5

On-off Control of a Damper

… in which energy functions and phase plane plots replace modal analysis as general tools for damping assessment and controller design.

In order to study the practical problems of load control damping, a field test was planned. The scope was limited to damping of a local mode, which is a suitable first step as it involves only a single machine. Provided that the control signal magnitude is appropriate, *on-off control* can be applied to damping of electro-mechanical oscillations. It requires less sophisticated power electronics than continuous control and is therefore used in the field test. The natural feedback signal is the rotor angular velocity of the machine, but it is difficult to measure. Instead estimated mode frequency as described in Section 4.5 is chosen for the experiment. In a single machine infinite bus system this signal is an estimate of the machine frequency. The analysis in this chapter assumes perfect agreement between estimate and machine frequency so that the latter can be considered available as feedback signal.

Because of its nonlinear nature, on-off or *relay* control requires other methods than those presented in the previous chapters. The necessary analysis tools are presented in this chapter, which thus lays the theoretical foundation for the field test.

Section 5.1 introduces an *energy function*, that can quantify damping caused by *any* control action. The efficiency of damper windings and of a relay controlled active load are shown for a single machine-infinite bus system. *Phase plane plots* are used in Section 5.2. to describe the behaviour of the nonlinear system with relay feedback. At a laboratory test the controller enters a limit cycle. The condition for a limit cycle-free equilibrium is determined. At the field test it became apparent that the procedure for relay parameter selection resulting from the previous analysis was not practically useful. Section 5.3 presents a more realistic procedure that was later designed.

5.1 Energy Function Analysis

The influence of damping can be demonstrated by the use of *energy functions* or Lyapunov functions that quantify the swing energy of the system. A proper energy function can give a qualitative answer to questions such as: is the system stable at this operating point? By formulating the energy function for a marginally stable system, it can help to determine if a certain control action will stabilize the system. Energy function analysis can handle both nonlinear control laws and nonlinear power system models and finds its use mainly in transient stability analysis or *large disturbance stability analysis*. Linear analysis is restricted to *small disturbance stability analysis*, but when it is valid it provides decoupling of the dynamics into modes. As shown in Chapters 3 and 4, it gives quantitative information about where to locate sensors and actuators. Examples of energy functions can be found in [Gronquist et al 1995], [Hiskens and Hill 1992] and [Stanton and Dykas 1989].

Entering the parameters of the single machine system of Fig. 2.4 with no load into the energy function in [Stanton and Dykas 1989] gives,

$$V = \frac{H}{\omega_R}\dot{\delta}^2 - P_m\left(\delta - \delta^0\right) - \frac{EV_\infty}{X'_d + X_t + X_{tl}}\left(\cos\delta - \cos\delta^0\right) \qquad (5.1)$$

δ^0 is the machine angle value at the equilibrium. When the system is at rest V is zero, while an undamped oscillation gives a constant value greater than zero. A control action that contributes to damping is characterized by its ability to make V decrease.

The active power consumed by damper windings or a damping controller can be introduced as P_d in the single machine model of (2.18),

$$\frac{2H}{\omega_R}\ddot{\delta} = P_m - \frac{EV_\infty}{X'_d + X_t + X_{tl}}\sin\delta - P_d \qquad (5.2)$$

where the load bus has been eliminated. Taking the time derivative of (5.1) and inserting (5.2) yields,

$$\dot{V} = \dot{\delta}\left[\frac{2H}{\omega_R}\ddot{\delta} - P_m + \frac{EV_\infty}{X'_d + X_t + X_{tl}}\sin\delta\right] = -P_d\dot{\delta} \qquad (5.3)$$

Equation (5.3) states that if P_d has the same sign as the velocity deviation $\Delta\omega=\omega-\omega_R$, the system will be damped. This verifies that damper windings, often modelled as $P_d=D\Delta\omega$, have a positive effect on damping. The additional active power γP_L drawn from the generator by a load P_L, can be approximately represented by P_d. According to (5.3), switching the load on and off in phase with the velocity deviation will also improve damping. This control can be performed by a relay that switches the load at certain levels of $\Delta\omega$, possibly with hysteresis as in Fig. 5.1.

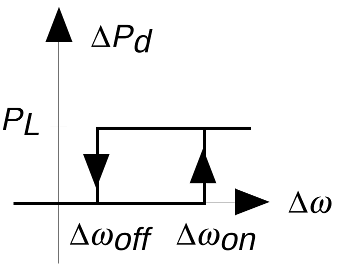

Fig. 5.1 Relay characteristics.

