

Chapter 2

POWER SYSTEM OSCILLATIONS

2.1 Introduction

Oscillations in power systems are classified by the system components that they effect. Some of the major system collapses attributed to oscillations are described.

2.2 Nature of electromechanical oscillations

Electromechanical oscillations are of the following types:

- Intraplant mode oscillations
- Local plant mode oscillations
- Interarea mode oscillations
- Control mode oscillations
- Torsional modes between rotating plant

2.2.1 Intraplant mode oscillations

Machines on the same power generation site oscillate against each other at 2.0 to 3.0 Hz depending on the unit ratings and the reactance connecting them. This oscillation is termed as *intraplant* because the oscillations manifest themselves within the generation plant complex. The rest of the system is unaffected.

2.2.2 Local plant mode oscillations

In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. The variation in speed of a generator is shown in Fig. 2.1.

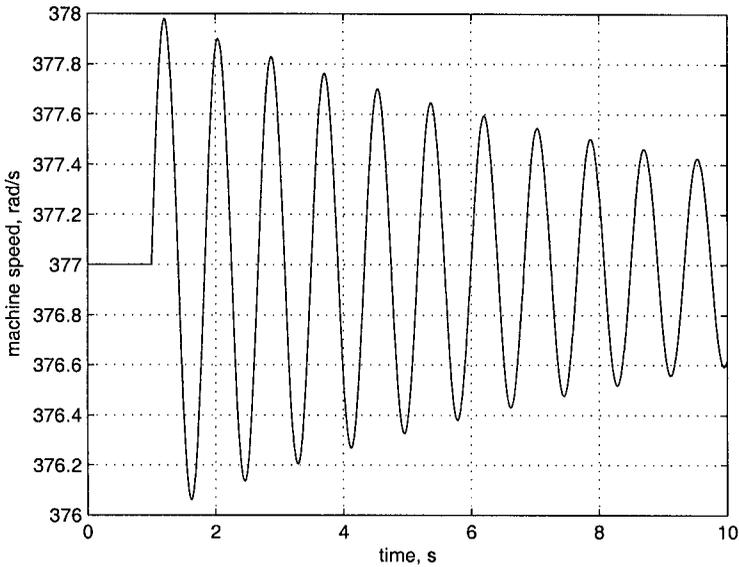


Figure 2.1. A typical example of local oscillation

The impact of the oscillation is localized to the generator and the line connecting it to the grid. The rest of the system is normally modelled as a constant voltage source whose frequency is assumed to remain constant. This is known as the single-machine-infinite-bus (SMIB) model. The damping and frequency vary with machine output and the impedance between the machine terminal and the infinite bus voltage. The oscillation may be removed with a single or dual input PSS that provides modulation of the voltage reference of the automatic voltage regulator (AVR) with proper phase and gain compensation circuit [Lee, 1992].

2.2.3 Interarea mode oscillations

This phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. The variation in tie-line power can be large as shown in Fig. 2.2. The oscillation frequency is approximately 0.3 Hz.

This complex phenomenon involves many parts of the system with highly non-linear dynamic behavior. The damping characteristic of the interarea mode is dictated by the tie-line strength, the nature of the loads and the power flow

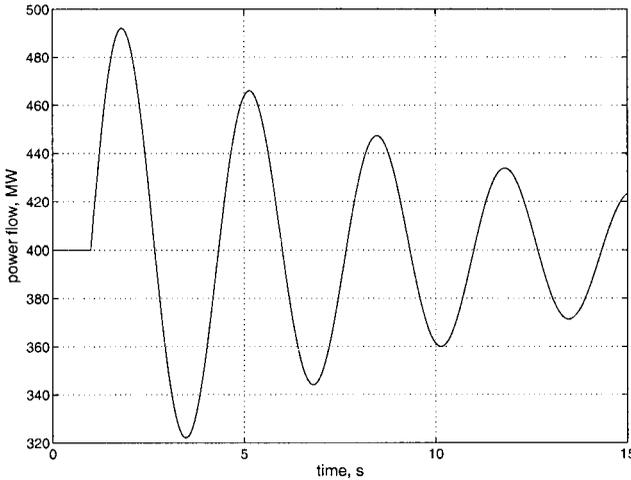


Figure 2.2. A typical example of interarea oscillation

through the interconnection and the interaction of loads with the dynamics of generators and their associated controls. The operation of the system in the presence of a lightly damped interarea mode is very difficult.

2.2.4 Control mode oscillations

These are associated with generators and poorly tuned exciters, governors, HVDC converters and SVC controls. Loads and excitation systems can interact through control modes [Rajagopalan et al., 1992]. Transformer tap-changing controls can also interact in a complex manner with non-linear loads giving rise to voltage oscillations [Cutsem and Vournas, 1998].

2.2.5 Torsional mode oscillations

These modes are associated with a turbine generator shaft system in the frequency range of 10-46 Hz. A typical oscillation is shown in Fig. 2.3.

