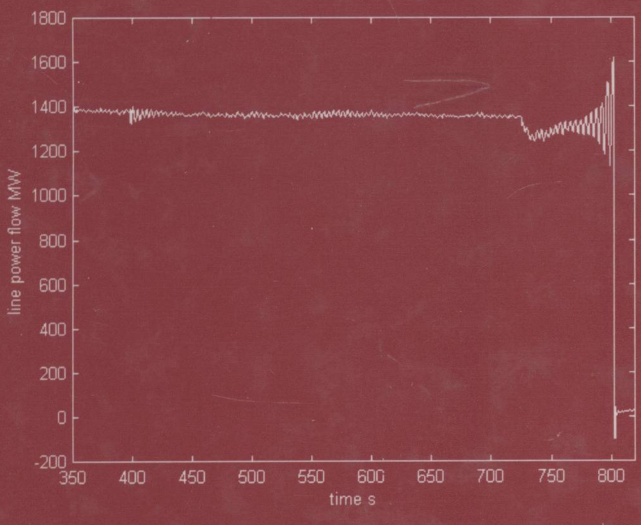
POWER SYSTEM OSCILLATIONS

Graham Rogers



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Graham Rogers
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Notice to Readers

I have prepared a CD_ROM containing the data and results for all examples used in this book. The data are in the form of MATLAB m-files, and the results are given as MATLAB binary files.

The CD_ROM is available, at cost. Please contact me at

Cherry Tree Scientific Software
RR#5 Colborne, Ontario, KOK 1S0
CANADA

or by email: cherry@eagle.ca

Graham Rogers

Dedication

I dedicate this book to Jean, my wife, best friend, and constant companion, who has sustained and supported me in my endeavours for so many years.

Contents

Chapter 1

Introduction

Electric power systems are among the largest structural achievements of man. Some transcend international boundaries, but others supply the local needs of a ship or an aeroplane. The generators within an interconnected power system usually produce alternating current, and are synchronized to operate at the same frequency. In a synchronized system, the power is naturally shared between generators in the ratio of the rating of the generators, but this can be modified by the operator. Systems, which operate at different frequencies, can also be interconnected, either through a frequency converter or through a direct current tie. A direct current tie is also used between systems that, while operating at the same nominal frequency, have difficulty in remaining in synchronism if interconnected.

Alternating current generators remain in synchronism because of the self-regulating properties of their interconnection. If one machine deviates from its synchronous speed, power is transferred from the other generators in the system in such a way as to reduce the speed deviation. The moments of inertia of the generators also come into play, and result in the speed overcorrecting in an analogous manner to a pendulum swinging about its equilibrium; the pendulum inertia is equivalent to the generator inertia, and the torque on the pendulum due to gravity is equivalent to the synchronizing torque between the generators in the power system. However, generators are much more complicated dynamic devices than are pendulums, and one must not be tempted to put too much emphasis on this analogy. However, it is true to say that power system oscillations are as natural as those of pendulums.

An interconnected power system cannot operate without control. This is effected by a combination of manual operator controls and automatic controls. The operators control the power that the generator supplies under normal operating conditions, and the automatic controls come into play to make the fast adjustments necessary to maintain the system voltage and frequency within design limits following sudden changes in the system. Thus, most generators have speed governing systems which automatically adjust the prime mover driving the generator so as to keep the generator speed constant, and voltage regulating systems which adjust the generators' excitation to maintain the generator voltages constant. These controls are necessary for any interconnected power system to supply power of the quality demanded by today's electric power users. However, most automatic controls use high gain negative feedback, which, by its active nature, can cause oscillations to grow in amplitude with time. The automatic controls in power systems must, as with other automatic feedback controls, be designed so that oscillations decay rather than grow.

This then brings us to the reason for this book. It is to discuss

- the nature of power system oscillations
- the mathematical analysis techniques necessary to predict system performance
- control methods to ensure that oscillations decay with time

Oscillations were observed in power systems as soon as synchronous generators were interconnected to provide more power capacity and more reliability. Originally, the interconnected generators were fairly close to one another, and oscillations were at frequencies of the order of 1 to 2 Hz. Amortiseur (damper) windings on the generator rotor were used to prevent the oscillations amplitudes increasing. Damper windings act like the squirrel cage winding of an induction motor and produce a torque proportional to the speed deviation of the rotor from synchronous speed. They absorb the energy associated with the system oscillations and so cause their amplitudes to reduce.

