematical Model for The Whole System :**

The two individual mathematical models of both stages can be related to each other through the DC-link voltage-equation :

$$V_D = V_{dc} + I_D \,.\, R_D + L_D \,.\, dI_D / dt \qquad \ldots (20)$$

where,

$$\left.\begin{aligned} V_{dc} &= (3.\sqrt{6} / \pi).\ V \,.\, \cos(\alpha_{in} + \gamma_{in} / 2) \,.\, \cos(\gamma_{in} / 2) \\ I_D &= I_{in} / [\,(\sqrt{6} / \pi).\ \cos(\gamma_{in} / 2)\,] \\ \gamma_{in} &= \sin^{-1} [\,\sqrt{1-4K^2} \,.\, \cos\alpha_{in} - 2.K.\ \sin\alpha_{in}] \\ K &= (\cos \alpha_{in}) / 2 - \sin^2(\gamma_o / 2) \end{aligned}\right\} \qquad \ldots (21)$$

Finally, the full mathematical model representing the suggested system can be processed according to the following sequence to get the system-state at each time interval :

1- Determination of the relative speed of the compensator Ω_o / Ω_r , and the corresponding position angle $\beta + \delta_c$ by solving the two differential equations (16) and (17) using a numerical method, then δ_c can be calculated where β is assumed constant .

2- Determination of the inverter current I_{in} from equation (18), then the DC-link current I_D and the voltage behind the smoothing reactor V_D from equations (21) and (20) ,respectively, can be found .

3- Determination of compensator power-factor angle φ_c and current I_c from the equations (9) and (10) .

4- Determination the induced voltages of compensator, E_c and E_p , from following equations:

