Regulation of Synchronous Generators by Means of Hydrostatic Transmissions

José Cidrás, *Member, IEEE*, and Camilo Carrillo

***Abstract*—In many applications within the engineering world, an isolated generator is needed (e.g. in ships). Diesel units (diesel engine and synchronous generator) are the most common solution. However, the diesel engine can be eliminated if the energy from another source (e.g. the prime mover in a ship) is used to move the generator. This is the case for the Shaft Coupled Generator, where the coupling between the mover and the generator is made via a hydrostatic transmission. So that the mover can have different speeds and the generator is able to keep a constant frequency. The main problem of this system is the design of a speed governor that make possible the desired behavior.**

In this paper a simulation model is presented in order to analyze the behavior of this kind of systems and to help in the speed governor design. The model is achieved with an parameter identification process also depicted in the paper. A comparison between simulation results and measurements is made to shown the model validity.

***Index Terms*— Modeling, Identification, Hydrostatic Transmission.**

I. Introduction

IN MANY engineering applications, a transference of energy between two systems that have different rotation speeds is needed. The Shaft Coupled Generator (SCG) is an example. This system is used as an alternative to diesel power stations e.g. in ships. So, by means of a Hydrostatic Transmission (HT), the necessary torque to move a Generator is obtained from the main Prime Mover (e.g. in a ship, it is the propulsion engine). Furthermore, the SCG Speed Governor must keep the speed in the Generator Shaft at its reference value.

The HT can be formed by a Hydrostatic Pump and a Hydrostatic Motor connected by pressure lines forming a closed circuit. In the lines, high pressures could be achieved when the hydrostatic fluid is pumped. The pump has Variable Displacement Volume, so the flown volume per revolution can be changed. As a result, the ratio between the rotation speeds of the pump and the motor can be modified. The electronic variation of the Displacement Volume is achieved by means of an Electrohydraulic Stroke Control installed on the pump.

This paper is focused on modeling and simulation of a SCG. The simulation results are compared with real measurements from a SCG installed in the laboratory. Therefore, a complete model is presented and the identification and simulation processes are depicted.

Manuscript received January 22, 1999; revised August 10, 1999. This paper was supported by the project “Regulación de Generadores Eléctricos en Buques” (TAP92-0389) of CICYT.

The authors are with the Departamento de Enxeñeria Eléctrica ETSIIM - Universidade de Vigo, SPAIN (e-mail: jcidras@uvigo.es).

Publisher Item Identifier S 0885-8950(00)03817-7.

II. Description of the SCG

The main SCG component is the HT. Commonly, this element is used to connect mechanical systems, called prime mover and mechanical load, which may have different and variable rotational speeds. So the energy transference between them is possible.

The primer mover in SCG's installed in ships is the Propulsion Engine which is connected to the pump. The mechanical load is a Synchronous Generator which is coupled to the shaft of Hydrostatic Motor. In this way, the propulsion engine may have a wide range of rotational speeds and the Generator can keep his rotational speed at the reference one. This behavior is achieved with a Speed Governor that acts on the Electrohydraulic Stroke Control, when the adequate variation on the Displacement Volume (α_{ref}) in the pump is chosen. A laboratory SCG (Fig. 1) has been used in order to obtain the measurements that allows the identification and validations processes. This equipment has the following components:

- *Prime Mover.* This element would be the propulsion engine on a SCG installed in a ship. However in a laboratory, it is more appropriate to use a DC Machine where an AC/DC converter is used to vary the speed.
- *Synchronous Generator.* It is the part of the system that produces the electric power.
- *Electric Load.* A set of resistances connected to the generator is used for this purpose. The amount of connected resistances is varied by means of electronic relays.
- *Hydrostatic Transmission (HT).* This is the main SCG component. The HT [1] [2] is the power transmission element between the Prime Mover and the generator. The Variable Displacement Pump is coupled to the Prime Mover. The motor with Fixed Displacement Volume is linked to the generator. Both elements, pump and motor, are connected via Pressure Lines.
- *Electrohydraulic Stroke Control* [2]. This is a displacement control installed on pump and it allows the electronic variation of the Displacement Volume.

Once the SCG elements are depicted, the equations for each element and the parameters involved in each equation are presented. The block diagram of the complete system is presented in Fig. 2, where the relationship between parameters and variables can be seen. In Table II a relation of the main parameters is shown.

III. Shaft Coupled Generator Equations

As a previous step that will allow the analysis of the SCG behavior, it is necessary to get its set of equations. The equations

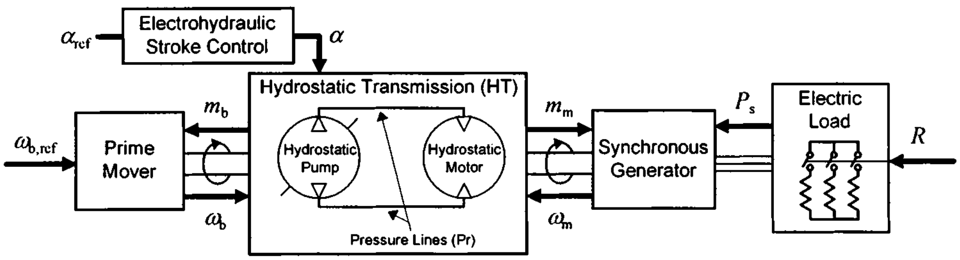

Fig. 1. Components of a Shaft Coupled Generator (SCG).