Usually these modes are excited when a multi-stage turbine generator is connected to the grid system through a series compensated line [Padiyar, 1999]. A mechanical torsional mode of the shaft system interacts with the series capacitor at the natural frequency of the electrical network. The shaft resonance appears when network natural frequency equals synchronous frequency minus torsional frequency.

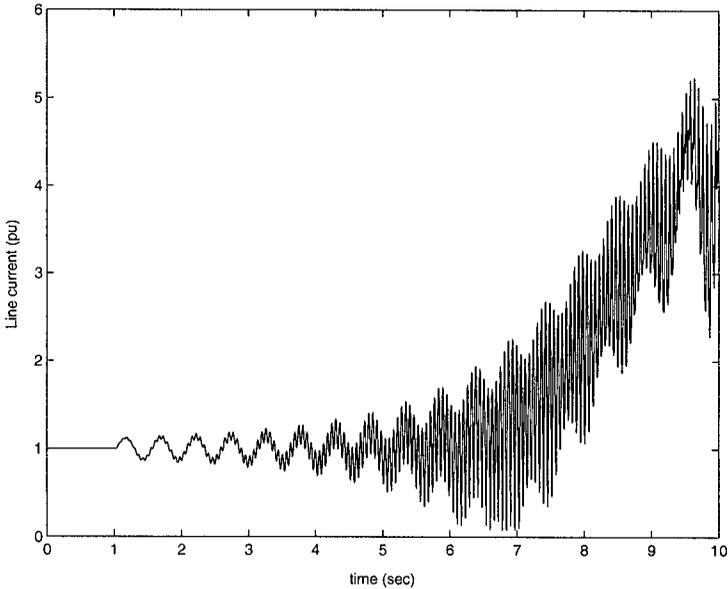


Figure 2.3. A typical example of torsional mode oscillation

2.3 Role of Oscillations in Power Blackouts

Interarea oscillations have led to many system separations but few wide-scale blackouts [Pal, 1999, Paserba, 1996]. Note worthy incidents include:

- Detroit Edison (DE-Ontario Hydro (OH)-Hydro Quebec (HQ) (1960s, 1985)
- Finland-Sweden-Norway-Denmark (1960s)
- Saskatchewan-Manitoba Hydro-Western Ontario (1966)
- Italy-Yugoslavia-Austria (1971-1974)
- Western Electric Coordinating Council (WECC) (1964,1996)
- Mid-continent area power pool (MAPP) (1971,1972)
- South East Australia (1975)
- Scotland-England (1978)
- Western Australia (1982,1983)
- Taiwan (1985)
- Ghana-Ivory Coast (1985)

- Southern Brazil (1975-1980,1984)

The power blackout of August 10, 1996 in the Western Electricity Co-ordination Council (WECC) (formerly WSCC) area is described below. It indicates the importance of understanding and managing oscillations for secure operation of the grid.

2.3.1 Oscillations in the WECC system

Power transfer capability in this system has been limited by stability considerations for 40 years because of the long distance between load centers and power sources. Oscillations have resulted in system separation on several occasions. They were caused by insufficient damping and synchronizing torque. The history of interarea oscillations in this system has influenced the system planning, design and operation strategy. Insufficient damping turned out to be the major constraint when in 1964, the Northwest United States and Southwest United States were interconnected through the Colorado River Storage Project. In less than a year of interconnected operation, there were at least a hundred tie-line separations due to system oscillations of power, frequency and voltage. In 1965, the problem was solved by modifications to one of the hydro-unit governors [Schleif et al., 1967].

About that time work was initiated to develop time domain stability programs for more detailed analysis of interconnected systems. This was very useful since it coincided with the planning of many 345 kV and 500 kV transmission projects, including the Northwest-Southwest Inter-tie which consisted of two 500 kV ac lines and ± 400 kV dc circuits. The initial plan was to carry 2000 MW through the ac circuits and 1440 MW through the dc line. Stability performance assessment showed that there was insufficient damping torque for ac power flows exceeding 1300 MW. It was found from the study that undamped oscillations of power, frequency and voltage at about 0.33 Hz was the major restraint on a larger transfer [Schleif and White, 1966]. It was later realized that many of the generator high gain automatic voltage regulators (AVR) produced negative damping at around 0.33 Hz which led to the development and application of PSS. It was found from the time domain simulations that there would be sufficient damping for the most severe disturbance with 1800 MW transferred through the ac lines if all generators in the system were equipped with PSS. After all the units were retrofitted with PSS, the oscillations disappeared and the stability limit depended only upon the synchronizing torque.

The Bonneville Power Authority (BPA) implemented a 1400 MW braking resistor at Chief Joseph Dam in 1974 to improve first swing stability of the system. This indicated that the system could operate with up to 2500 MW

flowing through the AC interconnection with adequate stability margin following a severe disturbances such as a close in three phase fault. With even higher loading, however, slowly growing oscillations were observed, indicating that insufficient damping torque was again a problem at the higher loading level. The problem was relieved by the development of a scheme [Cresap et al., 1978] to modulate the northern terminal of the Northwest-Southwest dc line in such a manner as to provide positive damping to the ac system at the inter-tie frequency.

