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Power Criterion for Emulating a Gas Turbine Engine with an Electric Motor

ABSTRACT

A power criterion for selecting the electric motor used in a gas turbine emulator is defined. The power criterion is derived in terms of the ratio of inertias between the gas turbine engine and the electric motor, rotational losses and load torque. The gas turbine emulator allows emulating the speed-torque behavior of a gas turbine engine. Using simulation models, we show that the steady-state speed response of the gas turbine emulator tracks that of the gas turbine engine. The Bode plots of the gas turbine and gas turbine emulator are obtained by using system identification. Frequency analysis shows that the gas turbine emulator tracks the speed response of the gas turbine within the linear region.

INTRODUCTION

When testing an experimental machine such as a new generator it may be necessary to initially drive it with a surrogate prime mover. For instance, one could test a new generator by driving it with an electric motor (surrogate prime mover) instead of with a gas turbine engine (final prime mover). This is the case at the NAVSEAWarfare Center Philadelphia where it is intended to test the generator part of a high-frequency, medium-voltage AC (HFAC) turbogenerator system, operating at the medium power level, by substituting the gas turbine engine part of the system with a synchronous motor.

It is well known how to design the controls in cases where the surrogate prime mover has low inertia compared to the intended prime mover, such that the surrogate accurately emulates the torque and speed characteristics of the planned prime mover. This is the case when an electric motor is used to emulate a reciprocating piston engine or a wind turbine (Boulter 2000), (Chinchilla, Arnaltes, and Rodrigues-Amenedo 2004), (Dolan and Lehn 2005). But in other cases where a high-power-density prime mover such as a gas turbine engine must be emulated, the electric machine often has an inertia value much higher than the turbine engine that will be emulated.

When considering which motor to use to emulate a gas turbine engine it is tempting to specify one having a power rating that just meets the rated shaft power requirements. This would allow the generator to be tested up to full rated output power under steady state conditions. But then the power of the motor would be insufficient to test the response of the generator under transient loading conditions. Under these transient loading conditions, the speed response of the surrogate prime mover must match that of the intended prime mover and in particular it must be capable of accelerating or decelerating at rates comparable to that of the prime mover. The power required for the surrogate prime mover may then be larger than the rated power of the final prime mover. And of course, not only must the surrogate prime mover be over-rated in power, but so too must be the electronic motor drive, and the controls must be designed accordingly.

In this paper, we describe the design of a gas turbine emulator system that uses a vector controlled synchronous motor to emulate the speed-torque performance of a gas turbine engine, in simulation. Moreover, we define a power criterion for selecting this electric motor so that it can properly emulate the characteristics of a gas turbine prime mover. Frequency analysis, within the linear operation, is performed by obtaining the bode plots of the gas turbine and gas turbine emulator using system identification techniques. This frequency analysis as well as the ratio of the inertias of the intended prime mover and the surrogate prime mover, defines a power criterion for selecting the electric motor used in the gas turbine emulator.

GAS TURBINE EMULATOR

The gas turbine emulator system is shown in simplified form in Fig. 1 and it is implemented in simulation as a vector-controlled synchronous motor using a gas turbine observer that provides the appropriate speed reference. The synchronous motor drives a six-phase synchronous generator in simulation.

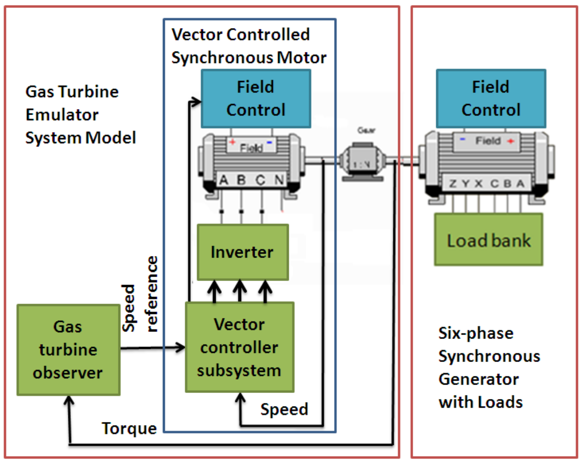

Figure 1. Schematic of gas turbine emulator system considering a generator as a load