Relay controllers have a number of properties, that are different from linear controllers. The relay uses the entire rating of the actuator at each control action. This leads to fast damping of small deviations, as the control signal magnitude depends only on the sign and not on the magnitude of the deviation. A stable equilibrium point in the linear case requires a suitable gain to be selected using eigenanalysis. For the relay, the level $\Delta\omega_{on}$, below which no measures are taken, needs to be set. This level is usually selected using empirical methods and numerous simulation runs. As an alternative, Section 5.2 shows how a general technique for nonlinear dynamic systems can be used to analyse the properties of the equilibrium point and how to select $\Delta\omega_{on}$ for the single machine system.

5.2 Phase Plane Analysis

A general tool for analysis of data from simulations of second order nonlinear dynamic systems is the phase plane plot. It shows the trajectory of one state as function of the other. As relay characteristics can be included in the phase plane plot, it is the perfect tool for analysis of relay feedback and will be the basis for all analysis in the following.

Switching the Load On and Off

The relay can turn an active load on and off. Fig. 5.2 shows plots from two simulations in Simulink [Simulink] of the single machine system. The generator is considered connected to a two-pole. The load is modelled as an impedance that is incorporated in the two-pole equivalent leading to two sets of two-pole parameters depending on if the load is on or off.

In the first case (solid lines) a load of 20 kW is suddenly added, while in the other (dashed lines) the load is removed. Note that both simulations start at steady state and that the added load actually leads to a value δ_1 that is smaller than that without the load δ_0.

The lower left and upper right graphs of Fig. 5.2 show machine angle δ in *rad* and the velocity deviation $\Delta\omega$ in *rad/s*, as functions of time (Note the different directions of the time axes). Plotting these two quantities against each other, yields the phase plane plots to the upper left. These plots have time as an implicit parameter and their direction is clockwise. The energy function V performs a step as the loading situation is changed. After time zero, no swing energy is removed from the system, which is then said to be *conservative*. The load switching causes $\Delta\omega$ to peak at 0.034 rad/s.

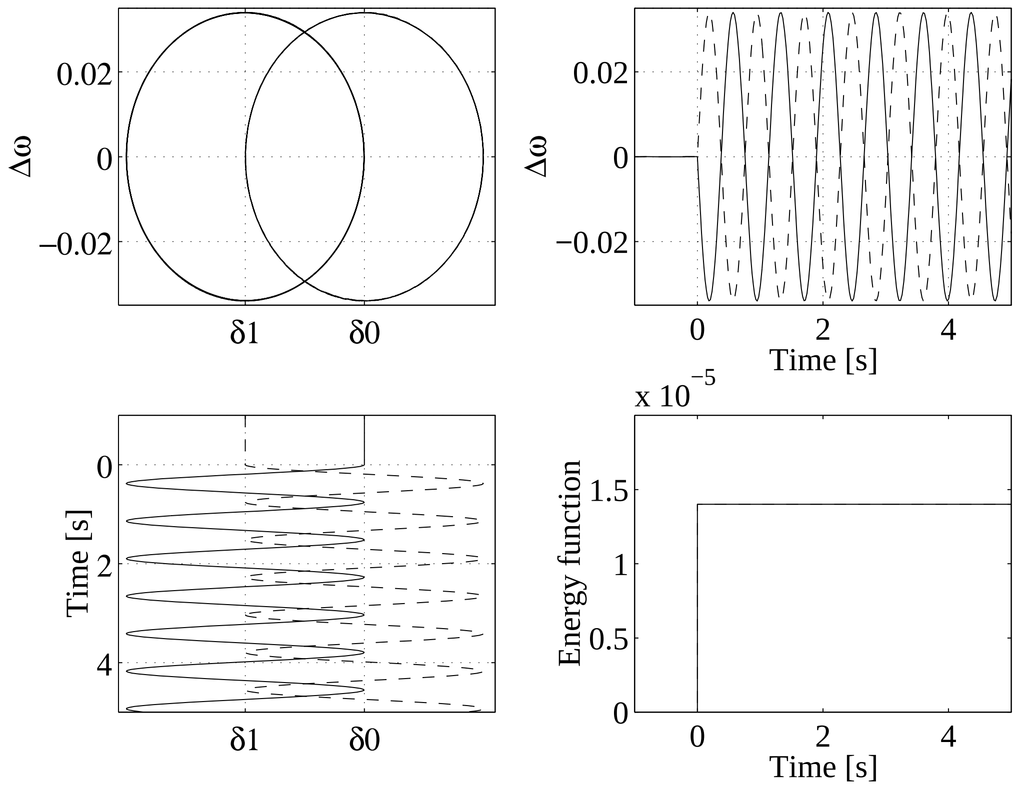

Fig. 5.2 From upper left to lower right: phase plane plots, time histories of the states and energy function for sudden load increase (solid) and decrease (dashed). The identities of the phase plane plots are determined from the time histories of the states.