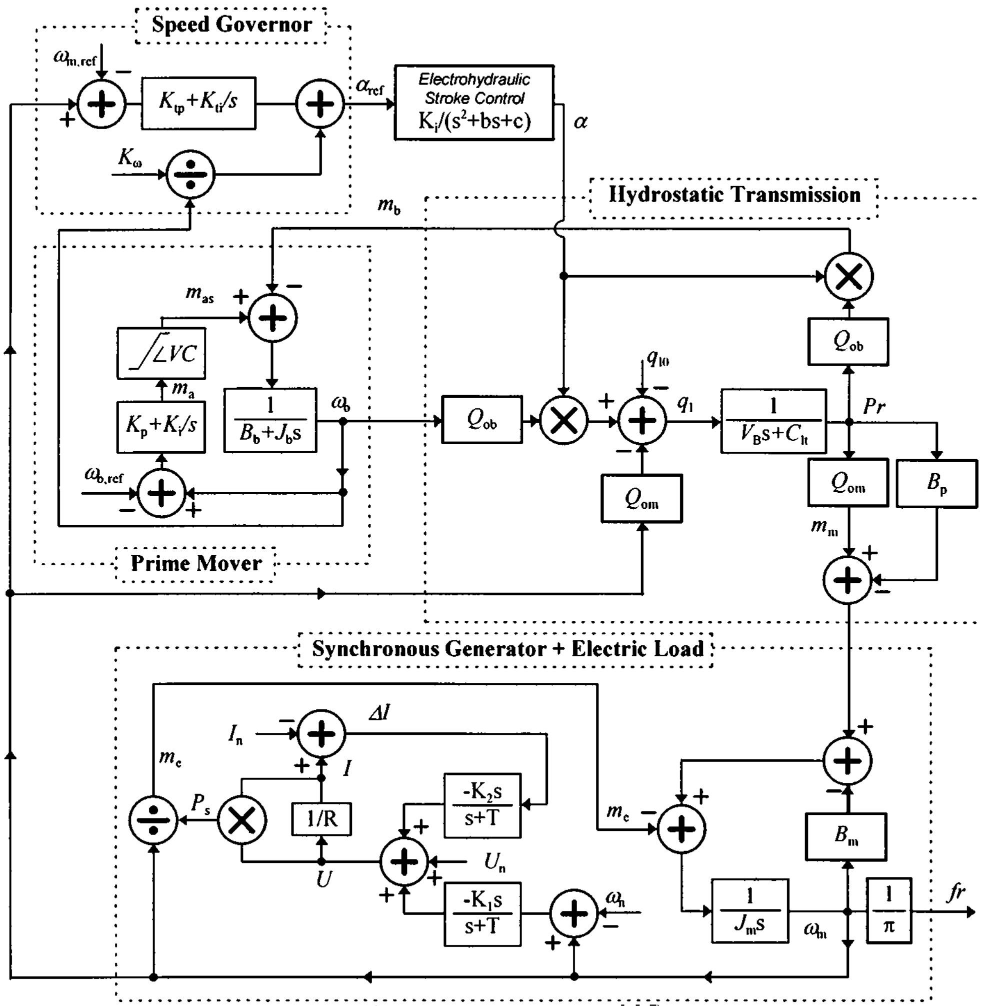

Fig. 2. Block Diagram of the SCG.

for each element will be presented, nevertheless in the Fig. 2 the complete system equations are shown.

As can be seen all the equations in this figure and in the paper are presented in the Laplace Domain [3]. All the variables and parameters that appear in this block diagram are depicted in Table I and Table II (see APPENDIX).

The Reference Value for the Prime Mover Speed Governor $\omega_{b,ref}$, the reference value for the pump displacement α_{ref} setting and the electric load (R) are considered as inputs in the presented model. If the governor is considered, the reference for the generator speed ω_{bref}, instead of α_{ref}, is taken as input. Therefore, the outputs are all the other variables, paying special attention to the pressure (Pr), the speed (ω_b) in the pump shaft, the speed (ω_m) in the motor shaft and Electric Power (P_s) delivered by the generator.

In the following paragraphs the equations for each element will be given.

A. Equations of Prime Mover

In the SCG installed in the laboratory a DC Motor with a AC/DC Converter as Speed Controller has been employed as

TABLE I
MAIN VARIABLES

Variable	Units	Description
α_{ref}	0…1	Reference value for the Hydrostatic Pump displacement setting (input to the Electrohydraulic Stroke Control)
α	0…1	Effective Hydrostatic Pump displacement setting (output of the Electrohydraulic Stroke Control)
fr_{ref}	Hz	Reference frequency for the Speed Governor of the SCG
$\omega_{b,ref}$	sec^{-1}	Reference Value for the Prime Mover Speed Governor
ω_b	sec^{-1}	Speed in the Hydrostatic Pump shaft
ω_m	sec^{-1}	Speed in the Hydrostatic Motor shaft
q_l	m^3/sec	Leakage Flow
m_e	Nw·m	Resistant Torque from the mechanical load
m_m	Nw·m	Ideal Delivered Torque by HT
m_a	Nw·m	Reference value for the Delivered Torque to the Prime Mover
m_{as}	Nw·m	Smoothed Delivered Torque to the Prime Mover
m_b	Nw·m	Delivered Torque to the Hydrost. Pump
P_S	W	Electric Power delivered by the Synchronous Generator.
U	V	Voltage in the Synchronous Generator
I	A	Output Current in the Synchronous Generator
R	Ω	Impedance of the electric load
Pr	Pa	Pressure in the main HT lines

TABLE II
PARAMETERS

Name	Value	Units	Description
Q_{ob}	$1{,}198\cdot 10^{-5}$	m^3/rad	Max. displacement volume of the Hydrostatic Pump
Q_{om}	$8{,}642\cdot 10^{-6}$	m^3/rad	Max. displacement volume of the Hydrostatic Motor
J_b	0,111	$kg\cdot m^2$	Inertia Moment of the coupled H. Pump + Prime Mover
J_m	0,169	$kg\cdot m^2$	Inertia Moment of the coupled H .Motor + S. Generator
C_{lt}	$4{,}87\cdot 10^{-12}$	$m^3/sec/Pa$	Ratio between the leakage flow and the pressure in main lines between pump and motor.
V_B	$7{,}41\cdot 10^{-13}$	m^3/Pa	Ratio between the leakage flow and pressure variations
B_b	6,924	Nw·m·sec	Ratio between the loss torque in the pump and shaft speed
B_p	$7{,}074\cdot 10^{-7}$	Nw·m/Pa	Dry friction coefficient
B_m	0,145	Nw·m·sec	Ratio between the Loss Torque in the motor and shaft speed
q_{l0}	$4{,}703\cdot 10^{-4}$	m^3/sec	Constant Leakage Flow
b c	30,97 208,84	-	Transfer function of the Electrohydraulic Stroke Control
VC	2267,63	Nw·m/sec	Rate limit for Torque applied to the Prime Mover
K_p K_i	-0 -35,643	-	Speed Governor Parameters for the DC Motor (Prime Mover)
K_1 K_2 T	2,529 0,596 15,300		Synchronous Generator parameters
K_{pt} K_{it} K_ω	0,001 0,002 135,93		Speed Governor Parameters of the SCG

Prime Mover. The related blocks (see Fig. 2) are those that represent the dynamic equations (J_b and B_b), PI [3] speed governor (K_i and K_p) and a change rate limit (VC) for the applied torque.

