Appendix D

Under-Frequency and Over-Temperature Protection of Gas-Turbine Driven Generators

When a large increase in active power is applied to a gas-turbine driven generator two important transient responses occur. Firstly the shaft speed and hence the system frequency decreases, which happens at a rate mainly determined by the total moment of inertia of the rotating masses in the gas turbine and the generator, and the magnitude of the change in power. Initially the fuel valve does not change its state because the feedback of the speed change takes time to be detected and amplified. The gas turbine initially responds in its open-loop control mode. After a short delay the fuel valve responds and allows more fuel to be burned in the combustion chamber. Hence the combustion or 'operating' temperature increases and more power is delivered to the shaft. Closed-loop control action is applied to the fuel valve, whilst the valve stem is within its limiting positions.

If the increase in active power is small then the change in the valve stem position will also be small and will remain within its limits. In this situation the response of the frequency and temperature will be an initial overshoot followed by a convergence to a new steady state. The response may exhibit some oscillatory behaviour, depending upon the amount of forward gain and feedback damping used in the control system.

If the increase in active power is large then the change in the valve stem position will also be large, and may be large enough for it to reach its upper hard limit. When the valve is fully open it will pass a finite amount of fuel. The operating temperature will reach its maximum possible value, which will be above its preset shutdown or tripping value. No closed-loop control action can take place unless the power generated by the limited fuel is enough to recover the shaft speed. If the speed recovers sufficiently to be within the limits of the control system, then the fuel valve will be corrected by the necessary feedback control action.

Figures D.1 through D.6 show the responses described above. Figures D.1–D.3 apply to a single-shaft gas-turbine generator rated in the order of 5 MW. Figures D.4–D.6 apply to a two-shaft gas-turbine generator that has a similar rating. The results shown are derived from the control system diagrams in Figures 2.16 and 2.17. In general the single-shaft machine is more responsive, and is more tolerant of the larger changes in power. However, the excursions of operating temperature are greater. The excursions of temperature in the two-shaft machine are smaller due to the intervention of the 'least signal selector' safety control system. In all of the 11 cases considered the single-shaft

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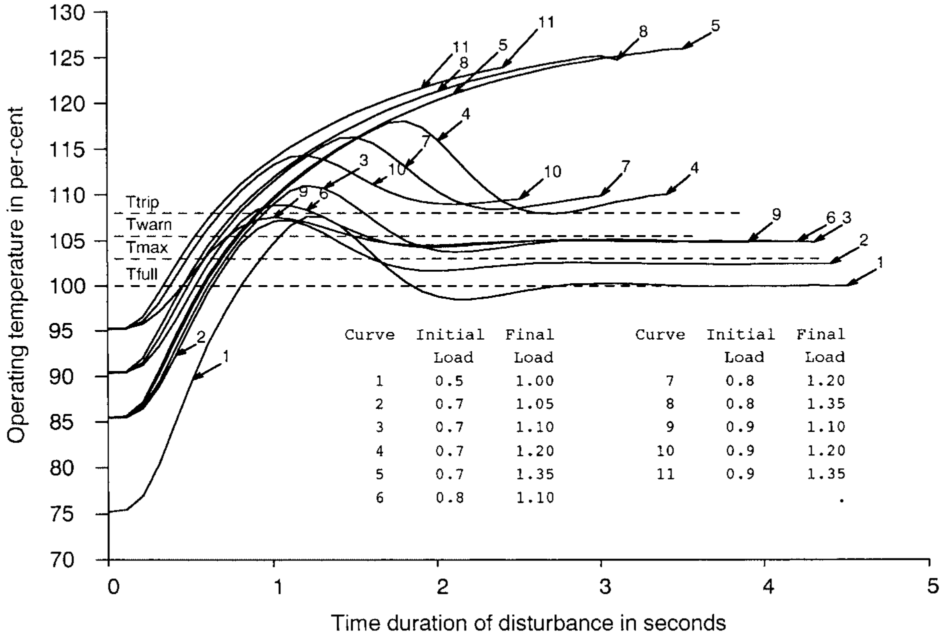
machine recovers its shaft speed and system frequency. Note that some of the larger disturbances would not normally occur in a practical power system, but are included to illustrate and compare the operation of the control systems involved. The two-shaft machine exhibits a wider deviation in shaft speed and system frequency than the single-shaft machine, and generally takes longer to recover. This illustrates the customarily held view that a single-shaft machine has a more superior performance than a two-shaft machine for electrical power applications.

