Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

On The Stability of Generators Load Sharing

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Abstract: This paper deals with the dynamic performance of the active power control of two or more generators electrically connected in parallel, the average power control is used to enable the generators to share the load equally with constant speed.

The new system suffered from instability due to the interaction between the different loops.

Base on the multi-variable linear equivalent machine system model, the system was analyzed and its stability limits were obtained using MATLAB. The system was simulated using Simulink.

A phase-lag network was introduced in the load sharers, and had a major effect on the stability of the system which enables the increase of the gain of the controllers without breaking into instability.

Keywords: Generator, Stability, Isochronous, Load, Sharing, Analysis, Design, Multivariable.

1. INTRODUCTION

As the world becomes more reliant on electric power to function and grow, backup power systems, such as generators, are playing an increasingly significant role in ensuring uninterrupted supply of power. The choice of a generator depends primarily on the amount of backup power that is required for the specific application.

Parallel standby power systems have always been significantly advantageous over single large generator units. However, implementation of such systems has historically been limited to large projects or mission critical applications due to the constraints of higher cost, space, and the high level of complexity involved to setup and maintain. Until recently, many businesses both large and small have refrained from parallel operation of generator sets. With the introduction of sophisticated integrated digital control technologies, it has now become much easier to operate systems in parallel and benefit from the additional advantages these systems can provide.

The single-loop control of speed (isochronous governing) can maintain the requested speed precisely, if two or more generators are electrically paralleled to increase the total generated power capability, one generator set increases its power and the other decreases its power, which yields motorizing one or more of the generator sets.

The load sharing device is usually independent of the original speed control system and is added to the system when parallel operation of generators is required. It must be provided to tools to enable robust and versatile system performance, (i.e the system performance must be improved from the load sharing device as in from the governor.

This paper is concerned with providing means to analyze and design stable active power control of two or more generators connected to the same load, which helps in engineering the components of generators active power control (speed control unit "Governor" and load sharing module).

2. SYSTEM SIMULATION

Simulink simulation environment was used to simulate the performance of the system, a synchronous generator model provided by MATLAB's library "simpowersystems" was used in the simulation environment. A model of a diesel engine and a speed control unit was used as a case study. Figure 1 shows the Simulink's simulation of the system.

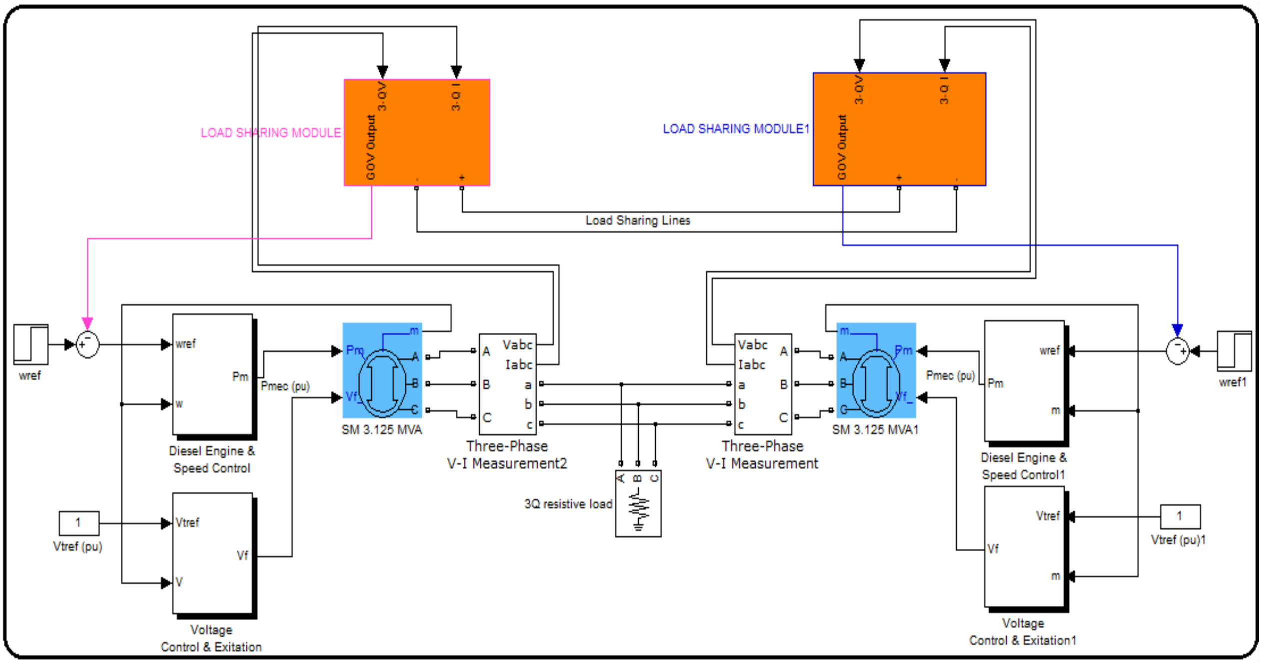

Figure 1. Simulink block diagram for two generators sharing a common load.