Effect of Damper Windings

As mentioned, damper windings can be added to the undamped system as $P_d=D\Delta\omega$. Fig. 5.3 shows a simulation of load increase and decrease with D=3 p.u./p.u. The energy function now decreases and indicates that the system is *dissipative*, as swing energy vanishes.

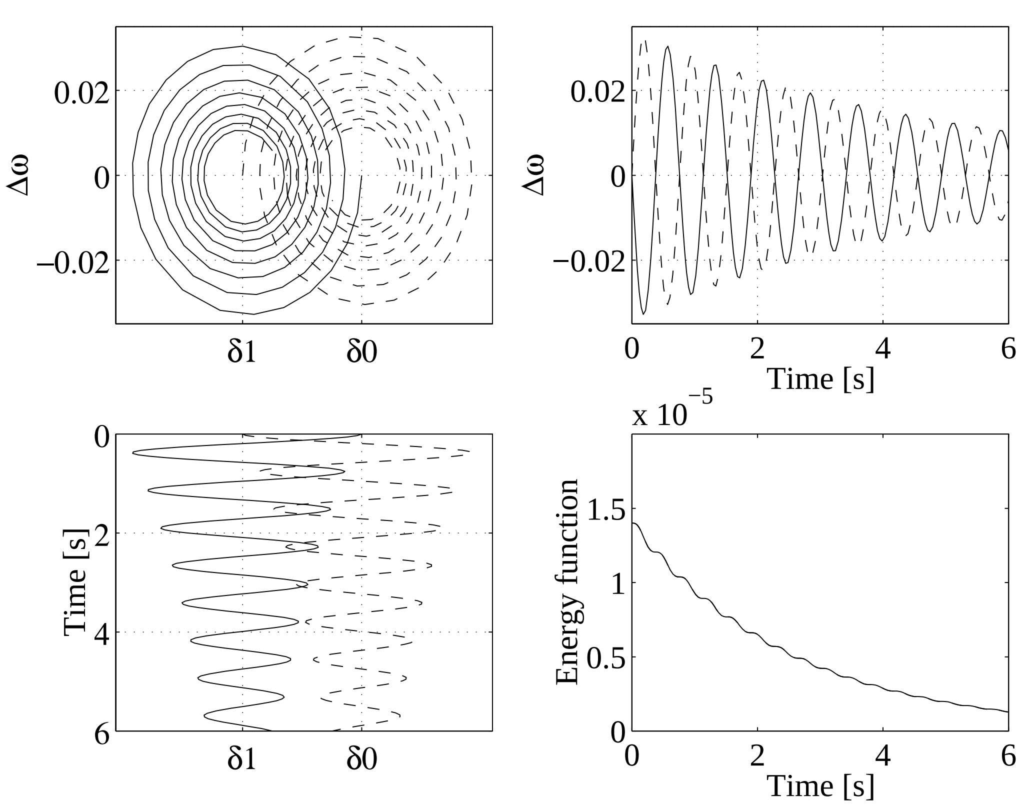

Fig. 5.3 From upper left to lower right: phase plane plots, time histories of the states and energy function for sudden load increase (solid) and decrease (dashed) for system with damper windings.

Relay Feedback

If the load P_L is controlled in accordance with $\Delta\omega$ it will add damping. The characteristics of the relay that can perform this action can easily be included in the phase plane plot: when the relay turns the load on and off, it selects one of the steady state values δ_0 and δ_1 as points around which the system orbits. The load should be turned on at $\Delta\omega_{on}$ and off at $\Delta\omega_{off}$, which both can be drawn as horizontal lines. By noting that the direction of motion in the plot is clockwise, it is realised that the load should be turned on when passing $\Delta\omega_{on}$ upwards, and turned off when passing $\Delta\omega_{off}$ downwards.