Typical alarm and tripping limits are also shown in Figures D.1 and D.4. The single-shaft machine reaches these limits generally faster than the two-shaft machine, again due to the effect of the 'least signal selector' safety control system. The trip setting for the over-temperature limit for the two-shaft machine is seen to be rather sensitive due to the 'flat' shape that follows the initial response. The warning alarm for the two-shaft machine is reached in about twice the time taken for the single-shaft machine.

Figures D.3 and D.6 show the responses of frequency in the first one second. Both machines respond in much the same way in the first half second. This is due to the fact that this part of the response is 'open loop' and is mainly determined by the mechanical inertia and the size of the disturbance, as discussed in Chapter 21 of Reference 1; see also sub-section 2.5 herein. Also shown in these two figures are typical setting levels for underfrequency (81) multi-stage relays. In addition to the setting levels the relays should also have time delay settings, so that coordination with other power system equipment can be achieved, e.g. automatic voltage regulators of generators, automatic re-acceleration of induction motors, see also sub-section 7.6 herein. For the settings shown the relays would respond in the range of about 70 to 150 milliseconds, which is typically about half the response



Curve	Initial Load	Final Load	Curve	Initial Load	Final Load
1	0.5	1.00	7	0.8	1.20
2	0.7	1.05	8	0.8	1.35
3	0.7	1.10	9	0.9	1.10
4	0.7	1.20	10	0.9	1.20
5	0.7	1.35	11	0.9	1.35
6	0.8	1.10			

Figure D.1 Over-loading a single-shaft gas-turbine generator. Operating temperature versus time.

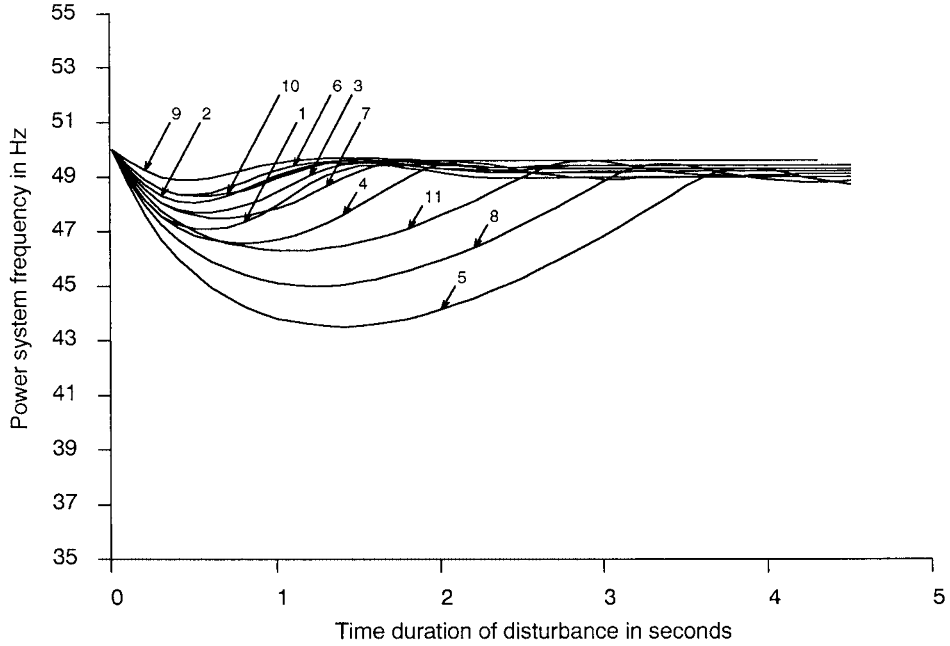


Figure D.2 Over-loading a single-shaft gas-turbine generator. Power system frequency versus time.