3. SYSTEM ANALYSIS

The system block diagram for the actuator, diesel engine, governor and the generator was obtained as shown in figure 2.

The engine was modelled by a time delay, that is approximated using Pade approximation[4].
One important note is that the saturation on the actuator (valve) was neglected in the analysis since it's a non-linear element. The simulation showed the effect of the saturation on the performance of the system.

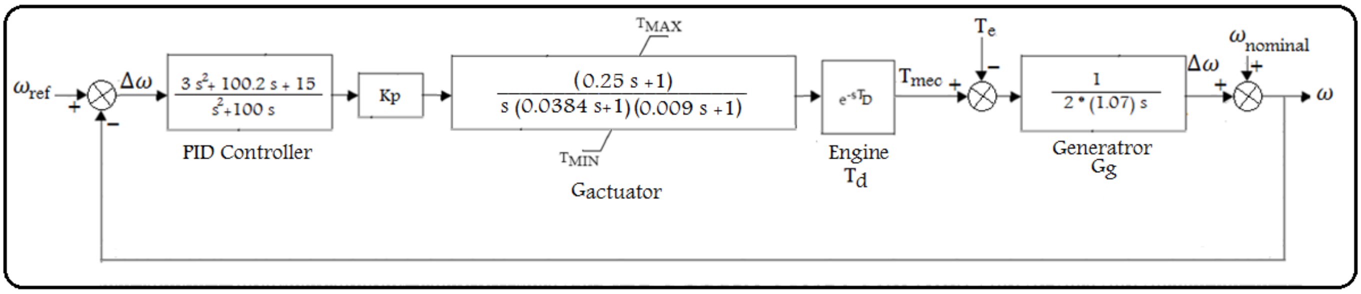

Figure 2.A Block diagram representation of a synchronous generator speed control system.

The system was analysed using classical control theory. The step response of the system and its stability limits were obtained using MATLAB to calculate the following equations. Refer to equation no. (1):

$$\frac{\omega}{\omega_{ref}} = \frac{\mathrm{OLTF}}{(1 + \mathrm{OLTF})} \quad (1)$$

$$OLTF = PID * K_p * G_{actuator} * T_d * G_g \quad (2)$$

Where: PID=proportional-derivative-integral, Gg=generator model. The PID parameters were tuned to achieve a suitable behaviour of the system in Figure 2 (refer to results).

When two or more generators are connected to a transmission line, by assuming that the frequency will be constant, the generators models can be lumped into an equivalent that is driven by the sum of the individual mechanical torque output [1].
This arrangement was made as shown in the figure 3. In figure 3, W1 and W2 were separated in order to feedback each measured value to its corresponding controller. However, this arrangement doesn't make a difference in the model.