The limit VC prevents the presence of sharp torque variations by applying a limit for the variation rate, i.e., this limit guaranties that:

$$\begin{aligned} &if\ \ sm_a \le VC\ \ then\ \ m_{ax} = m_a \\ &if\ \ sm_a > VC\ \ then\ \ m_{ax} = VC/s \end{aligned} \tag{1}$$

The remaining equations for the Prime Mover are:

$$\begin{aligned} m_{as} &= m_b + (B_b + J_b s)\omega_b && Dynamic\ Equation \\ m_a &= (K_p + K_i/s)(\omega_b - \omega_{b,ref}) && Speed\ Governor \end{aligned} \tag{2}$$

The parameter J_b represents the inertia moment for the linked set formed by Prime Mover and pump, so it could be included in the set of equations for the HT. Nevertheless, this parameter has been considered in this element in order to achieve a more comprehensive treatment. For the same reason, the parameter B_b has been included here.

B. Equations of Synchronous Generator

The following element to be modeled is the generator. Two kinds of behavior can be considered for this element, these are the electric behavior and the mechanic one.

The electric behavior [4] [5] is depicted with the following equations:

$$\begin{aligned} \Delta U &= \Delta E - B\Delta\omega_m - C\Delta I && Generation \\ \Delta E &= K_e I_{fn}\Delta\omega_m + K_e\omega_n\Delta I_f && Excitation \\ \Delta I_f &= K_{g,p}(1 + K_{g,I}/s)\Delta U && Voltage\ Regulator \end{aligned} \tag{3}$$

where:

ΔU is the difference between the actual voltage U and the nominal voltage U_n (e.g. 220V) in the generator.

ΔI is the difference between the actual current delivered by the generator and its nominal value.

ΔE is the difference between the internal voltage E and its nominal value E_n.

ΔI_f the difference between the field current I_f with respect to its nominal value I_{fn}.

$\Delta\omega_m$ if the difference between the shaft speed ω_m in the generator and its nominal (i.e. 1500 rpm) value ω_n.

$K_{g,p}$ and $K_{g,I}$ are the proportional and integral constants for voltage regulator.

This set of equations can be written in a more compact form:

$$\Delta U = -\frac{K_1 s}{s+T}\Delta\omega_m - \frac{K_2 s}{s+T}\Delta I \tag{4}$$

The next equations are used to obtain the delivered electric power (P_s):

$$P_s = \frac{U^2}{R} = \frac{(U_n + \Delta U)^2}{R} \tag{5}$$

where R represents the value in Ohms for the electric load. In the laboratory this value can be changed by means of electronic relays. As will be seen (see paragraph IV), the variation of the electronic load causes the most important transient behavior.

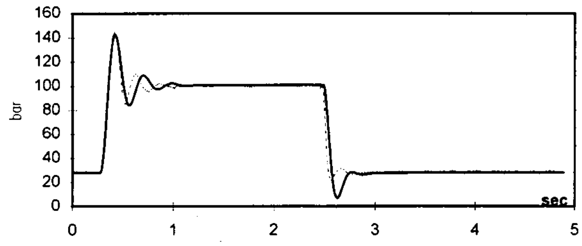

Fig. 3. Simulated and measured (dotted) Pressure.

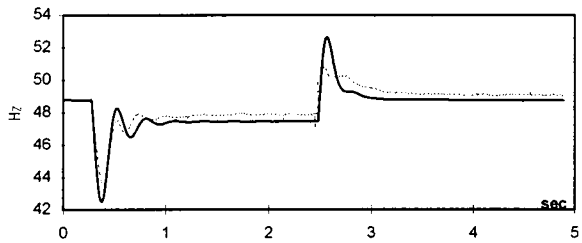

Fig. 4. Simulated and measured (dotted) output frequency.

The mechanic behavior is represented by the following equation:

$$m_m - m_e = (B_m + J_m s)w_m + B_p \Pr \tag{6}$$

where m_e is the electric torque supplied to the generator defined as: $m_e = Ps/\omega_m$

C. Equations of Hydrostatic Transmission

In fact, almost all equations for the elements of a SCG have been depicted, except those for the HT [1] [2] [6]. So:

$$\begin{aligned} m_b &= Q_{ob} a \Pr && H.\ Pump\ Torque \\ m_m &= Q_{om} \Pr && H.\ Motor\ Torque \\ \alpha\omega_b &= (Q_{om}\omega_m + q_l)/Q_{ob} && Flow\ Equations \\ q_l &= (C_{lt} + V_b s)\Pr + q_{l0} && Leakage\ Flow \end{aligned} \tag{7}$$

As can be seen, there is a direct relationship between torque and pressure. Nevertheless, the speed depends on pressure only through the leakage flow q_l. In this way, the steady state behavior, from the point of view of speeds, is very stable against pressure variations, and so against electric load variations.

The set of equations shown above can be presented as:

$$\begin{aligned} V_b s \Pr &= Q_{ob} a w_b - C_{lt} \Pr - q_{l0} - Q_{om} w_m \\ J_m s w_m &= Q'_{om} \Pr - B_m w_m - m_e \end{aligned} \tag{8}$$

Where $Q'_{om} = Q_{om} B_p$.