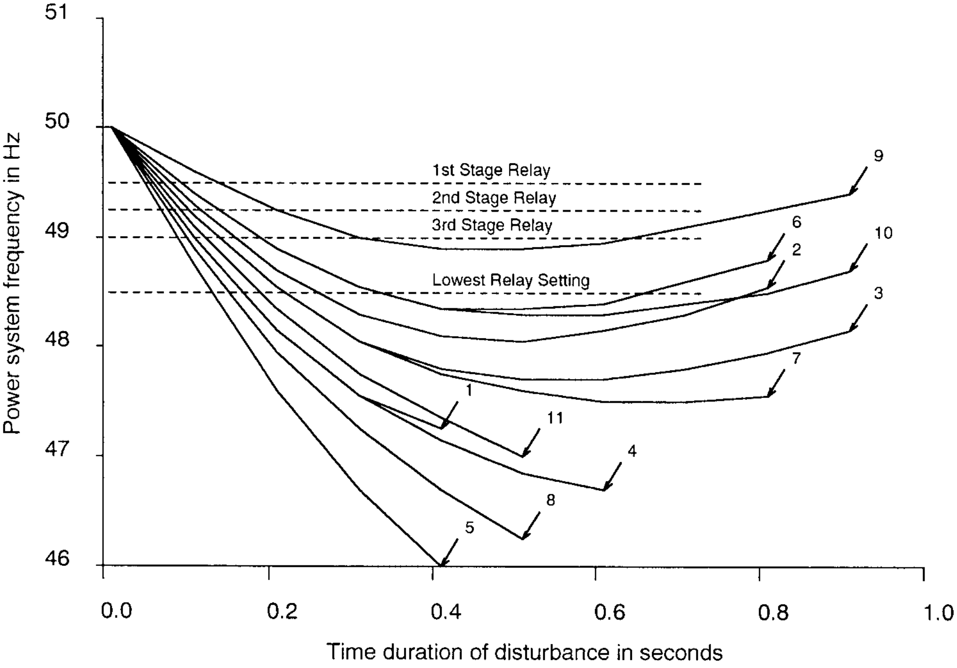
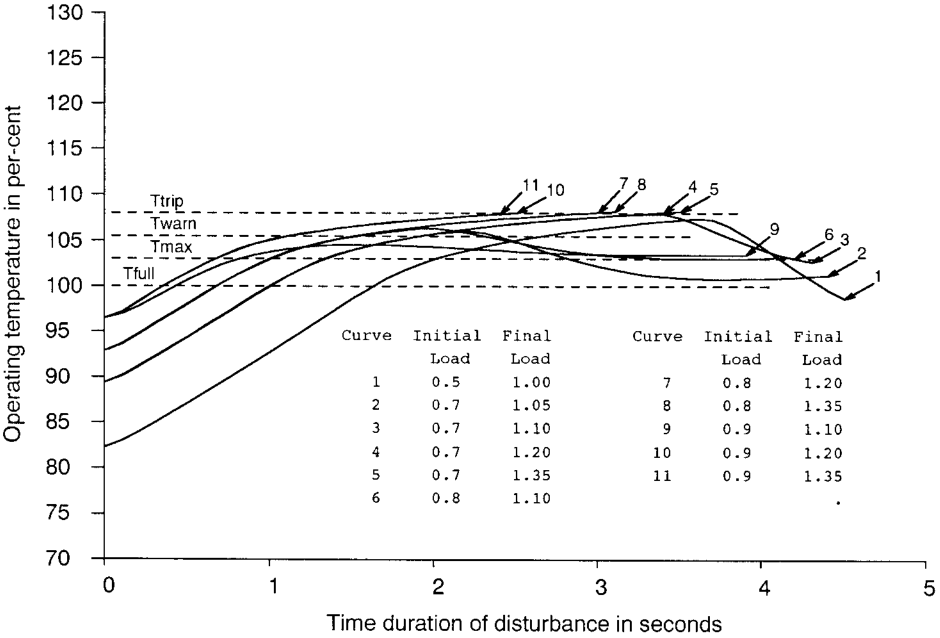


Figure D.3 Over-loading a single-shaft gas-turbine generator. Power system underfrequency relay settings.



Curve	Initial Load	Final Load	Curve	Initial Load	Final Load
1	0.5	1.00	7	0.8	1.20
2	0.7	1.05	8	0.8	1.35
3	0.7	1.10	9	0.9	1.10
4	0.7	1.20	10	0.9	1.20
5	0.7	1.35	11	0.9	1.35
6	0.8	1.10			.

Figure D.4 Over-loading a two-shaft gas-turbine generator. Operating temperature versus time.