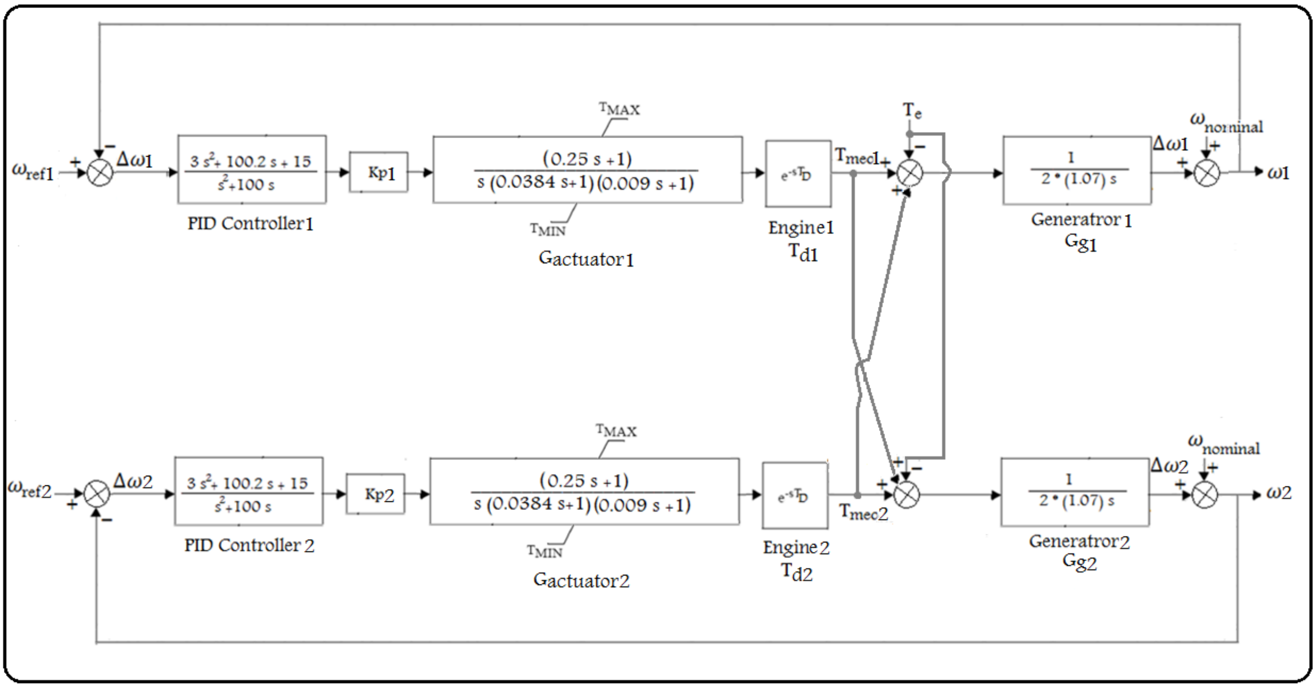

Figure 3.A Block diagram representation of two generators sharing the same load.

The new system was analyzed using the Signal Flow Graph method of representing the block diagram. And by applying Mason's rule to find a relationship between any chosen input and an output.
The relation between W1 and Wref1 con be written as shown in equation no. (3):

$$\frac{\omega_1}{\omega_{ref1}} = \frac{\omega_2}{\omega_{ref1}} = \frac{\text{OLTF}_1}{(1 + \text{OLTF}_1 + \text{OLTF}_2)} \qquad (3)$$

Where (OLTF1) is as shown in equation (4):

$$OLTF_1 = PID_1 * K_{p1} * G_{actuator1} * T_{d1} * G_{g1} \qquad (4)$$

And (OLTF2) is as shown in equation (5):

$$OLTF_2 = PID_2 * K_{p2} * G_{actuator2} * T_{d2} * G_{g2} \qquad (5)$$

The mechanical torques as functions of Wref1 can be written as shown in equations no.(6) and (7).

$$\frac{T_{mec1}}{\omega_{ref1}} = \frac{(PID_1 * G_{actuator1})(PID_1 * \text{OLTF}_2)}{(1 + \text{OLTF}_1 + \text{OLTF}_2)} \qquad (6)$$

$$\frac{T_{mec2}}{\omega_{ref1}} = \frac{(-PID_2 * \text{OLTF}_1 * G_{actuator2})}{(1 + \text{OLTF}_1 + \text{OLTF}_2)} \qquad (7)$$

The load sharing devices were modelled and represented in a block diagram as shown in the figure 4.

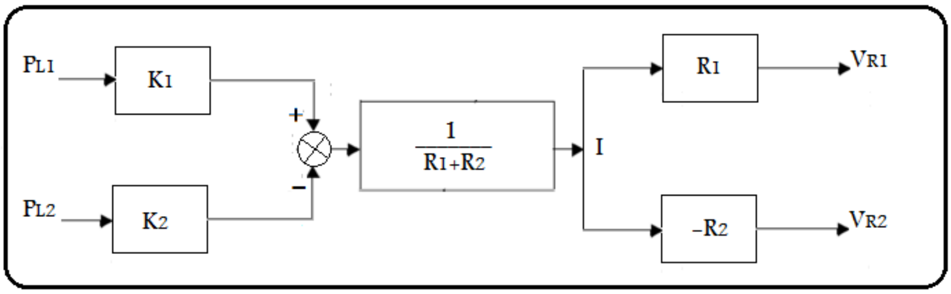

Figure 4. Modelling of average power measuring load sharing.

The load sharing model obtains the difference between each generator's power and the average power, and feed the signal back the corresponding speed control unit. Since there are no electrical powers represented in the model the following modification was made to insert the load sharing model: The signals "PL1" and "PL2" (electrical powers) were taken from the mechanical torques "Tmec1" and "Tmec2", since we can assume PL≈Pmec and since Pmec=Tmec*W, and W has some value near 1. This arrangement affects the results

obtained by the analysis, but the indications that the analysis provides are still valid.
The block diagram of two generators connected to a common load with load sharing is shown in figure 7.
The system was represented in Signal Flow Graph form, as shown in figure 5. Further reduced in figure 6 using the following equalities (8), (9) and (10):

$$U_1 = \frac{(PID_1 * G_{a1})}{(1 + \mathrm{K}_1 \frac{\mathrm{R}_1}{\mathrm{R}_1 + \mathrm{R}_2} * \mathrm{PID}_1 * \mathrm{G}_{a1})} \qquad (8)$$

$$U_2 = \frac{(PID_2 * G_{a2})}{(1 + \mathrm{K}_2 \frac{\mathrm{R}_2}{\mathrm{R}_1 + \mathrm{R}_2} * \mathrm{PID}_2 * \mathrm{G}_{a2})} \qquad (9)$$

$$P_1 = P_2 = \frac{-\mathrm{K}_1 * \mathrm{R}_1}{(\mathrm{R}_1 + \mathrm{R}_2)} \qquad (10)$$