Assume that there is no time delay and use $\Delta\omega_{off}$=0 and $\Delta\omega_{on}$=0.05, which is larger than 0.034. Starting from the state [$\Delta\omega$ δ]=[0 0.9δ_0], Fig. 5.4 shows that $\Delta\omega$ is damped until its amplitude is less than $\Delta\omega_{on}$.

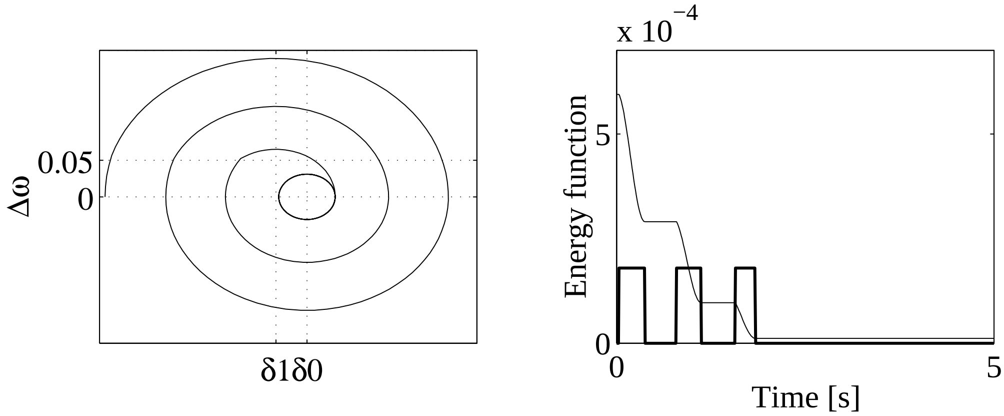

Fig. 5.4 Relay controlled system with $\Delta\omega_{on}$ =0.05 rad/s and $\Delta\omega_{off}$=0. Phase plane plot (left) and energy function (right) with switching actions (wide) indicated (not to scale).

$P_e(t)$ from the same simulation is shown in Fig. 5.5 and demonstrates the desired performance of an on-off controlled damper.

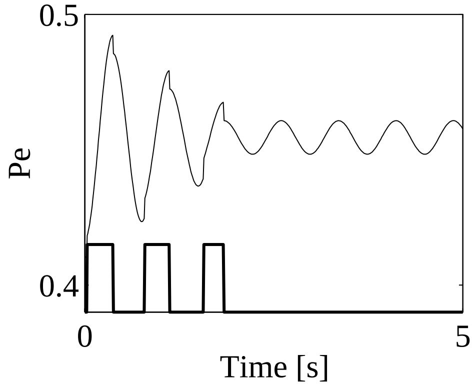

Fig. 5.5 Relay controlled system with $\Delta\omega_{on}$ =0.05 rad/s and $\Delta\omega_{off}$=0. Electrical output of generator with switching actions (wide) indicated (not to scale).

Each switching of P_L, both on and off, reduces the amplitude of P_e with γP_L, where γ is the fraction of P_L taken from the generator. The factor γ is determined from (5.4), which indicates that in order to be effective, P_L should be electrically close to the machine,

$$\gamma = \frac{x}{x + x'} \tag{5.4}$$

The system with relay feedback is nonlinear, which is indicated by the envelope of P_e: it decreases linearly rather than exponentially as the relay feedback removes a constant amount of swing energy each swing period. If the relay is the dominating source of damping, the slope of the P_e envelope is constant and can be used a measure of damping.

If $\Delta\omega_{on}$ is chosen too small, γP_L will finally become larger than P_e and reverse the phase of the oscillation. Fig. 5.6 shows a simulation with $\Delta\omega_{on}$=0.01 rad/s. The system settles down after a sequence of switchings, that are considerably faster than the period of the undamped oscillation.