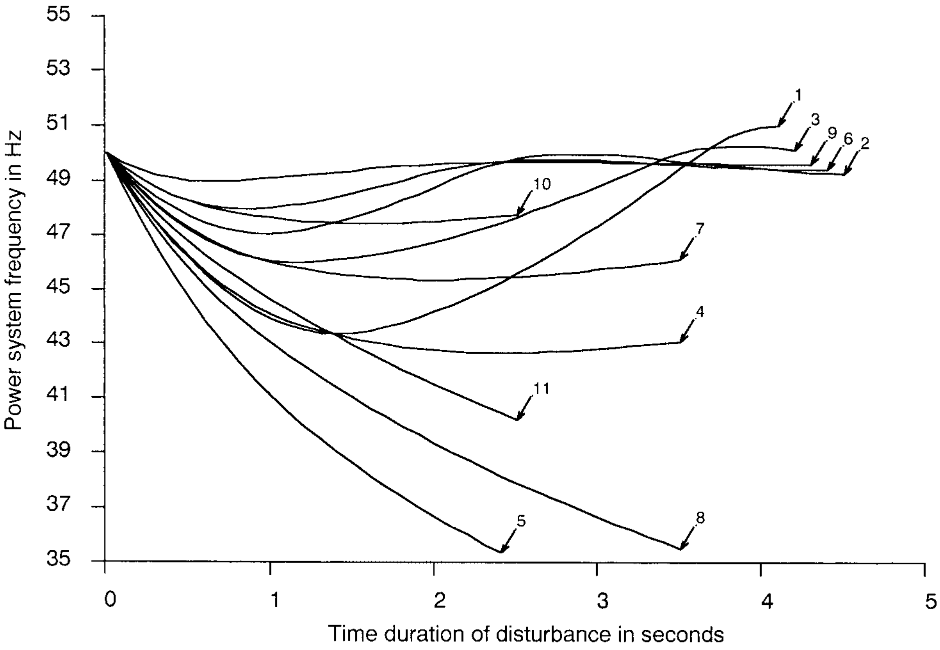


Figure D.5 Over-loading a two-shaft gas-turbine generator. Power system frequency versus time.

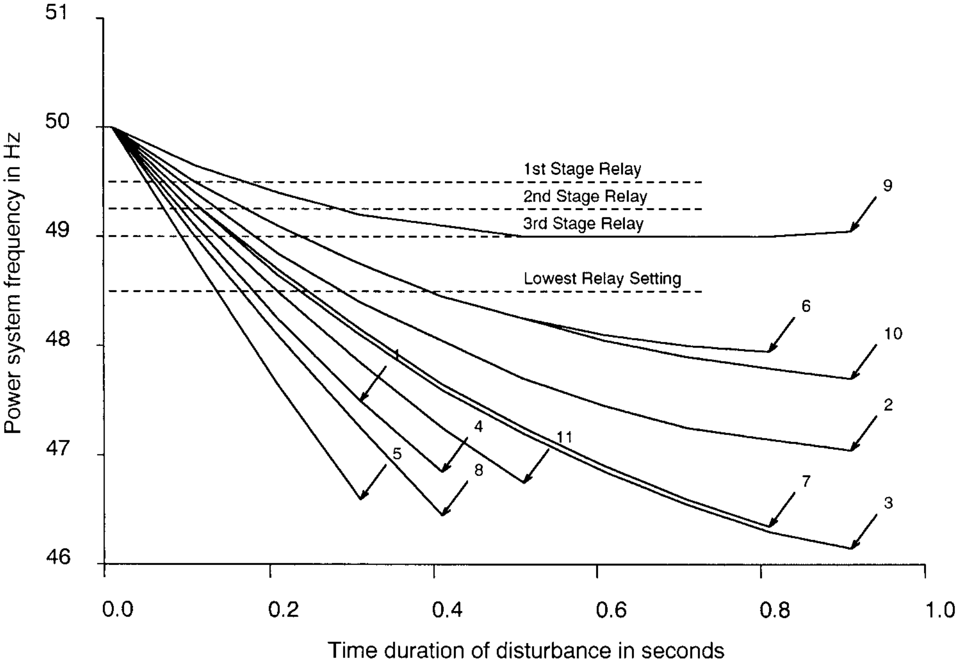


Figure D.6 Over-loading a two-shaft gas-turbine generator. Power system underfrequency relay settings.

time of the over-temperature alarms. Hence there is an implied relationship between underfrequency and over-temperature protection of the power system. When the power system is being designed, and the protection systems established, these two functions should be treated in a coordinated manner, so that the best overall performance is obtained.

REFERENCE

1. Applied protective relaying. Westinghouse Electric Corporation, 1976 Relay-Instrument Division, Newark, NJ 07101. Library of Congress Card No. 76-8080.