Again, the system was analysed using Mason's rule to obtain the input-output relationships and the open-loop transfer function equivalent was obtained to obtain the limits of the stability.
To find the open-loop equivalent, the characteristic equation of the system (Δ) must be obtained, it can be written as shown in equation (11).

$$\Delta = 1 + U_1 * G_{g1} + U_2 * G_{g2} - R_1 * R_2 * P_2 * G_{g1} - R_1 * R_2 * P_3 * G_{g2} - R_1 * R_2 * P_2 * P_3 \qquad (11)$$

The open-loop equivalent (U1*Gg1 + U2*Gg2 - R1*R2*P2*Gg1 - R1*R2*P3*Gg2 - R1*R2*P2*P3) now can be used to make the Nyquist diagram of the system.

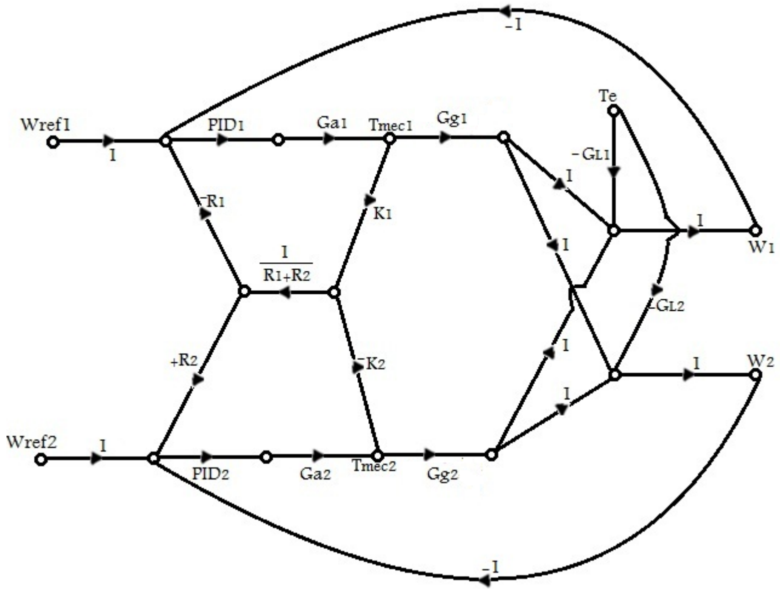

Figure 5. Signal flow graph representation of the system.

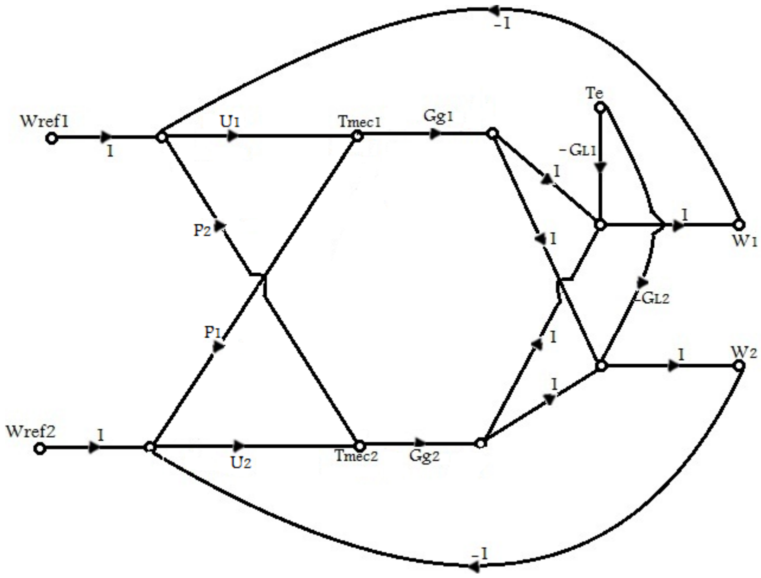

Figure 6. Signal flow graph representation of the system with a degree of reduction.