$$E_c = (V + I_c \,.\, Z_c \,.\, \cos \xi_c) / \cos \delta_c$$

$$E_p = (V + I_c \,.\, Z_p \,.\, \cos \xi_p) / \cos \delta_p$$

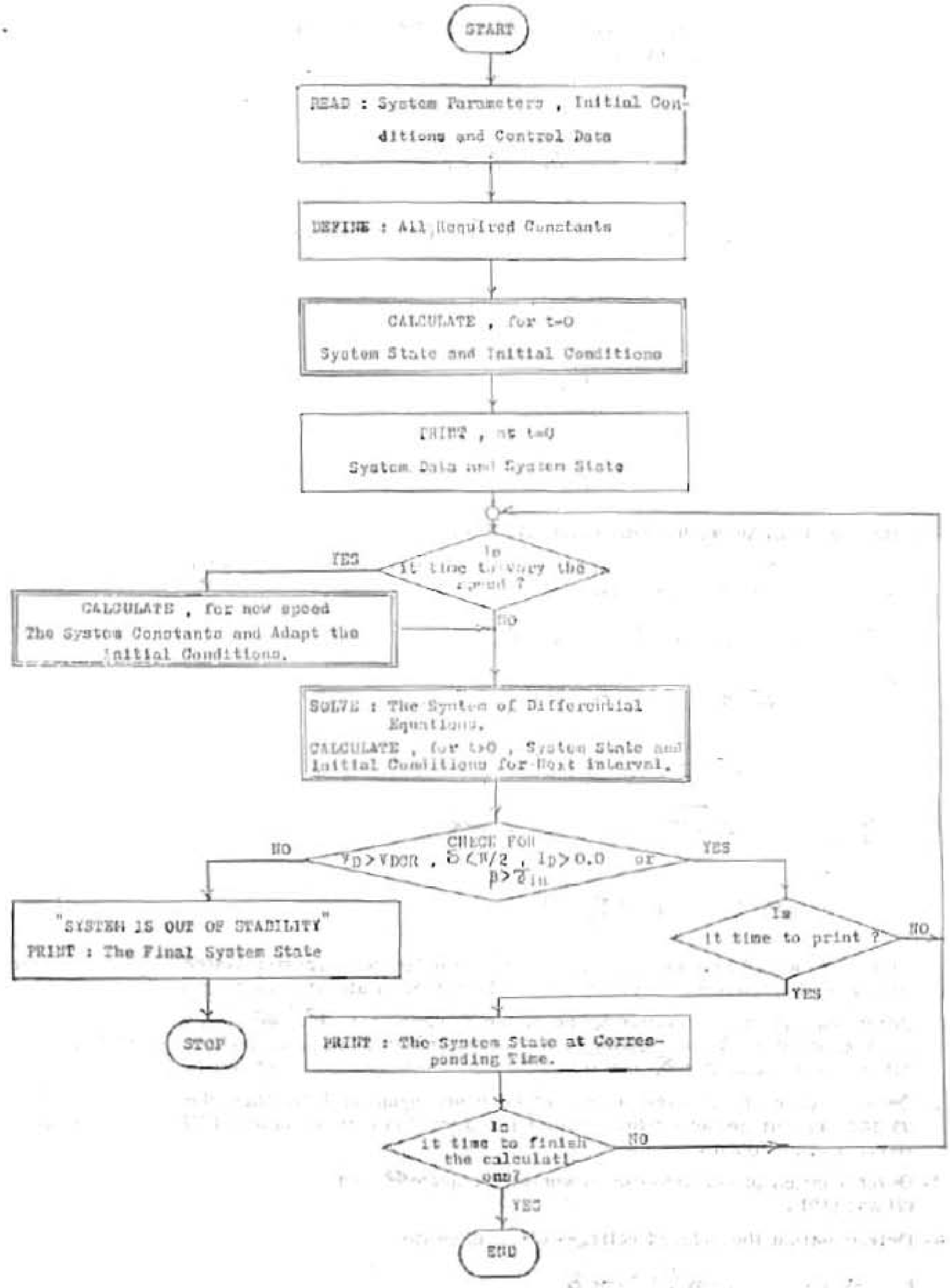


Fig. (3) : Flow-Chart of the Coded Program .

where,

$\xi_c = \varphi_c + \theta_c - \pi$; and

$\xi_p = \varphi_c + \theta_p - \pi$

5- Determination for rectifier α_{re} and γ_{re} from Eqs. (7) and (8) .

6- Determination of shaft-alternator parameters as follows :

power-factor angle $\varphi_g = \alpha_{re} + (\gamma_{re} / 2)$;

armature current $I_g = (\sqrt{6} / \pi) . I_D . \cos (\gamma_{re} / 2$;

power output $P_g = 3 . V . I_g . \cos \varphi_g$; and

torque angle δ_g from equation (1) .

If it is time of speed variation both of E_g and X_g must be recalculaed according to the new relative speed .

4. COMPUTER PROGRAM :

The mathematical model described in the previous section has been coded in a FORTRN program according to the flow-chart given in figure (3) . The mathematical model contains two types of equations ; algebraic equations and ordinary differential equations.

The ordinary differential equations are solved, using time varying effective value, by using fourth order Runge Kutta method. The time interval of the calculations is taken 0.01 seconds .

4.1. Program Ternination :

Program termination will be recorded for the following cases :

(a) If voltage behind the smoothing-reactor, V_D, becomes less than the critical value. V_{DCR} : this occurs, when the speed of the shaft-alternator is less than the critical value which reults in zero delay angle .

(b) If the DC-link current falls to zero for a long duration ; under the condition that V_D is greater than V_{DCR} .

(c) If the value of inverter commutation angle γ_{in} , exceeds the value of the chosen advance angle β .

(d) If the torque angle of the synchronous compensator δ_c , exceeds $\pi / 2$: this occure during the oscillation period and forces the machine , as well as the system, to go out of stability .

4.2. Data of System Example :

The data of a system example at rated speed is as follows :

- Shaft Alternator : V_g / line = 4800 volt , X_g = 45 ohm , R_g = 0.0
- Rectifier Bridg : α_{re} = 22.5° elec. , γ_o = 25° elec .
- DC-Link : L_D = 224 mH , R_D = 0.55 ohm
- Synchronous Compensator : V/line = 4800 volt , R_c = 0.256 ohm
  X_a = 30.15 ohm , X_p = 1.25 ohm ,
  R_k = 0.25 ohm , Friction and windage
  losses = 5 % of rated KVA .