After a linearization process ω_b and m_e as inputs, the set of equations is presented in the transfer function form. For the motor speed ($\Delta\omega_m$) this results in:

$$\Delta\omega_m = \frac{Q_{ob}Q'_{om}/V_b J_m}{s^2 + Bs + C}\Delta(\alpha\omega_b) - \frac{(V_b s + C_{lt})/V_b J_m}{s^2 + Bs + C}\Delta m_e \tag{9}$$

where

$$B = \frac{C_{lt} J_m + V_b B_m}{V_b J_m} \quad C = \frac{Q'_{om} Q_{om} + B_m C_{lt}}{V_b J_m}$$

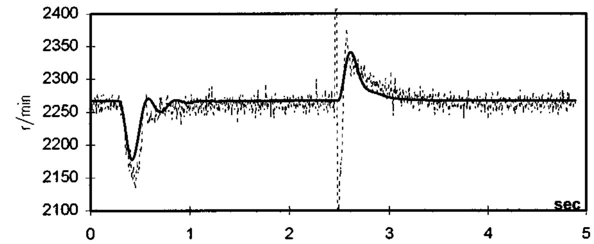

Fig. 5. Simulated and measured (dotted) pump Speed.

The pressure $\Delta \Pr$ (or $\Delta\omega_m$) can be divided into two terms: one called $\Pr_m$ related with the electric torque Δm_e and, the other one $\Pr_\omega$ related with the speed in the pump shaft ω_b. So:

$$\Delta \Pr = \Delta \Pr_m + \Delta \Pr_\omega \tag{10}$$

where:

$$\Delta \Pr_m = \frac{Q_{om}/V_b J_m}{s^2 + Bs + C}\Delta m_e \tag{11}$$

$$\Delta \Pr_\omega = \frac{B_m Q_{ob}/V_b s}{s^2 + Bs + C}\Delta(\alpha\omega_b) \tag{12}$$

As a first approximation the term $s\Delta(\alpha\omega_b)$ can be neglected, then $\Pr = \Pr_m$. In this way, a 2^{nd} order system is used to approximate the pressure ($\Pr$) response. So the transfer function [3] can be written as:

$$G(s) = \frac{\Delta \Pr}{\Delta m_e} = K_m \frac{C}{s^2 + Bs + C} = K_m \frac{\omega_d^2}{(s+\sigma)^2 + \omega_d^2} \tag{13}$$

where:

$$K_m = \frac{Q_{om}}{Q'_{om} Q_{om} + B_m C_{lt}}$$

The response of this transfer function is closely related to its poles ($r_{12} = \sigma \pm j\omega_d$). Where the damping factor (σ) is the real part, and the damping frequency (ω_d) is the absolute value of the imaginary part. Using typical expressions that can be found in the bibliography [3], the output $\Delta \Pr$ when the input Δm_e is a step $u(t)$ with amplitude M_e can be written as:

$$\Delta \Pr = \frac{Q_{om} M_e \left[1 - e^{-\sigma t}\left(\cos(\omega_d t) - \frac{\sigma}{\omega_d}\,\mathrm{sen}(\omega_d t)\right)\right]}{V_b J_m(\sigma^2 + \omega_d^2)} . u(t) \tag{14}$$

In order to reflect more closely the behavior of a real HT, the effect of the neglected term $s\Delta(\alpha\omega_b)$ could be taken into account.

D. Equations of Electrohydraulic Stroke Control

In the above paragraphs the variable Displacement Volume (α) for the pump appears. It is the output for the Electrohydraulic Stroke Control, and it is a mechanical variable. Meanwhile the Displacement Volume Reference (α_{ref}) is the electric

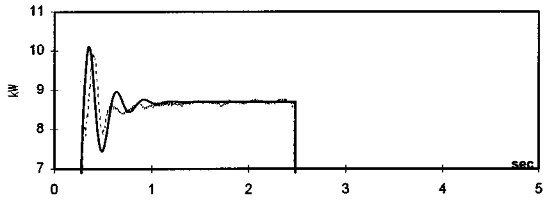

Fig. 6. Simulated and measured (dotted) Electric Power.

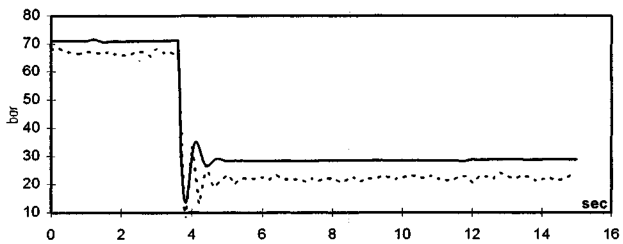

Fig. 7. Simulated and measured (dotted) Pressure.

variable used as input for this element. For this element, a behavior of a 2nd order system has been supposed [2] [7] whose transfer function is:

$$G(s) = \frac{\alpha}{\alpha_{ref}} = \frac{c}{s^2 + bs + c} \tag{15}$$

E. Equations of Speed Governor

In a SCG its main objective is to keep the reference speed in the pump or generator shaft despite the speed variations in the Prime Mover speed or changes in the electric load. So the frequency of the voltage generated by the generator is maintained at its typical value (e.g. 50 Hz). A Speed Governor which input is the reference value for the frequency (fr_{ref} or $\omega_{m,\,ref}$) is needed for this purpose. The governor output is the reference value for the Displacement Value (α_{ref}) which is the input for the Electrohydraulic Stroke Control. The proposed equations for this element are:

$$\alpha = \left(K_{pt} + \frac{K_{it}}{s}\right)(fr - fr_{ref}) + K_\omega \omega_b \tag{16}$$

where K_{pt} and K_{it} are the parameters of a PI [3] regulator. The error is the difference between the frequency ($fr = \omega_m/\pi$) of the generator and its reference value fr_{ref} (i.e. 50 Hz). The proportional term K_ω is included in order to improve the system behavior when speed variations for the Prime Mover (ω_b) are considered. The influence of this term has been slightly smoothed in order to avoid unstable situations.

IV. Complete SCG Simulation

A. Simulation Without Speed Governor

In order to validate the model (Fig. 2) with the identified parameters (see Appendix) some test are done. Then the real measurements and the simulation results are compared. In this paragraph, the results for a Type I test are presented as an example.