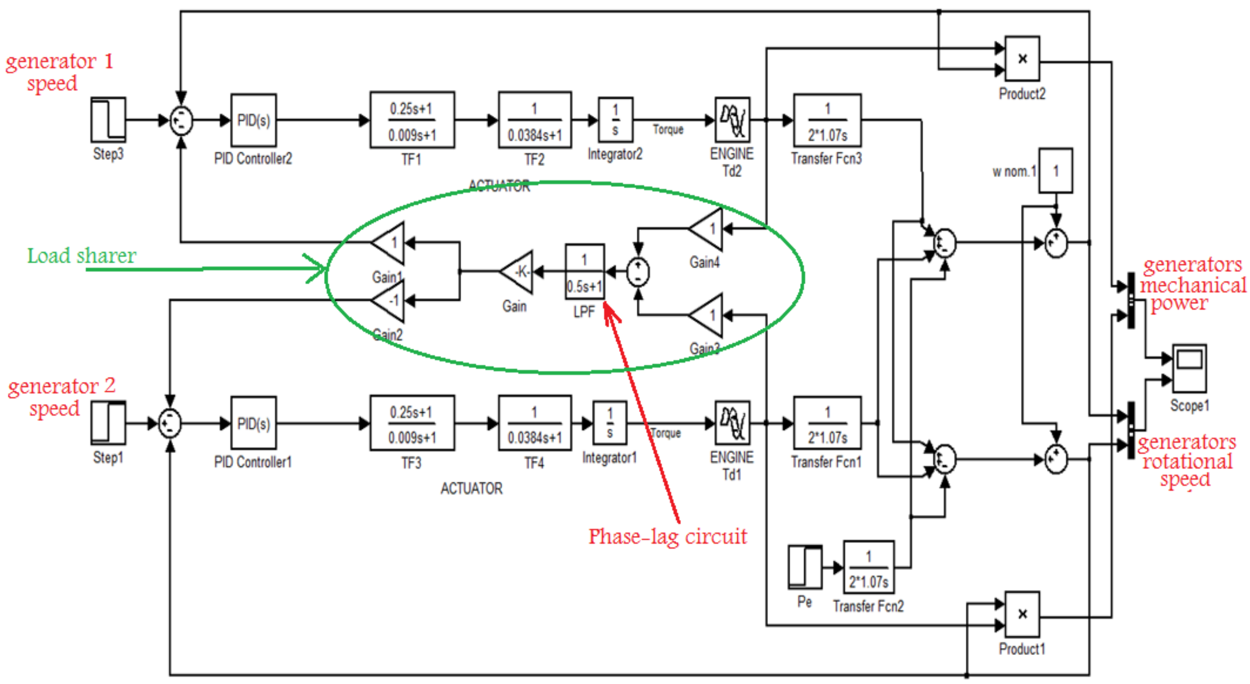

Figure 7. Simulink model of two generators connected to a common load with an average power load sharing.

The system with load sharing showed unstable response (with gains K1=K2=20) which suffers from growing oscillations with frequency of about 70 rad/sec (see results).
A phase-lag network was added to the system in the load sharer (see figure 7), the phase-lag network had a large effect in stabilizing the system. This made it possible to improve the system transient response from the loads sharing device.

4. RESULTS

A. Step response of the single generator speed control system (gain K=20):

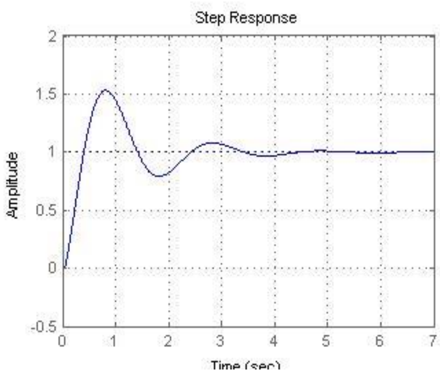

Figure 8. Step response of a single generator angular speed (reference speed change).

B. Nyquist diagram and stability limits for the single generator speed control system (gain K=20):

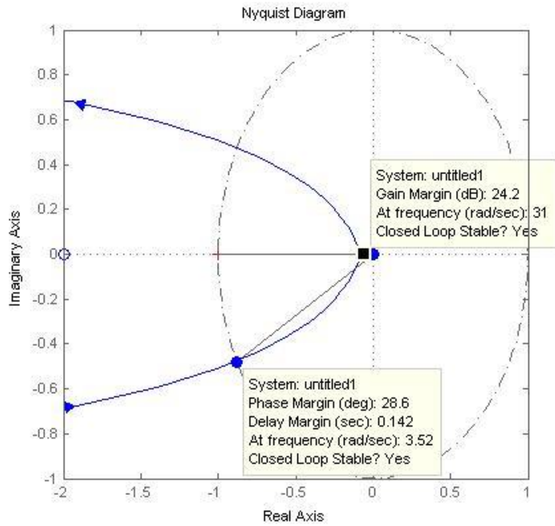

Figure 9. Nyquist diagram of a single generator speed control system.