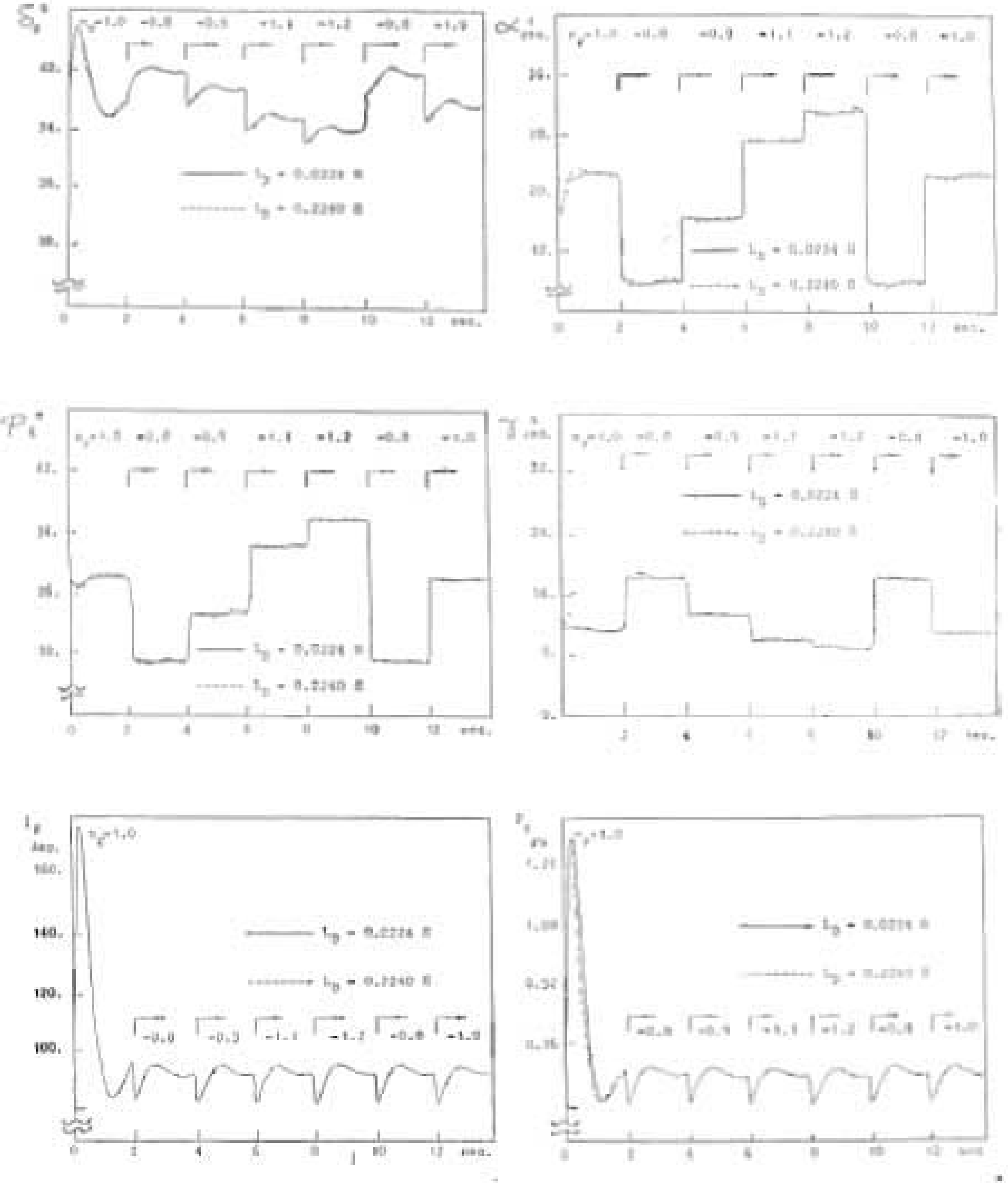


Fig. (4) : Effects of L_D on the Parameters of the Shaft-Alternator and the Rectifier Bridge Where ; R_K = 0.25 ohm and Ω_r / Ω_o = 1.0 .