As power system reliability became increasingly important, the requirement for a system to be able to recover from a faults cleared by relay action was added to the system design specifications. Rapid automatic voltage control was used to prevent the system's generators loosing synchronism following a system fault. Fast excitation systems, however, tend to reduce the damping of system oscillations. Originally, the oscillations most affected were those between electrically closely coupled generators. Special stabilizing controls (Power System Stabilizers) were designed to damp these oscillations.

In the 1950s and 1960s, electric power utilities found that they could achieve more reliability and economy by interconnecting to other utilities, often through quite long transmission lines. In some cases, when the utilities connected, low frequency growing oscillations prevented the interconnection from being retained [1]. In some instances, lowering automatic voltage regulator gains was all that was necessary to make the system interconnection successful. However, in other cases the interconnection plans were abandoned until asynchronous HVDC interconnections were technically possible. AC tie lines became more stressed, and low frequency oscillations between some interconnected systems were found to increase in magnitude. In the worst cases, these oscillations caused the interconnection to be lost with consequent inability to supply customer load.

From an operating point of view, oscillations are acceptable as long as they decay. However, oscillations are a characteristic of the system; they are initiated by the normal small changes in the systems load. There is no warning to the operator if a new operating condition causes an oscillation to increase in magnitude. An increase in tie line flow of as little as 10 MW may make the difference between decaying oscillations which are acceptable and increasing oscillations which have the potential to cause system collapse. Of course, a major disturbance may finally result in growing oscillations and system collapse. Such was the case in the August 1996 collapse of the

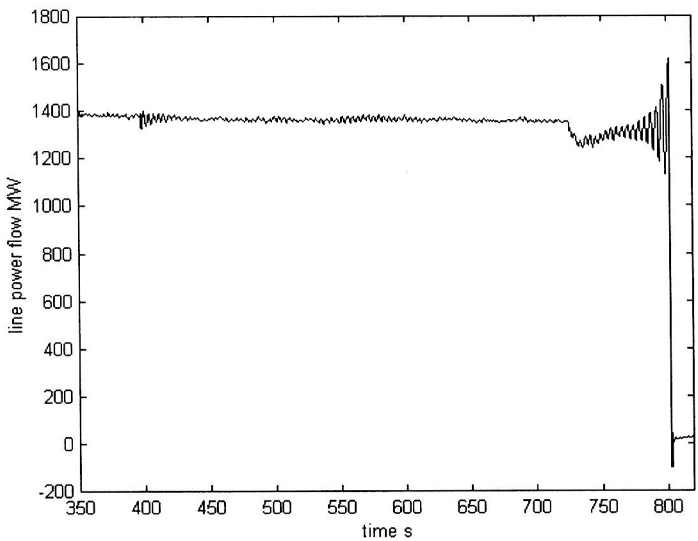

Figure 1. Line flow transient - August 10, 1996 western USA/Canada system

western US/Canada interconnected system. The progress of this collapse was recorded by the extensive monitoring system, which has been installed [2], and its cause is explained clearly in [3]. A record of the power flow in a major transmission line is shown in Figure 1. The recording starts well before the incident, which triggered the system's collapse, and continues until the line is disconnected. Details of this record in Figure 2 and 3 show the response of the system to the initial fault, and to subsequent smaller disturbances. The system oscillates at about 0.26 Hz and the oscillations decay. Such oscillations, which may last for 30 s, are not noticeable by the system's operators unless they have special instrumentation that detects them. The final collapse was caused by the growing oscillations shown in Figure 4. The decaying oscillations of figures 2 an 3 were turned into growing oscillations by the sequence of faults and protective relay operations. The amplitude of the oscillations eventually caused the system to split into a number of disconnected regions, with the loss of power to a considerable number of customers.