C. Step response of two generators speed control system (gains K1=20 and K2=20):

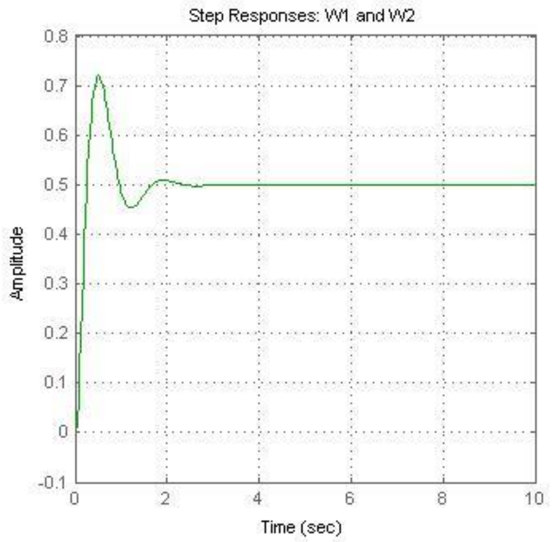

Figure 10. Step response of two generators angular speed (one generator reference speed change (Wref2=0)).

D. Step response of the mechanical torques for two generators without load sharing:

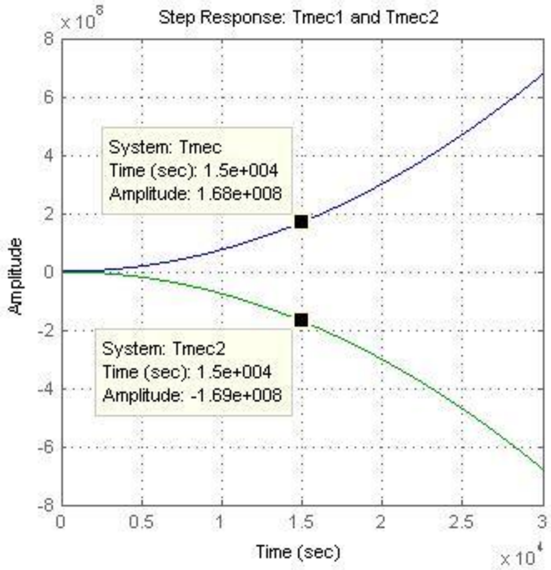

Figure 11. Step response of two generators mechanical torques, which shows the problem of isochronous governing (one generator reference speed change (Wref2=0)).

E. Nyquist diagram and the stability limits of two generators connected to a common load:

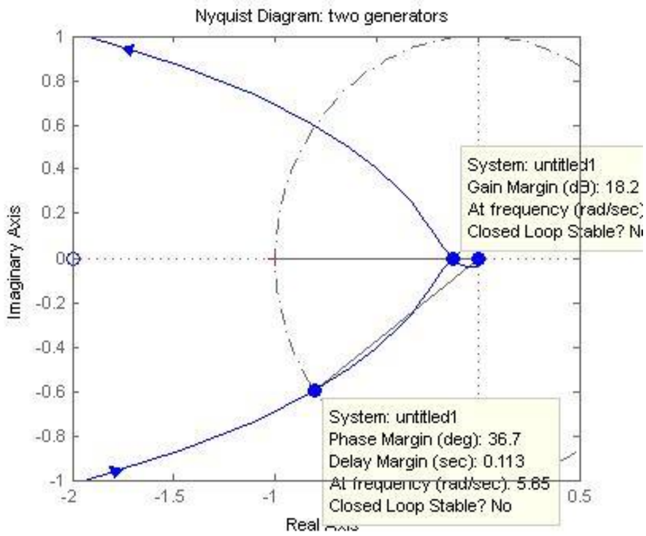

Figure 12. Nyquist diagram of two generators connected to a common load (K1=20, K=20), which shows a drop in Gain Margin from 24.2 dB to 18.2 dB (equivalent to the gain margin of a single generator control loop with gain K=40).

F. Nyquist diagram and the stability limits of the system with load sharing (gains K1=20 and K2=20 (unstable system)):

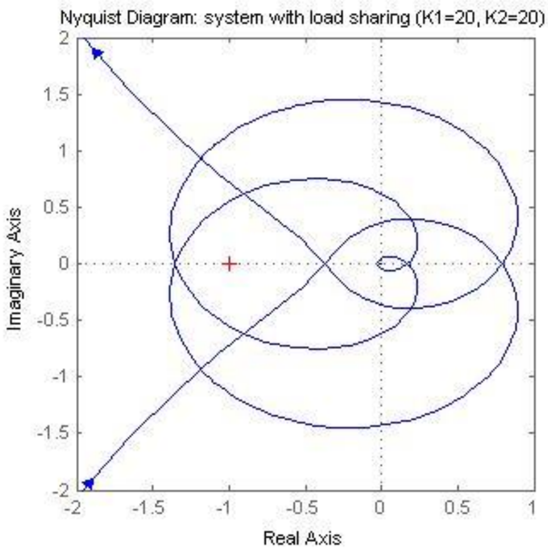

Figure 13. Nyquist diagram of two generators connected to a common load (K1=20, K=20).