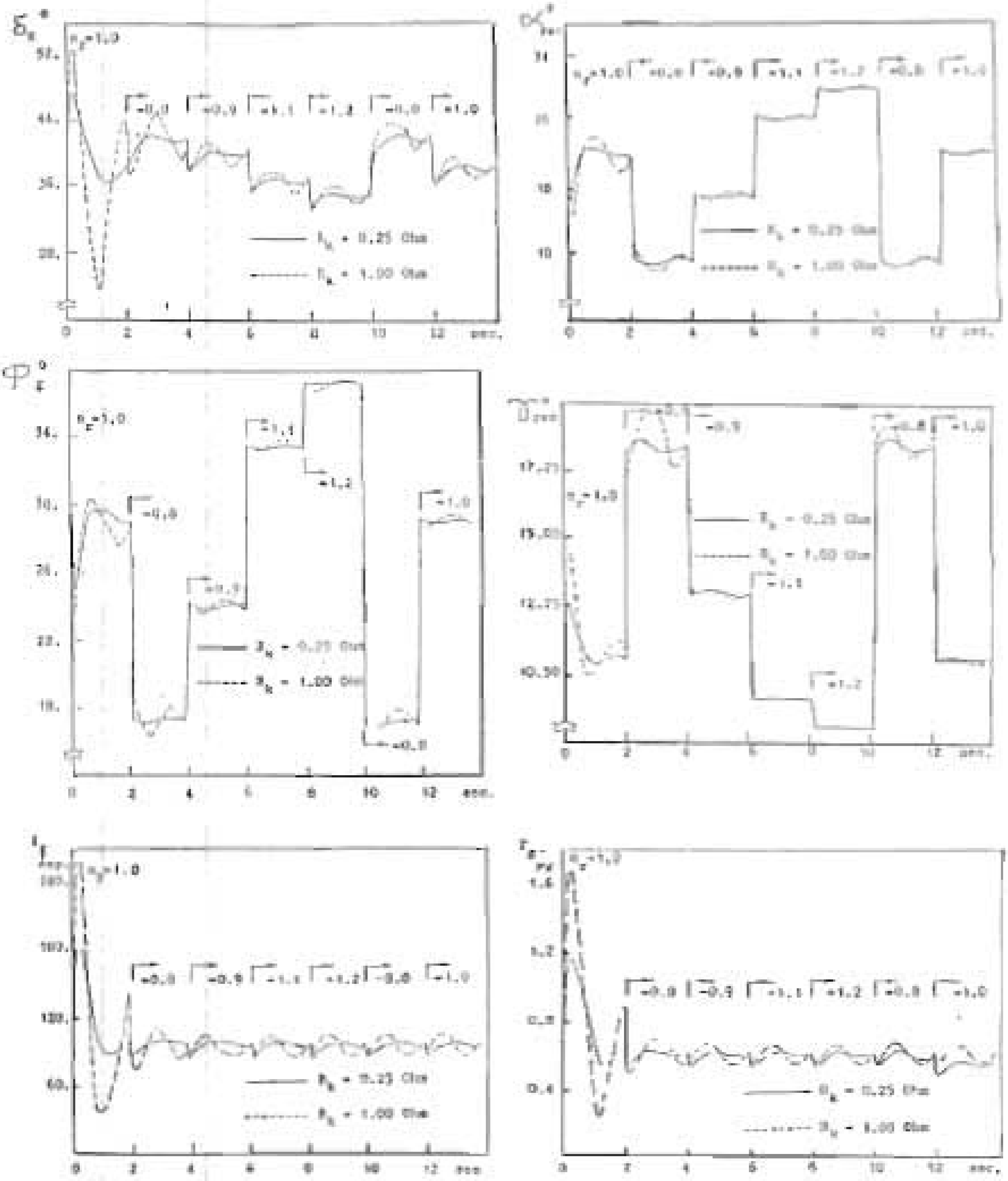


Fig. (5) : Effects of R_k on the Parameters of the Shaft-Alternator and the Rectified Bridge Where ; L_D = 224 mH and $\Omega_r / \Omega_o = 1.0$.