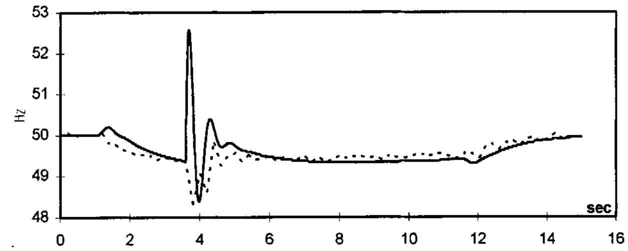

Fig. 8. Simulated and measured (dotted) Output Frequency.

The test conditions are:

☐	Prime Mover Reference	$\omega_{b,\,ref} = 2267$ r/min
☐	Reference Frequency	$fr_{ref} = 48,76$Hz
☐	Electric Load	0W to 8700 in $t = 0,2$sec
		8700W to 0W in $t = 2,5$sec

The Displacement Volume Reference remains constant during the test. In the simulation, its value is calculated in order to achieve the initial references indicated above.

The results can be observed in the following figures. As can be seen, there is good agreement between simulation results and measurements, despite the model simplicity.

B. Simulation with Speed Governor

Once the model is achieved and validated, the complete system behavior for the SCG with a Speed Governor is analyzed. The correct design of the governor is critical in these kind of systems. Because, the stability on frequency (or motor speed) and the ability to maintain it at the reference value has its major dependence on the governor design. Furthermore, an ideal SCG keeps the reference frequency in the generator, against sharp electric load variations and Prime Mover speed changes, by only achieving the adequate Displacement Volume (α) in the pump. Obviously this behavior cannot be achieved, however obtaining a similar behavior depends in the choice of the correct governor.

The simulation method is very useful in the Speed Governor design. It allows us to do lots of tests under the worst conditions, consequently damages or heavy stresses on the real systems are prevented. Furthermore, the simulation has a high flexibility in order to try several designs and parameters for the governor. The governor is achieved by means of a compromise between the steady state error and the transient behavior.

In the above paragraph an example of Speed Governor design, whose parameters has been achieved through several tests, is presented. This design has been implemented in a DSP (Analog Devices ADSP-2181) in order to do tests in a real system. The parameters of the implemented regulator can be seen in Table II. The measurements obtained have a low sampling frequency, however these can be used in order to compare simulations and measurements and to analyze the real behavior.

The error between measurements and simulation are greater than the system without governor. Mainly this is due to:

- The Electrohydraulic Stroke Control identification is very difficult, so its parameters has been partially obtained from the specification sheet. This could be the source of the observed inaccuracy.

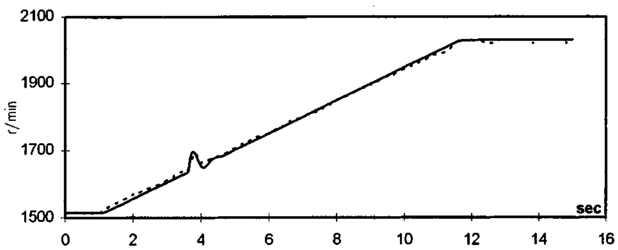

Fig. 9. Simulated and measured (dotted) Pump Speed.

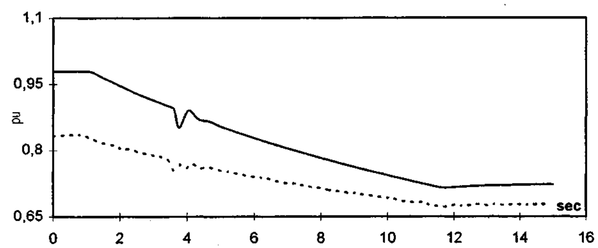

Fig. 10. Simulated and measured (dotted) Displacement Volume Reference.

- The test conditions are very far from the test conditions during the identification process.
- In the presented model several simplifications (some parameter dependencies have been neglected) are made in order to make the simulation process easier.

During this simulation the test conditions are:

☐ Prime Mover Reference $(\omega_{m,ref})$: from 1515 r/min to 2024 r/min in 4,5sec

☐ Reference frequency (fr_{ref}): 50,0Hz

☐ Electric Load (P_s): from 5,275kW to 0kW $(t = 3{,}6\text{sec})$

The simulation results and measurements can be seen in the following figures. The effects of Prime Mover speed variations and electric load changes can be observed.

The Prime Mover speed (ω_b) variation has a quasiproportional effect in the motor speed (ω_m), however the mover inertia moment makes this variation slow. For this reason, its main effect can be observed during the steady state. The governor parameter K_ω is highly involved in the correction of this effect. A smoothing process is used to prevent unstable situations (see paragraph III.E).

The electrical load changes can be considered as instantaneous ones when mechanical variations are also taken into account during the system analysis. SCG belongs to this kind of systems. So, the load change effects have their most important effect during the transient behavior. Large transients oscillations in pressure and speed are present for this reason. In the transient domain, the hydrostatic fluid in the pressure lines acts like a spring [see differential term of leakage flow in (7)], this provokes the mentioned transient oscillations.

As a conclusion, the ability of Electrohydraulic Stroke Control to vary the Displacement Volume in few msec is very important in order to keep the generator speed constant when electric load changes are present.

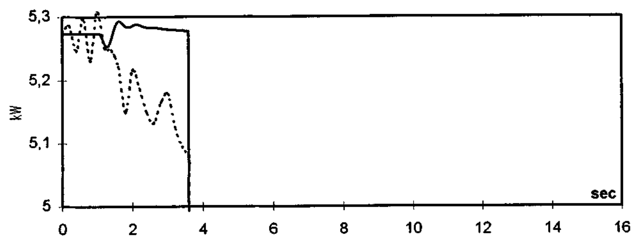

Fig. 11. Simulated and measured (dotted) Electric Power (P_s).

V. Conclusion

Finally the main conclusion from the SCG analysis are presented.