This system model is implemented in the Virtual Test Bed software (Dougal, Lovett, Monti and Santi 2001) as shown in Fig. 2. Since the actual synchronous motor that will be used is capable of running up to only half of the speed of the gas turbine engine, it is connected to the synchronous generator by a gear box with a ratio of 1:2.

Gas turbine observer

A simple-cycle, two shaft gas turbine system model with intercooler is modeled in VTB as shown in Fig. 3. This system model is used as a reference speed observer in the gas turbine emulator system. This approximate gas turbine model is based on mechanical and thermodynamical equations (Gerhart, Gross, Hochstein 1992), (Moran, Shapiro, Hochstein 2000). The fuel input is modulated by a speed controller in order to maintain a constant speed under varying loads.

Vector controller

The vector control scheme for the drive motor is shown in Fig. 4. : The output of the outer loop of the two-loop structure establishes the reference value of the electromagnetic torque, Te, needed to control the speed and the inner current control loop tries to follow the reference currents produced by the outer loop. The speed tracking controller uses a proportional-integral strategy that was designed according to the double ratios rule (Vukosavić 2007). The rule is focused on extending the range of frequencies where the amplitude of the closed-loop transfer function remains unity. This value is frequently referred to as the absolute value optimum. As a result, the bandwidth frequency is increased yielding a fast step response with sufficient damping. The constants of the proportional-integral controller are given as

$$K_P^{opt} = \frac{J_M}{2\tau_{TA}} \tag{1}$$

$$K_I^{opt} = \frac{J_M}{8\tau_{TA}^2} \tag{2}$$

, where J_M is the synchronous motor inertia and τ_{TA} is a time constant, which is related to the stator inductance and resistance of the motor.

Speed-torque performance of the gas turbine emulator

Fig. 5 compares the speed-torque characteristic of the gas turbine with that of the gas turbine emulator superimposed at 754 rad/s, 854 rad/s and 954 rad/s. In both cases, the speed begins to decrease once the fuel supply reaches its limit just after the engine has reached its maximum output power. In this simulation test the synchronous motor was assigned an inertia of 10 kg*m^2 and the gas turbine was assigned an inertia of only 1 kg*m^2. Although both of these numbers are artificially low, it can be seen that both machines have similar performances.