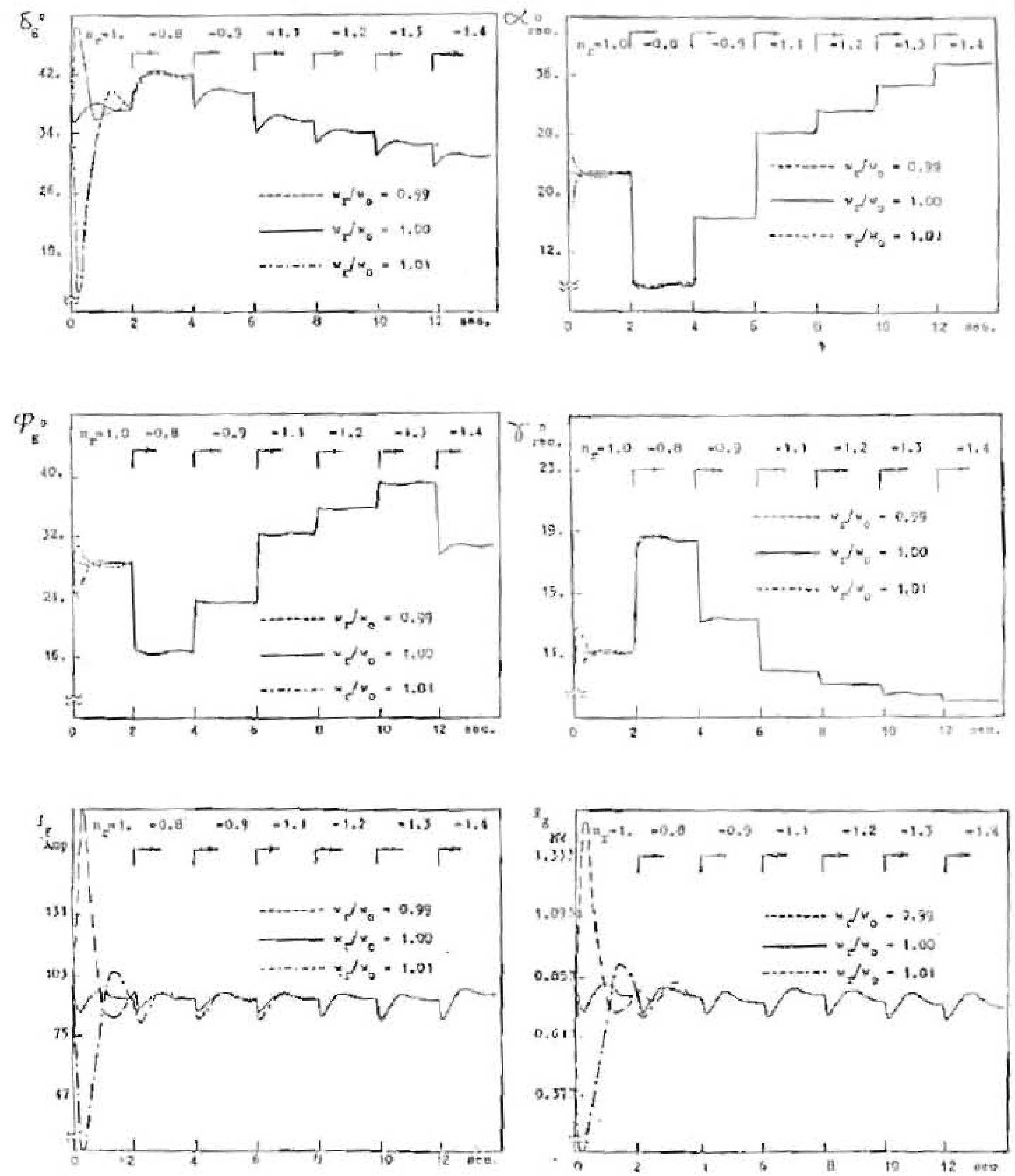


Fig. (6) : Effects of Ω_r / Ω_o on the Parameters of the Shaft-Alternator and the Rectified Bridge , where ; R_k = 0.25 ohm and L_D = 224 mH .