G. Step responses of the mechanical torques for a step input of (Wref1) with load sharing:

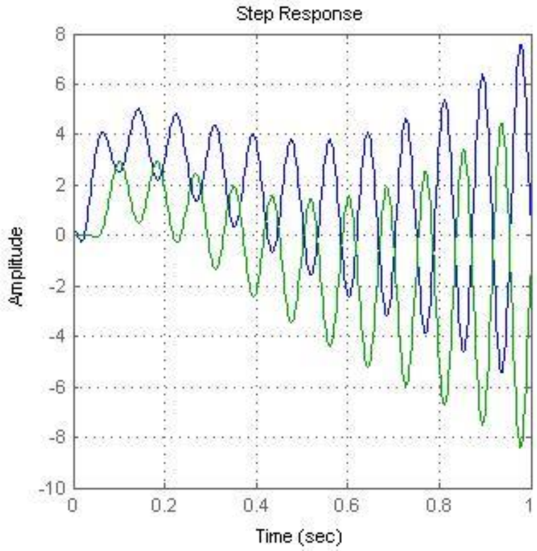

Figure 14. Step response of two generators mechanical torques, which shows the instability problem (one generator reference speed change (Wref2=0)).

H. Step responses of the mechanical torques for a step input of (Wref1) with load sharing and a phase-lag network in the load sharer:

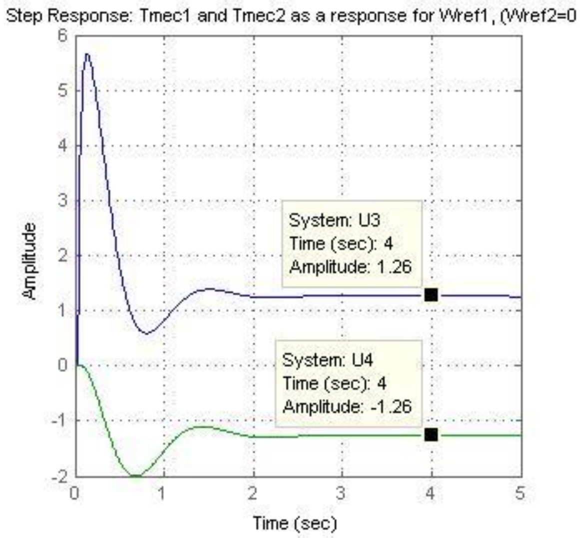

Figure 15. Step response of two generators mechanical torques, with the addition of a phase-lag network (time constat=0.5), which shows the effect on the stability of the system (one generator reference speed change (Wref2=0)).

I. Showing the effect of introducing a phase-lag network in the load sharer:

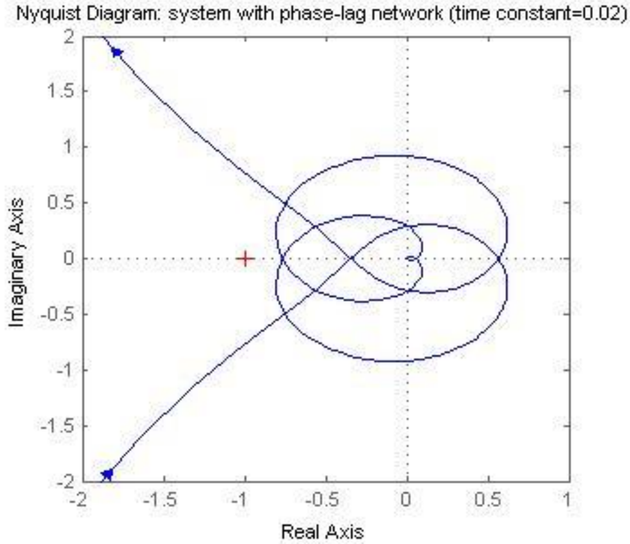

Figure 16. Nyquist diagram of two generators connected to a common load (K1=20, K=20), with the addition of a phase-lag network (time constant=0.02).