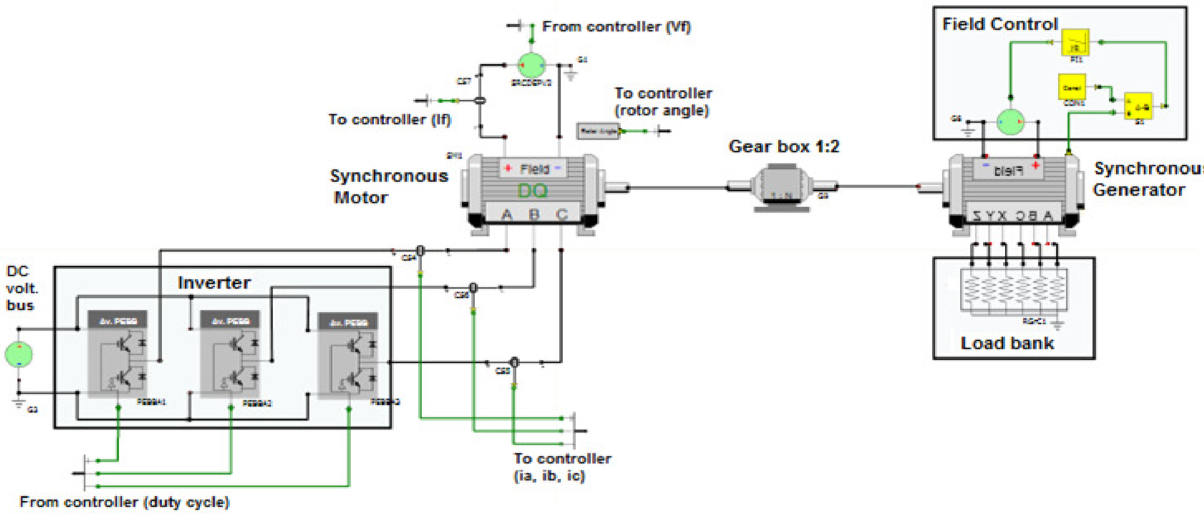

Figure 2. VTB model of synchronous motor connected to synchronous generator

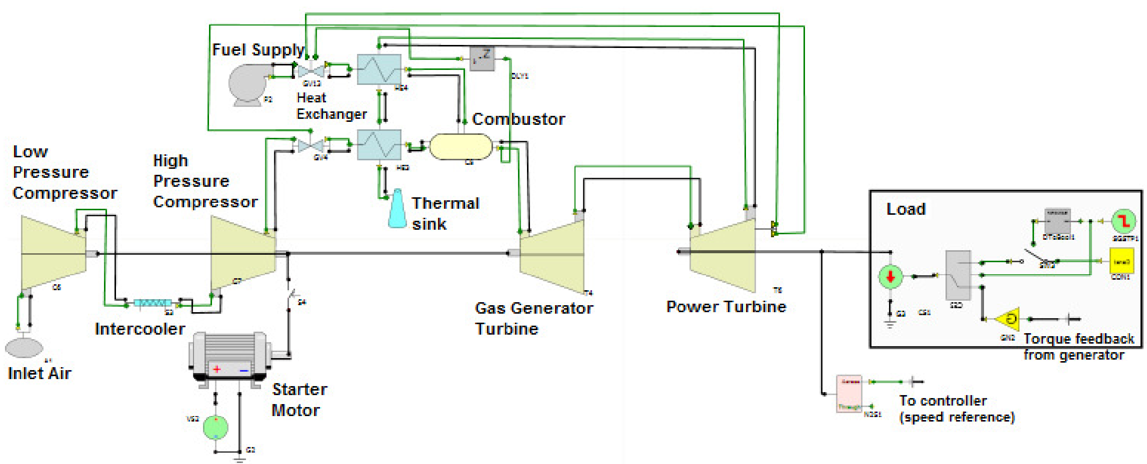

Figure 3. VTB implementation of gas turbine system model

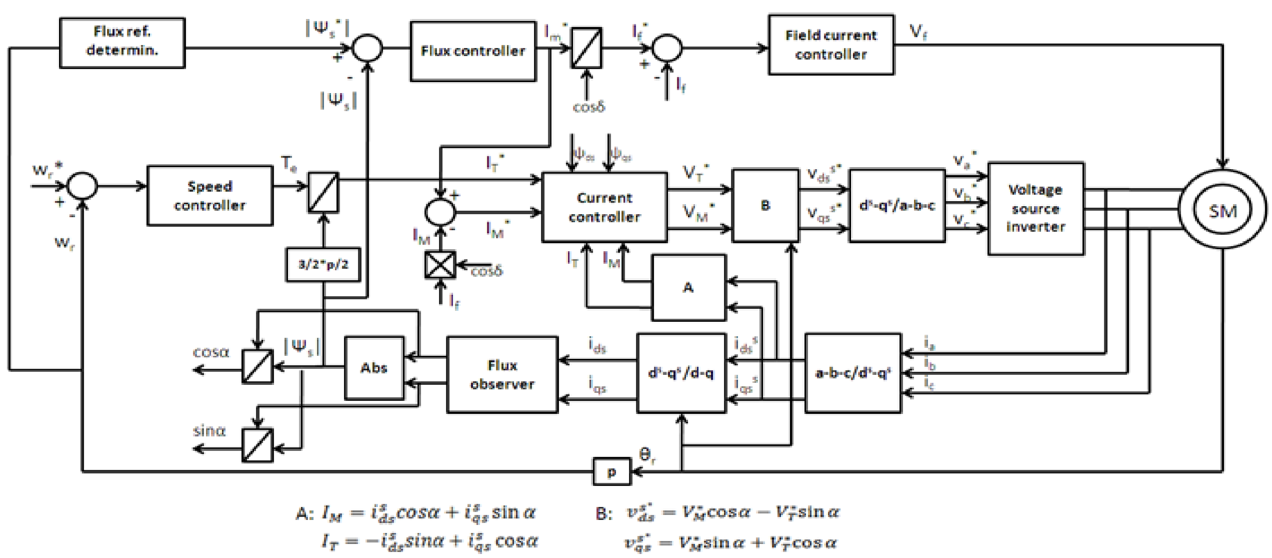

Figure 4. Schematic of the synchronous motor vector control

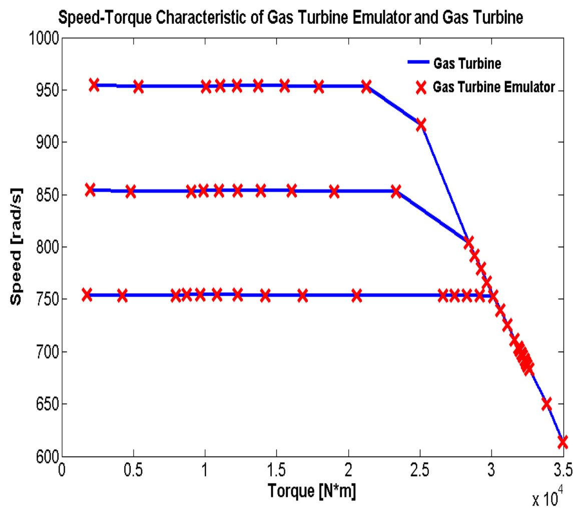

Figure 5. Comparison of speed-torque characteristic of gas turbine engine and gas turbine emulator

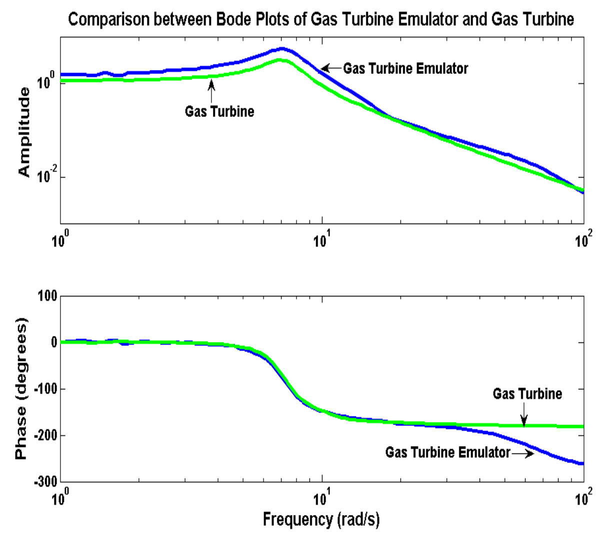

Figure 6. Comparison between Bode plots of gas turbine emulator and gas turbine

FREQUENCY ANALYSIS

System identification is the process by which models are constructed or fitted to experimental data. This data consists mainly of the records of input and output variables that are obtained at a quasilinear operating point of the system (Franklin, Powell, Workman 1997). The Bode plot of the gas turbine and gas turbine emulator were obtained by using a chirp input signal.