- The Hydrostatic Transmissions are a robust and stable solution when a constant output speed is needed, e.g. when the problem is to maintain at reference speed the generator of a SCG.
- The main perturbations that affects the generator speed are the Prime Mover speed (its effect is mainly in the steady state) and the electric load (load changes are of special interest during transient behavior). The Displacement Volume is the only control variable.
- The fast response of Electrohydraulic Stroke Control is the principal inconvenient for these systems.
- A simple model is used for simulation, although the agreement between measurement and simulation results is high. For this reason, the simulation is a powerful tool in order to design the adequate speed governor for the system, preventing a great deal of real tests and measurements.

Appendix
Parameter Identification of Shaft Coupled Generator

In the identification process a set of real measurement is needed. In the present paper two kind of tests are considered:

- Type I: A sharp change in the electric load (R) is provoked.
- Type II: A fast change in Prime Mover speed (ω_b) is provoked.

In the above tests, the Speed Governor is not implemented.

In this paper, an identification method based on the Melder–Mead Simplex Algorithm [8][9] has been used. This algorithm is employed to minimize a quadratic error defined for each set of parameters. The numerical results for the identification process are summarized in Table II.

In order to validate the identified parameters, simulations for each block are also presented. In these simulations the real measurements are used as inputs and the outputs are presented in the Figs. 12–15.

A. Prime Mover Parameters

The necessary parameters for a complete identification are: B_b, J_b, VC, K_p and K_i (2). In order to obtain them, the following error is minimized means the simplex method:

$$error = \sum_{n=1}^{N} (\omega_b^r - \omega_b^s)^2 \tag{17}$$

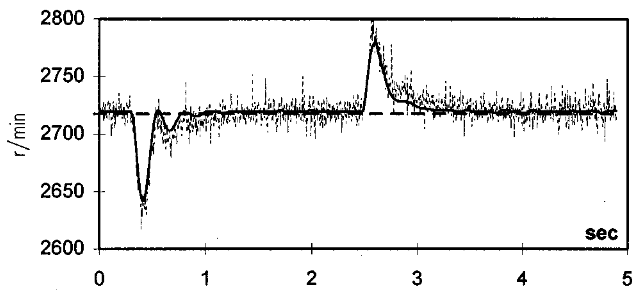

Fig. 12. Simulated, reference (dashed) and measured (dotted) Prime Mover speed. Type I conditions.

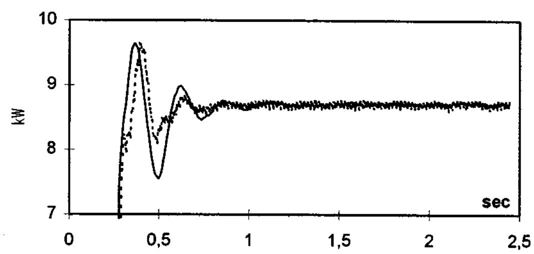

Fig. 13. Simulated and measured (dotted) Electric Power.

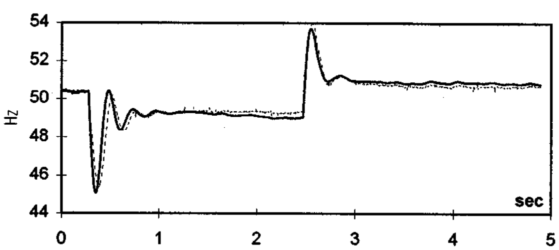

Fig. 14. Simulated and measured (dotted) output frequency.

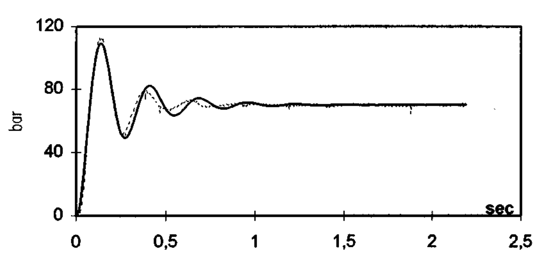

Fig. 15. Simulated and measured (dotted) Pressure.

where superindex "r" means that the speed is the measured one and superindex "s" that the speed is the simulated one. As an example the simulation of the Prime Mover with these parameters is presented in Fig. 12 and Table II.

B. Synchronous Generator Parameters

The electric behavior is related with K_1, K_2 and T (4)(5), the error minimized is:

$$error = (P^r_{peak} - P^s_{peak})^2 \tag{18}$$

where P^r_{peak} and P^s_{peak} are the peak values of the real and simulated power delivered by the generator P_s. (see Fig. 13).

B_m (6) is calculated as the mean value of steady state measurements and (8). The J_m value is calculated with:

$$error = (\max\{\omega^r_m\} - \max\{\omega^s_m\})^2 + (\min\{\omega^r_m\} - \min\{\omega^s_m\})^2 \tag{19}$$

where *max* and *min* represent the maximum and minimum values obtained during Type I Tests (see Fig. 14).

C. Hydrostatic Transmission Parameters

The two first parameters to be calculated are C_{lt} and V_b (7). In order to get a couple of initial values, these considerations for Type I tests are made:

- The Prime Mover speed (ω_b) and the displacement volume (α) are supposed to be constant. So, the term $s\Delta(\alpha\omega_b)$ (9) is neglected.
- The m_e variation is approximated by a step, therefore its transient oscillations during the load change are neglected.

From measurements on Type I tests the amplitude M_e of the torque step is obtained. As shown before, the system behavior can be considered like a 2$^{\text{nd}}$ order system (14). Hence the parameters [3] overshoot M_p, peak time t_p and settling time t_s can be obtained. At that time an identification process is applied in order to obtain the damping factor σ and the damping frequency ω_d (13). The minimized error during this process is:

$$error = \left(\frac{M^r_p - M^s_p}{M^r_p}\right)^2 + \left(\frac{t^r_p - t^s_p}{t^r_p}\right)^2 + \left(\frac{t^r_s - t^s_s}{t^r_s}\right)^2 \tag{20}$$

In order to achieve a better approximation, the influence of the Prime Mover speed $s\Delta(\alpha\omega_b)$ (9) is now taken into account, then σ and ω_d can be newly obtained and so Cl_t and V_b are calculated.

Now, the parameter called q_{l0} (see Table II and Fig. 15) that is related with the leakage flow (7) is identified. It is obtained from the mean value of steady state values from different tests.