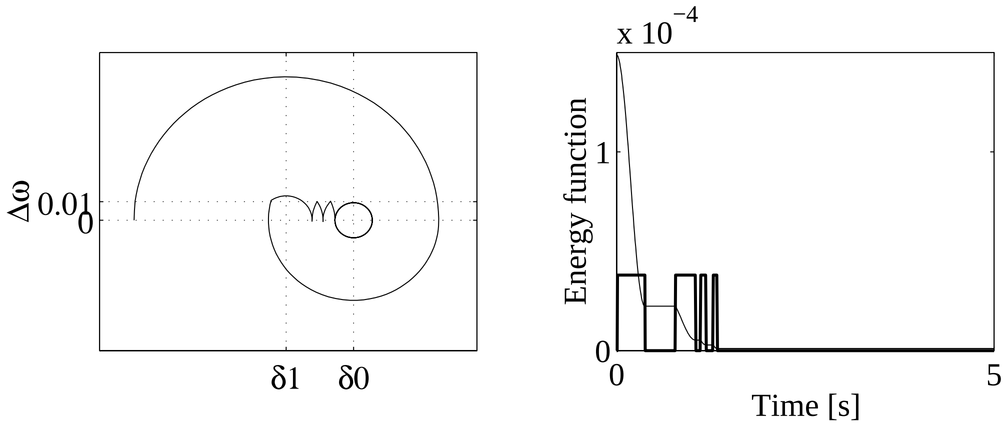

Fig. 5.6 Relay controlled system with small $\Delta\omega_{on}$ and $\Delta\omega_{off}$=0. Phase plane plot (left) and energy function (right) with switching actions (wide) indicated (not to scale).

Effect of a Delay

The fast switching caused by a small value of $\Delta\omega_{on}$ makes the system more susceptible to time delays introduced by for example low pass filters. Fig. 5.7 illustrates the influence on the previous case of a 50 ms time constant inserted before the relay input. While the delay leaves the behaviour for $\Delta\omega_{on}$=0.05 practically unaffected (not shown), the system here enters a stable limit cycle, leading to unnecessary switchings. This was experienced in the laboratory testing of the field test equipment. It is evident that the limit cycle is disadvantageous and should be avoided.

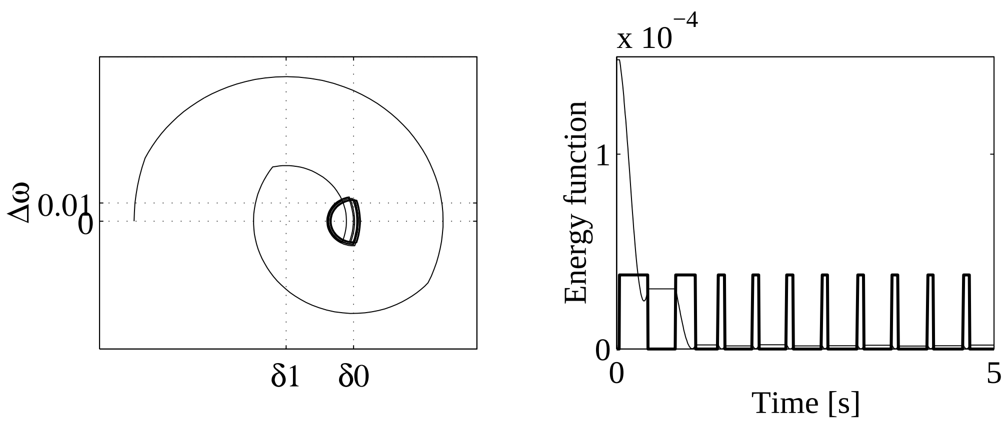

Fig. 5.7 Relay controlled system with small $\Delta\omega_{on}$, $\Delta\omega_{off}$=0 and time delay. Phase plane plot (left) and energy function (right) with switching actions (wide) indicated (not to scale).

5.3 Procedure for Selecting Relay Parameters

The first two simulations in Section 5.2 show that the control action itself gives rise to a $\Delta\omega$. If $\Delta\omega_{on}$ is set above this value $\Delta\omega_{on,min}$ (here 0.034 rad/s) fast switching and possibly a limit cycle can be avoided. The limit value is the magnitude of a step response – the result of a *single* switching. While thus being simple to determine in principle, the field test showed that in practice the velocity deviation $\Delta\omega_{on,min}$ is too small to be detected.

If the switching is instead repeated with the swing frequency of the system, the amplitude increases linearly with time as seen in Fig. 5.8.

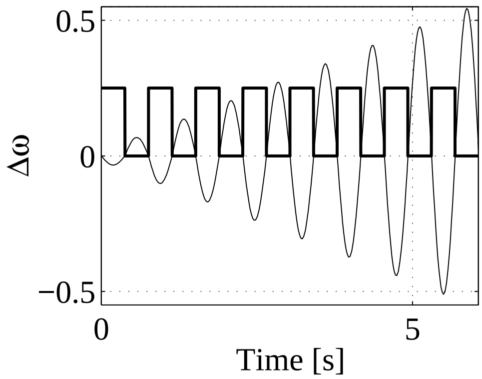

Fig. 5.8 Excitation through load switching without damper windings. Velocity deviation with switching actions (wide) indicated (not to scale).