Fig. 6 shows the frequency response of the gas turbine emulator compared to the frequency response of the gas turbine. The gas turbine emulator is able to track the gas turbine over a bandwidth of 20 Hz. As can be seen the crossover frequency of the gas turbine is 7 Hz. Fig. 7 shows the frequency response of the vector controlled synchronous motor without the gas turbine observer. It can be appreciated that the frequency response is much faster than that of the gas turbine since the crossover frequency is 70 Hz.

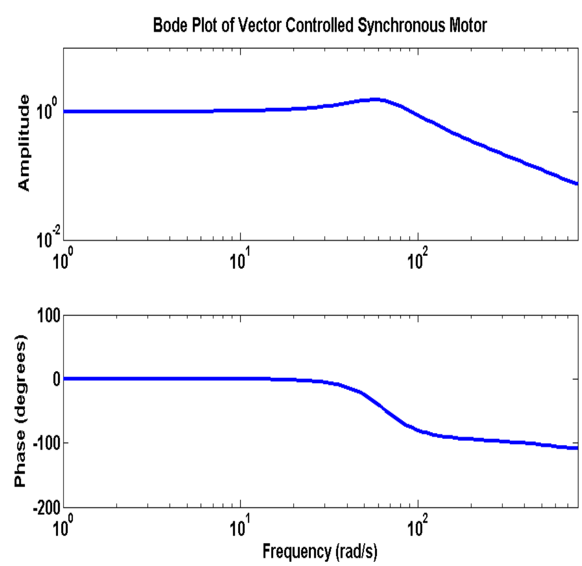

Figure 7. Bode plot of vector controlled synchronous motor

POWER CRITERION

The power criterion for selecting a motor to emulate the performance of an arbitrary prime mover is derived from the torque equations defined for the surrogate prime mover, Eqn. 3, and gas turbine, Eqn. 4. The accelerating torques of the gas turbine and surrogate prime mover are equated, to yield Eqn. 5. If rotating losses are not considered, the key result is that the power requirement is not $P_e = P_{Load}$, but is instead, approximately dependent on the inertia ratio between the surrogate prime mover and the gas turbine as defined by Eqn. 5. The terms in Eqn. 3, 4 and 5 are defined in Table 1.

$$T_E = J_E \frac{d\omega_E}{dt} + B_E \omega_E + T_L \qquad (3)$$

$$T_{GT} = J_{GT} \frac{d\omega_{GT}}{dt} + B_{GT} \omega_{GT} + T_L \qquad (4)$$

$$P_E = P_{GT} \frac{J_E}{J_{GT}} \qquad (5)$$

More precisely, if rotating losses are considered, the expression becomes ($\omega = \omega_E = \omega_{GT}$)

$$P_E = P_{GT} \frac{J_E}{J_{GT}} + \left(\frac{B_E}{B_{GT}} - \frac{J_E}{J_{GT}}\right) B_{GT} \omega^2 + \left(1 - \frac{J_E}{J_{GT}}\right) T_L \omega \qquad (6)$$

TABLE 1

Parameter definitions of Eqn. 3, 4 and 5

Parameter name	Parameter definition
T_E	Surrogate prime mover torque
T_{GT}	Gas turbine torque
J_E	Surrogate prime mover and load inertia
J_{GT}	Gas turbine and load inertia
B_E	Surrogate prime mover damping coefficient
B_{GT}	Gas turbine damping coefficient
ω_E	Surrogate prime mover speed
ω_{GT}	Gas turbine speed
T_L	Load torque
P_E	Surrogate prime mover power
P_{GT}	Gas turbine power