- Load Receiver : 1-phase power = 740 KVA , power factor = 0.86 lag.
  line voltage = 4800 volt , frequency = 50 Hz
- Inverter Bridge : advance angle = 30° elec. , γ_0 = 25° elec.
  frequency of impulses = 50 Hz .

5. COMPUTER RESULTS AND DISCUSSIONS ;

The scope of computer results are concentrated on the different parameters of the shaft-alternator when connected to a controlled rectifier bridge. These parameters are torque angle δ_g , power-factor angle φ_g , output power P_g and armature-current I_g. In addition the rectifier delay angle α_{re} and the corresponding commutation angle γ_{re} are also investigated. These parameters are affected by L_D , R_K and Ω_r / Ω_0 , which are chosen as :

- two values of smoothing-reactor inductance of : 224 mH and 22.4 mH
- two values of compensator cage resistance of : 0.25 ohm and 1 ohm
- three values of compensator relative speed at synchronization process of : 1, 0.99 and 1.01 .

The value of shaft-alternator parameters are investigated during two operating periods : synchronization and speed variation. The computer program is ordered to change the speed of the shaft-alternator instantaneously every two seconds and the results are shown by figures (4) , (5) and (6) .

5.1. Discussion of Results :

Figure (4) shows the effect of two-values of smoothing-reactor on the parameters of the shaft-alternator and rectifier-bridge. Both values give almost the same effects. High magnitudes of P_g , I_g and δ_g occur during synchronization. While during speed variation, the change of parameters occurs steadily .

Figure (5) shows the effect of two-values of compensator damping resistance on the mentioned parameters. Higher magnitudes of all of them occur either during the synchronization period or at speed variation for large value of R_K diminishes the damping effect.

Figure (6) shows the effect of three-values of the rotor-relative speed of compensator, at the instant of synchronization, on the above parameters .
The relative speed of compensator rotor, only affects the stability of the system during the synchronization period. The deviation of synchronization slip , $(1 - \Omega_r / \Omega_0)$, from zero, results in more system oscillations. The time duration and amplitude of these oscillations depend on the value of deviation. The starting direction of any oscillation corresponding to a given parameter depends on the sign of the synchronization slip .

6. CONCLUSIONS ;

The quasi steady-state behaviour of a shaft-driven alternator supplying isolated AC loads through a DC link has been numerically investigated by applying the presented mathematical model , coded in form of a FORTRAN program , to a system example. According to the computer results , it is recomended to synchronise the inverter at zero compensator rotor slip . This can be happen if the compensator prim-mover , which is required just before synchronization , is provided with sensetive speed control . In addition a proper value of L_D , as well as smaller value of R_K , must be chosen in order to get stable synchronization process and to avoid a quasi steady-state operation.

Consequent conclusions, which can be deduced from the steady results, are given in Fig. (7). The figure shows the steady values of the angles of the shaft-alternator and the controlled rectifier againts the relative speed. It is shown as the speed increases, both of φ_g and α_{re} will be also increasing while both of δ_g and γ_{re} will be decreasing. The extreme limits of φ_g and α_{re} , which correspond to minimum- and maximum-speed, are shown to be reasonable.