This gives larger amplitudes, that are easier to measure. The $\Delta\omega_{on}$ limit is now simple to determine as,

$$\Delta\omega_{on,min} = \frac{\Delta\omega_m}{2N} \tag{5.5}$$

where $\Delta\omega_m$ is the oscillation magnitude after N switching periods. It is assumed that the excitation starts at steady state.

The behaviour of the system changes with the loading situation. For the simulated system, the difference in $\Delta\omega_{on,min}$ was 3 %, when changing from P_m=0 (0.0337 rad/s) to P_m=1 p.u. (0.0348 rad/s). Since $\Delta\omega_{on}$ is chosen with some safety margin to the limit value, this variation should not be a problem.

$\Delta\omega_{off}$ can be set to zero or to a small positive value to assure that no control action occurs at steady state.

Consequences of Damper Windings

The simulations of Section 5.2 are not influenced by the damping term, as it is very small close to the equilibrium. When it comes to exciting a larger oscillation to determine $\Delta\omega_{on,\mathrm{min}}$ more conveniently, the effect of damping is noticeable as illustrated by Fig. 5.9 where D is 3 p.u./p.u.

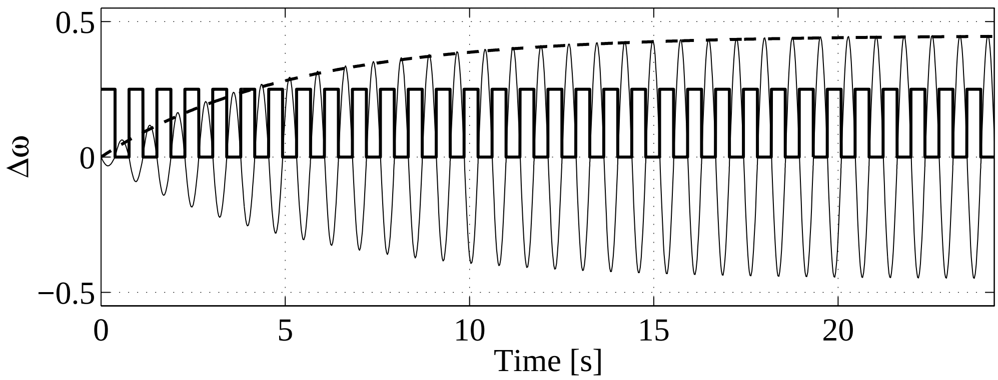

Fig. 5.9 Excitation through load switching with damper windings giving D=3 p.u./p.u. Velocity deviation with switching actions (wide) indicated (not to scale) and fitted exponential (dashed).

Provided the early part of the growing oscillation can be used, the damper effect can be ignored and (5.5) applies. The tangent of the envelope of $\Delta\omega$ at the start of the oscillation then replaces the true slope used when no damper windings are present.

If the initial part of the oscillation cannot be distinguished, the slope can be reconstructed from the dashed line in Fig. 5.9. It is a step response of a first order system with the time constant 2τ, where

$$\tau = \frac{2H / \omega_r}{D / \omega_r} = \frac{2H}{D} \tag{5.6}$$

The numerator in the first part of (5.6) is the gain from the input (active power) to the time derivative of $\Delta\omega$, while the denominator is the feedback gain D/ω_r. The use of twice the time constant stems from the fact that the variation of P_L is not symmetric around zero. Having determined τ, the limit value of $\Delta\omega_{on}$ can be expressed as,

$$\Delta\omega_{on,min} = \frac{\hat{\omega}}{2\,\tau f_{osc}} \tag{5.7}$$

where $\hat{\omega}$ is the stationary amplitude of $\Delta\omega$ and f_{osc} is the oscillation frequency. τf_{osc} is the number of switching periods in the time τ. This fact indicates the close relationship between (5.5) and (5.7).

5.4 Conclusions

The use of phase plane plots has proven useful, when studying relay feedback of the single mode system. The capability of an energy function to quantify the oscillation magnitude has also been illustrated. The simulations in this chapter treated temporary *connection* of an active load in Section 5.2 and temporary *disconnection* in Section 5.3. These two alternatives are equally effective, but if the load can both consume and generate active power, so that P_L can go both positive and negative, damping will be twice as fast.

The cases demonstrated here show the consequences of time delay and a too small value of the parameter $\Delta\omega_{on}$. As the time to perform a field test is very limited, it is very valuable to have identified possible problem such as these in advance.