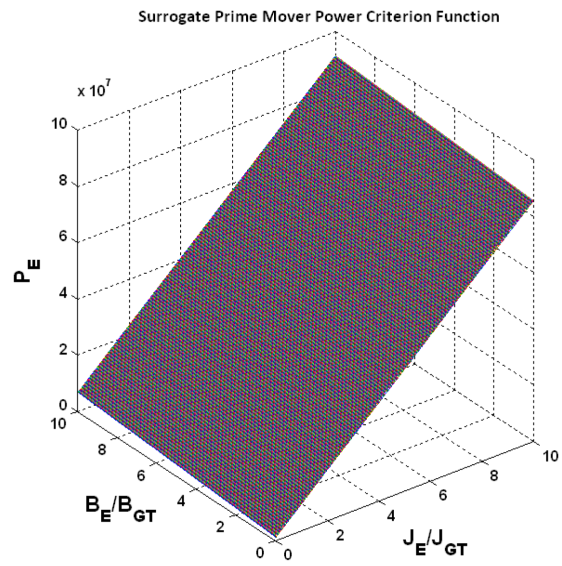

Figure 8. Surrogate prime mover power criterion function plotted parametrically in terms of the ratio of inertias and damping coefficients

Eqn. 6 is plotted parametrically in terms of the ratios $\frac{J_E}{J_{GT}}$ and $\frac{B_E}{B_{GT}}$ in Fig. 8. The ratios between inertias and damping coefficients are varied between 0.01 and 10, and P_{GT} = 10E7 W, B_{GT} = 1 N*s/m, ω=754 rad/s and T_L=1300 N*m. If the ratios between inertias and damping coefficients are unity then the power of the surrogate prime mover equals the power of the final prime mover. The maximum power is obtained when the ratios between inertias and damping coefficients are 10. Therefore, if the inertia of the surrogate prime mover is ten times larger than the inertia of the final prime mover then the power requirement of the surrogate prime mover is almost ten times that of the final prime mover.

CONCLUSION

This paper presented the design of a system that emulates the performance of a gas-turbine prime mover by using a vector controlled synchronous motor. This work demonstrated, in simulation, that the steady-state response of the gas turbine emulator matches that of the gas turbine engine. It is also demonstrated that, within the linear region, the frequency response of the gas turbine emulator matched that of the gas turbine very well. One important criterion for good matching is that the speed response of the vector controlled synchronous motor is faster than the gas turbine response even if the natural response of the synchronous motor is slower. More power must be supplied to the gas turbine emulator in order for this to happen. Therefore, a power criterion for selecting an electric motor to emulate the characteristics of a gas turbine prime mover was been defined in terms of the inertia ratio, rotating losses and the load torque.

REFERENCES

Boulter, B. T., "Designing a Dynamometer Test Stand with an Emulated Gasoline/Diesel Engine Power Source: A White Paper," Paper No. 13. ApICS LLC 2000.

Chinchilla, M., S. Arnaltes, and J.L. Rodrigues-Amenedo, "Laboratory Set-up for Wind Turbine Emulation," Proc. of 2004 IEEE International Conference on Industrial Technology, Hammamet, Tusinia, vol. 1, pp 553-57, December 2004.

Dolan, D. and P. W. Lehn, "Real-Time Wind Turbine Emulator Suitable for Power Quality and Dynamic Control Studies," Proc. of International Conference on Power Systems Transients, Montreal, Canada, pp. 1-6, June 2005.

Dougal, R. A., T. Lovett, A. Monti, and E. Santi, "A Multilanguage Environment for Interactive Simulation and Development of Controls for Power Electronics," IEEE PESC, Vancouver, Canada, vol. 3, pp. 1725 – 1729, 2001.

Franklin, G. F., J. D. Powell and M. L.Workman, Digital Control of Dynamic Systems, 3rd ed. Prentice Hall, 1997.

Gerhart P.R., R.J. Gross, J.I. Hochstein, Fundamentals of Fluid Mechanics, 2nd ed. Addison-Wesley, 1992.

Moran, M.J., H.N. Shapiro, J.I. Hochstein, Fundamental of Engineering Thermodynamics, 4th ed. John Wiley & Sons, 2000.

Vukosavić, S. N., Digital Control of Electrical Drives, 1st ed. Springer, 2007.

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