D. Electrohydraulic Stroke Control Parameters

It is the last element to be identified. For this purpose b and c (18) are the parameters to be obtained. The following expression for the error is employed:

$$error = \left(\frac{DR^r - DR^s}{DR^r}\right)^2 + \left(\frac{PL^r - PL^s}{PL^r}\right)^2 \tag{21}$$

where DR is the Dynamic Response (1,34Hz @ 3dB) and PL is the Phase Lag (2,3Hz @ 90°). These values are obtained from the specifications sheet.

REFERENCES

[1] J. Thoma, *Transmisiones Hidrostáticas*, Spain: Gustavo Gili, 1968.
[2] H.E. Merrit, *Hydraulic Control Systems*, USA: John Wiley & Sons, 1967.
[3] K. Ogata, *Ingeniería de Control Moderna*, Mexico: Prentice-Hall Hispanoamericana, 1980.
[4] M. Pavella and P.G. Murthy, *Transient Stability of Power Systems*, England: John Wiley & Sons, 1994.
[5] P. Crause, *Analysis of Electric Machinery*, USA: McGraw-Hill, 1986.
[6] J. Lnnevi, K. Rydberg, and J.-O. Palmberg, "Modeling, Simulation and Measurements of Hydrostatic Drives with Varied System Dynamics," in *Third Scandinavian International Conference on Fluid Power*, 1993.
[7] R. Ewald and J. Hutter *et al.*, *Técnica de válvulas proporcionales y de servoválvulas—Training Hidrálico*, Spain: Manesmann Rexroth GmbH, 1989.

[8] A. Grace, *Optimization Toolbox Manual (for use with Matlab)*, USA: The MathWorks Inc., 1992, pp. 3.16–3.19.
[9] G. L. Menhauser, A.H.G. Rinnooy Kan, and M. J. Tdd, *Optimization*, Netherlands: North-Holland, 1989, vol. 1, pp. 53–55.

José Cidrás received his degree in electrical engineering from the University of Las Palmas de G.C. (Spain). He obtained a PhD in electrical engineering from the University of Santiago (Spain) in 1987. He has been a professor at the University of Vigo (Spain) since 1982. He is a Member of IEEE.

Camilo Carrillo received his degree in electrical engineering from the University of Vigo (Spain), where he has been a lecturer since 1992.

Discussions and Closures

Discussion of "Regulation of Synchronous Generators by Means of Hydrostatic Transmissions"

Norton Savage

This paper[1] discusses the application of a hydraulic power transmission device to couple a ship's electric generator to the main propulsion engine of the ship, instead of having the generator driven by its own prime mover. As I interpret the paper,[1] the concept need not be restricted to shipboard application but may be applied in any situation in which one prime mover may be used to drive an electric generator as well as to perform some other function. In fact, the laboratory tests of the proposed hydraulic device were performed with the motive power provided by a DC motor controlled by an AC/DC converter.

The purpose of the proposed device appears to be the elimination of a separate prime mover for the ship's generator, with the hydraulic device permitting the generator to run at constant speed in spite of speed variations of the propulsion prime mover.

Without going into the details of the block diagrams and the mathematical analysis presented by the authors, I accept the validity of the tests reported and discuss only the concept of the paper.[1] My discussion does not depend on the details of the mathematics nor on the test arrangements.

Among the features that would appear to be relevant to the concept presented are the following:

1) Will the overall arrangement be more efficient, and to what degree, in terms of the use of fuel, than the conventional arrangement of separate prime movers for propulsion and power generation?

   The answer to this question depends on the particular situation studied; I believe it can not be answered in general terms. In order to accommodate the proposed scheme, the propulsion prime mover must be increased in size from that required only for propulsion, to include the power requirements of the ship's electrical load. The larger prime mover may be more efficient than the smaller one, but the overall improvement in fuel use should be compared to the overall fuel use required if the generator has its own prime mover. The interposition of the hydraulic transmission device may occasion a reduction of efficiency.
2) To what extent will variations in the electrical load be reflected back to the prime mover? For instance, would a short circuit of the generator cause a disturbance to the movement of the ship because of the effect on the prime mover? It appears to me that coupling of the electric load and the driving power of the ship may not be altogether desirable, for at least two reasons. One reason is that failure of the prime mover will affect not only the propulsive power of the ship but will also affect the electric power. Granted, the ship's emergency generator and batteries may be able to ride through the disturbance, depending on the duration of it, but the battery and emergency generator design would have to provide not only the usual emergency electric power but also the electric power required for machinery repairs at the same time. If the generator were driven by its own prime mover, electric power would be assured for the duration of the propulsion prime mover outage, and would provide some assurance of electricity to operate the necessary tools and lighting for repair work and communications.
3) Scheduling of maintenance would become somewhat more complicated because work on the prime mover would entail an outage of the electric generator and loss of electric power; the emergency battery should not be depended on for power supply under maintenance conditions.
4) The space requirements of the proposed arrangement would differ from the space requirements required where the propulsion prime mover and the generator prime mover are separate. The proposed hydraulic transmission device and the generator would now have to be added to the shaft end of the propulsion prime mover, and the space needed for the usual generator prime mover would be eliminated. I do not know whether this would be a major factor in ship design, but I believe it would require some consideration.

Manuscript received March 28, 2000.
N. Savage, P.E., Silver Spring, MD 20903 USA.
Publisher Item Identifier S 0885-8950(00)11298-2.

[1]J. Cidrás and C. Carrillo, *IEEE Trans. Power Systems*, vol. 15, no. 2, pp. 771–778, May 2000.

Closure to Discussion of "Regulation of Synchronous Generators by Means of Hydrostatic Transmissions"

José Cidrás and Camilo Carrillo

In the above papers,[1] the authors wish to thank Mr. Norton Savage for his suggestions and his interest in this subject, and would like to answer him:

1) As the discusser said, the conventional arrangement to produce electricity in ships uses diesel units only dedicated to this task. The system depicted by the authors has efficiency advantages and others over the classical scheme.

   In order to compare both arrangements, classical and SCG one, the consideration is made, that the prime mover power is much greater than that required by the electrical shipboard loads.