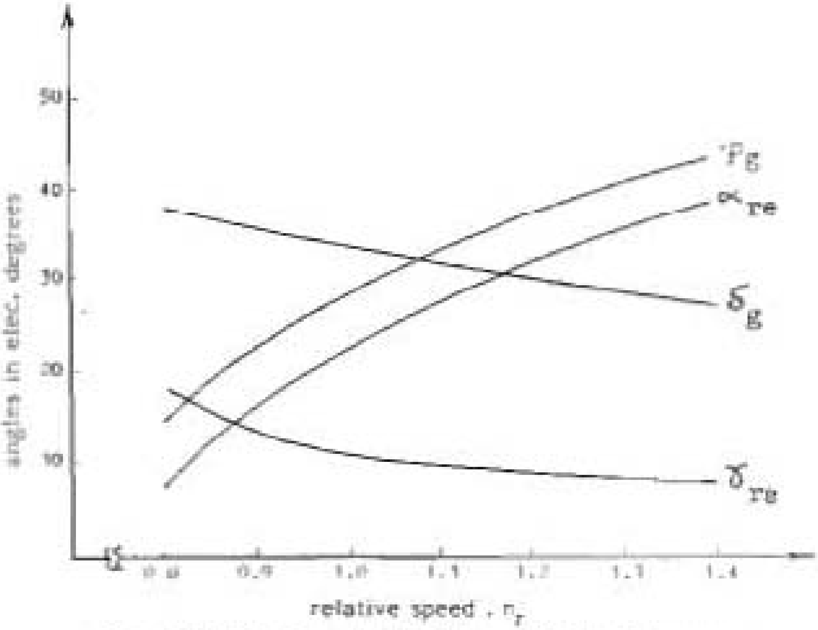


Fig. (7) : Variation of the Angles of Shaft-Alternator and Controlled-Rectifier against Relative speed.

In accordance with the power-factor of the alternator, it will vary between 0.73 at maximum speed and 0.966 at minimum speed. It reaches a rated value of 0.88 at rated-speed. Also, the steady values of the power of both alternator and compensator againts the relative speed, show that thier rated capacity can be taken as 725 KVA and 780 KVA, respectively.

7. REFERENCES :

1. EL-SERAFI A.M., SHEHATA S.A., "Effect of the Parameters of Synchronous Machines on their Losses under Thyristor Load Operation", Proceedings of International Conference on Electrical Machines "Part II" , Paper No. E 5/2 , Brussels-Belguim, pp. E 5/2-1 to E 5/2-14 , September 1978 .
2. EL-SERAFI A.M., SHEHATA S.A., "Effect of the Parameters of Synchronous Machines on their Losses under Thyristor Load Operation", Proceedings of International Conference on Electrical Machines "Part II" , Paper No. E 5/2 , Brussels-Belguim, pp. E 5/2-1 to E 5/2-14 , September 1978 .
3. ABOU-TABL H.A., EL-SHAMOTY M.M., EL-DRIENY S.A., "Mathematical Model of Synchronous Compensator Operating in Conjunction with a Rigidiy Impulsed Inverter", Bulletin of the Faculty of Engineering, EL-Massoura University, Vol. 10, No. 1, pp. E 113 - E 125, June 1985 .
4. ABDEL-RAZEK A.A., "Contribrtion a L'etude des Reqimes Transitoires Desequilibres.des Machines Synchrones dans Deux Cas : Courts-Circuits Bresques et Alimentation par Convertisseur Statique", Doctor Thesis, University of Grenoble. 1976.
5. EL-SHAMOTY M.M., "Design of Stabilizers of Voltage and Frequency in Networks Energized with Variable Speed Alternator", Bulletin of the Faculty of Engineering, EL-Mansoura University, Vol. 11, No. 1, pp. 11-20 , June 1986.
6. SCHEAFER J., "RectifierCircuits Theory and Design", John willey and Sons. Inc., New York. 1965.
7. DEWAN S.B., SLEMON G.R., STRAUGHEN A., "Power Semiconductor Drives" , John Wiley and Sons, Inc., New York, 1984.
8. EL-SHAMOTY M.M., "Synchronization of a Synchronous Machine to a Static Inverter with Rigid Frequency of Steering Impulses", International Conference on Elec. M/C, Lausanne-Switzerland, 18-21 Sept. 1984.