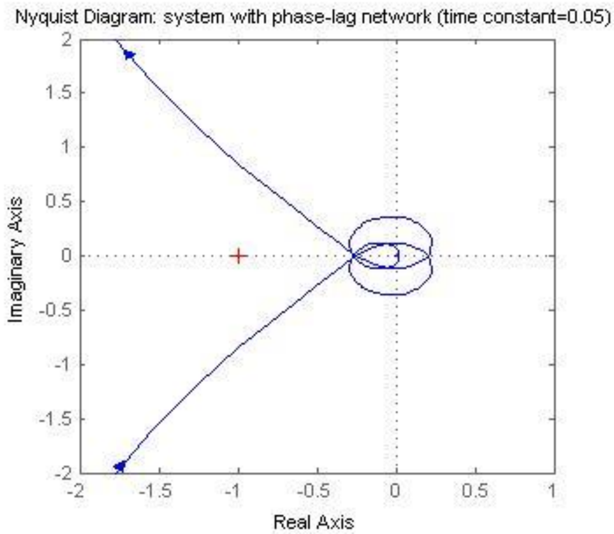

Figure 17. Nyquist diagram of two generators connected to a common load (K1=20, K=20), with the addition of a phase-lag network (time constant=0.05).

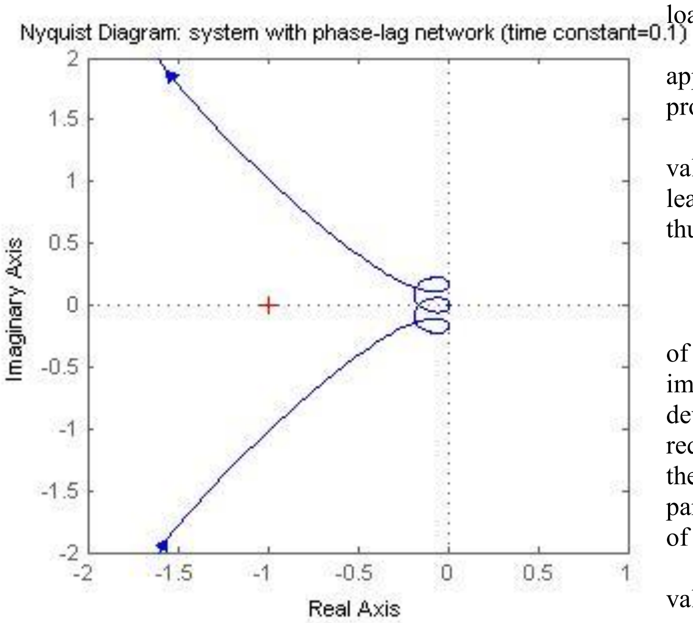

Figure 18. Nyquist diagram of two generators connected to a common load (K1=20, K=20), with the addition of a phase-lag network (time constant=0.1).

5. DISCUSSION

Although the system under studying is a (MIMO) system, classical linear theory was used to analyze the system, which was developed for SISO systems. So the data were obtained by recording the response of a single output at time for a single input, and taking the other inputs as equal to zero.

The single generator speed can be maintained very precisely using isochronous mode as shown in figure 8. Where figure 10 shows that the speed of the generator settled at (0.5), which is the average between (Wref1=1) and (Wref2=0).

Figure 11 shows the problem of connecting two generators with a common load using (isochronous governing), because that Tmec1 and Tmec2 are growing without limit to maintain the corresponding desired speed (Tmec1 is growing for Wref1 to reach 1, and Tmec2 is growing for Wref2 to reach 0).

By applying the load sharing method (average power measurement, see figure 7), the system became too sensitive and introduce additional frequency which led to instability (figure 13).

Introducing a phase-lag network in the load sharing device showed a stable behavior. As shown in figure 14, the mechanical torques (Tmec1 and Tmec2) were settling on (1.26) and (-1.26), for a step change in (Wref1), which shows an average value of 0 (since there is no electrical torque Te=0).

The phase-lag network acted as a low-pass filter that suppressed the additional frequency that was introduced by the load sharing, which eliminated the undesired effect of the load sharer.

The additional frequency was about 70 rad/sec, so an appropriate cut-off frequency of the phase-lag network can produce the required performance.

As shown in the figures 15, 16 and 17, with increasing the value of the time constant (decreasing cut-off frequency) leaded to more suppression of the additional frequency, and thus increasing the stability of the system.

6. CONCLUSION

The paper used analytic tools to studying the performance of generators load sharing, and presented a method to improve the stability of the system from the load sharing device, and thus no changing in the governor parameters is required when operating on a load sharing mode. However, the original system must have some stability margin before paralleling because generators paralleling reduces the stability of the system.

As stated previously, the analysis doesn't provide accurate values of the parameters because several approximations were made for the sake of the analysis, but it provides information about the effect of various parameters on the performance of the system, a more accurate model should be obtained to find the required values of the parameters to implement on the real system.

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