   Diesel unit efficiency grows with the power. Consequently, as prime mover power is greater than that of diesel unit, so is its efficiency. And, therefore, SCG fuel consumption per kWh is lower.

   On the other hand, in order to guarantee the electricity availability, diesel units must be operating the whole time, even during the periods when there is not electric shipboard consumption. So, fuel is wasted during this no-load operation.

Manuscript received January 22, 1999.
J. Cidrás and C. Carrillo are with the Departamento de Enxeñeria Eléctrica ETSIIM - Universidade de Vigo, Spain.
Publisher Item Identifier S 0885-8950(00)11297-0.

[1]J. Cidrás and C. Carrillo, *IEEE Trans. Power Systems*, vol. 15, no. 2, pp. 771–778, May 2000.

However, no-load consumption for the SCG is very low. This point must be taken into account in order to compare the efficiency of the two arrangements.

SCG have other advantages different from efficiency, e.g., consumption of oil and maintenance costs are reduced, SCG installation is easier, etc.

Nowadays, it is more appropriate to compare SCG with electronic solutions. For instance, a synchronous machine with an AC/AC converter coupled to the prime mover shaft. This kind of solutions is more complex and, so, its reliability is lower than that for mechanical systems. However, from the point of view of efficiency, installation, maintenance, etc., electronic schemes could be the most appropriate.

2) As has been assumed, the prime mover power exceeds the electric power requirements, so the electric load variations must not affect the prime mover. In the case of a short-circuit, electric protections usually act in a few milliseconds. As a result, it should not affect the mechanical system. However, we agree with the discusser in that use of a SCG creates dependence between prime mover and electricity generation although an emergency group exists. And therefore, reliability of classical arrangements is a clear advantage with regard to SCG ones.
3) The above-mentioned dependence between Prime Mover and SCG also affects maintenance works.
4) In general, space requirements are higher for diesel units than for SCG. However, these requirements can be comparable in some cases. Nevertheless, situation of components is more flexible in the SCG scheme which implies additional space saving.

Discussion of "Radial Basis Function (RBF) Network Adaptive Power System Stabilizer"

G. Ramakrishna and O. P. Malik

The authors have described an interesting paper[1] to tune the parameters of a conventional power system stabilizer (CPSS) using a RBF network. The discussers would like to know the authors' comments on the following issues in the paper:[1]

1) In the introduction the authors indicate the paper[1] as a maiden attempt to design an RBF network based adaptive PSS (RBFAPSS). In [1] a RBF network is used to find the control parameters for an excitation controller with generalized minimum variance controller (GMV). In [2] a scheme for combining back-propagation neural network with conventional PID control is proposed. How is authors' work different from the above papers?
2) For designing the RBFAPSS, the authors used a reduced number of training patterns. What methodology is adopted to select the training patterns from the training set so as to sample the input–output domain adequately?
3) While making a comparative analysis between RBFAPSS and ANNAPSS, the authors highlight the quickness of learning of RBFAPSS (Table II) compared to ANNAPSS (Table III). In Table II, the training time for RBFAPSS is obtained using a reduced number of training patterns (10–100) while in Table III; the training time for ANNAPSS is obtained considering the complete training set (400 training patterns). Have the authors made a comparison between the two APSSs using the same number of training patterns?
4) While analyzing the dynamic performance of RBFAPSS with different number of centers, the authors state that the responses of RBFAPSS(7) and RBFAPSS(8) are inferior to those obtained with RBFAPSS(4) and RBFAPSS(5).

   In general, increasing the number of hidden nodes (centers) in a RBF network is directly proportional to reduction of sum-squared errors (SSE) [3]. The above discussion of the results contradicts the basic property of an RBF network. Even the authors in Section VI justify this property of RBF network by statement "the minimum value of SSE obtained with ANN is 0.159 (implying local minimum) while RBF network can be trained for any value of SSE."
5) In the paper,[1] the RBF network is trained off-line to find the parameters of CPSS on-line. It has been found in the literature [4], especially when the dynamics of the system vary over a broad range, simultaneously updating the centers and weights directly in real-time improves both the modeling and tracking capabilities of the RBF network.

References

[1] E. Swidenbank, S. McLoone, D. Flynn,, G. W. Irwin, M. D. Brown, and B. W. Hogg, "Neural network based control for synchronous generators," in *IEEE PES-SM*, Berlin, Germany, July 1997, Paper no. PE-803-EC-2-06-1997.

[2] F. C. Chen, "Back-propagation neural networks for nonlinear self-tuning adaptive control," *IEEE Control System Magazine*, vol. 10, no. 3, pp. 44–48, April 1990.

[3] S. Haykin, *Neural Networks: A comprehensive Foundation*. New York, NY: Macmillan, 1994.

[4] S. Chen, S. A. Billings, and P. M. Grant, "Recursive hybrid algorithm for nonlinear system identification using radial basis function networks," *Int. J. Control*, vol. 55, no. 5, pp. 1051–1070, 1992.

Closure to Discussion of "Radial Basis Function (RBF) Network Adaptive Power System Stabilizer"

Ravi Segal, M. L. Kothari, and Shekhar Madnani

The authors wish to thank the discussers for their interest in our research work and for their valuable comments on the paper.[1] Our response to the comments is as follows:

1) We are fully aware and have studied both the papers referred to by the discussers. Swidenbank *et al.* Ref. [1] have described

Manuscript received August 31, 2000.

G. Ramakrishna and O. P. Malik are with the Department of Electrical and Computer Engineering, The University of Calgary, Calgary, Albreta, Canada T2N 1N4.

Publisher Item Identifier S 0885-8950(00)11300-8.

[1]R. Segal *et al.*, *IEEE Trans. Power Systems*, vol. 15, no. 2, pp. 722–727, May 2000.

The authors are with the Department of Electrical Engineering, Indian Institute of Technology, Hauz Khas, New Delhi - 110 016, India.

Publisher Item Identifier S 0885-8950(00)11299-4.

[1]R. Segal *et al.*, *IEEE Trans. Power Systems*, vol. 15, no. 2, pp. 722–727, May 2000.