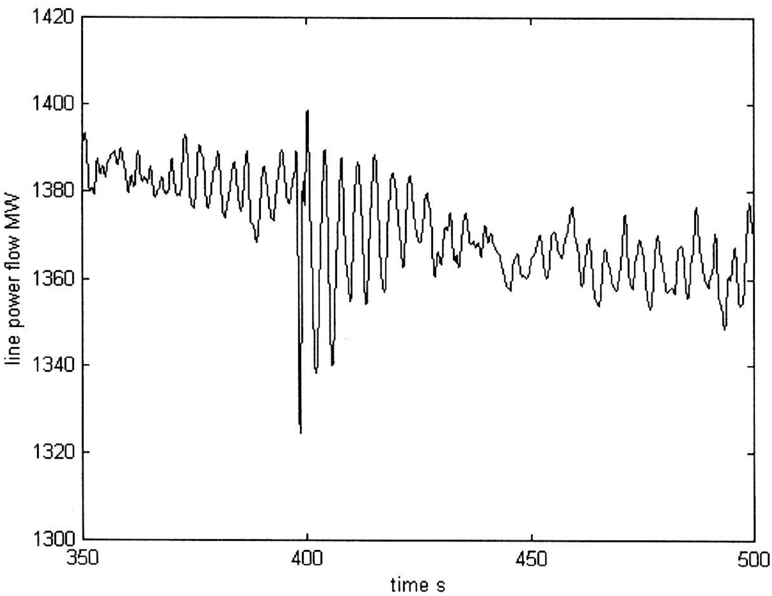

Figure 2. Detail of transient showing decaying oscillations following the initial fault

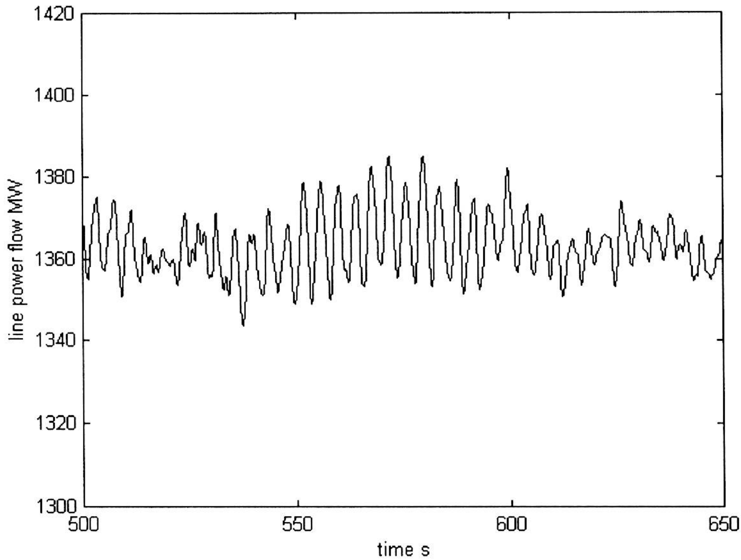

Figure 3. Detail of oscillations caused by a sequence of small disturbances

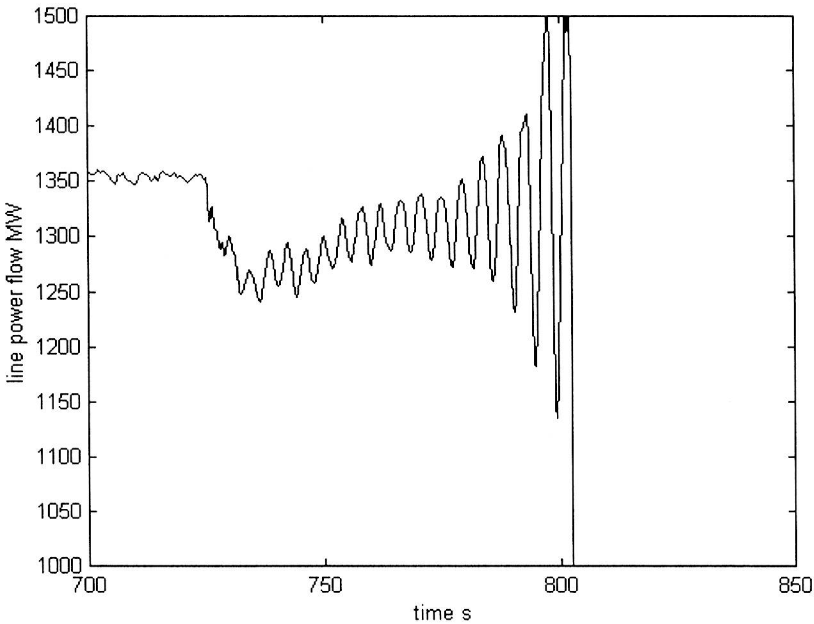

Figure 4. Detail of transient showing growing oscillations