Overall the transmission capacity was increased from 1300 MW to 2500 MW without adding any transmission circuits. The only system additions were PSS, braking resistors and HVDC modulation. Many other interfaces in western USA are limited by insufficient damping torque and are highly dependent on PSS and other devices to provide positive damping. Currently there is a 0.7 Hz lightly damped interarea mode identified from system models and analytical techniques. In one interface, nearly 750 Mvar of static VAR compensators have been installed to add damping so that the full planned transmission capacity will be available [Lee et al., 1994].

On August 10, 1996, the Pacific AC inter-tie (PACI) emerged from the dormant state that had lasted since 1974 when the entire inter-connected system split into four islands with the loss of approximately 30 GW of load. More than 7 million customers were affected by this catastrophic event [Kosterev et al., 1999]. The mechanism of failure was a transient oscillation, under conditions of high power transfer on long paths that had been progressively weakened through a series of fairly routine resource losses. This series of events was simulated based on the dynamic model data base with data assembled from the data bases of the utilities. The simulation showed a well damped response for the critical set of contingencies but did not show any voltage decay. The power flow through the pacific HVDC tie was observed constant because of constant power control in the simulation model. The simulated frequency dip was also only 60% of the recorded value. On the other hand, undamped oscillations in the inter-tie power flow were recorded whilst voltages at several locations were depressed. Also the power flow through the HVDC tie was observed to vary thereby showing a serious discrepancy between the simulation model and the actual system dynamic characteristics. The oversimplified model of the HVDC tie and its control were replaced with four-terminal links and control at converter levels. The automatic governor control (AGC) was included during the transient which is normally omitted from dynamic simulations. The presence of large turbo-generators delayed the power output pick-up immediately following a frequency decay. This was done by not representing the governor action for large units. With all these modifications, the simulated system response

differed appreciably from the recorded observation until a dynamic load model was included.

2.4 Summary

The long history of interarea oscillations in the WECC system and other interconnected systems, [Paserba, 1996], clearly identifies inadequate damping as the primary factor leading to system separation. The amount of damping and the frequency of oscillation varies with system operating conditions. The operating range of a power system is usually very wide, requiring an oscillation damping control strategy that is effective over this whole range. It is necessary to have comprehensive modelling and analysis techniques of all the components that may interact to produce oscillations.

References

- [Cresap et al., 1978] Cresap, R.L., Scott, D.N., Mittelstadt, W.A., and Taylor, C.W. (1978). Damping of pacific ac intertie oscillations via modulation of the parallel pacific hvdc intertie. *CIGRE Paper*, 14(5).
- [Cutsem and Vournas, 1998] Cutsem, T Van and Vournas, C (1998). *Voltage Stability of Electric Power Systems*. Kluwer Academic Press, USA.
- [Kosterev et al., 1999] Kosterev, D.N., Taylor, C.W., and Mittelstadt, W. (1999). Model validation for the august 10, 1996 wscs system outage. *IEEE Transactions on Power Systems*, 14(3):967–979.
- [Lee, 1992] Lee, D.C. (1992). *IEEE recommended practice for excitation system models for power system stability studies*. Energy development and power generation committee of power engineering society.
- [Lee et al., 1994] Lee, R.L., Beshir, M.J., Finely, A.T., Hayes, D.R., Hsu, J.C., Peterson, H.R., Deshazo, C.L., and Gerlach, D.W. (1994). Application of static var compensator for the dynamic performance of the mead-adelanto and mead-phoenix transmission projects. *IEEE PES T and D Conference and Exposition, Chicago, IL*.
- [Padiyar, 1999] Padiyar, K.R. (1999). *Analysis of Subsynchronous Resonance in Power Systems*. Kluwer Academic Publishers, USA.
- [Pal, 1999] Pal, B.C. (1999). *Robust Damping Control of Inter-area Oscillations in Power System with Super-conducting Magnetic Energy Storage Devices*. PhD thesis, Imperial College of Science Technology and Medicine, Department of Electrical and Electronic Engineering.
- [Paserba, 1996] Paserba, J. (1996). Analysis and control of power system oscillation. *CIGRE Special Publication 38.01.07*, Technical Brochure 111.
- [Rajagopalan et al., 1992] Rajagopalan, C., Lesieutre, B., Sauer, P.W., and Pai, M.A. (1992). Dynamic aspects of voltage/power characteristics in multi-machine power systems. *IEEE Transactions on Power Systems*, 7(3):990–1000.

- [Schleif et al., 1967] Schleif, F.R., Martin, G.E., and Angell, R.R. (1967). Damping of system oscillations with a hydro-generating unit. *IEEE Transactions on Power Apparatus and Systems*, 86(4):438–442.
- [Schleif and White, 1966] Schleif, F.R. and White, J.H. (1966). Damping for northwest-southwest tie line oscillations - an analogue study. *IEEE Transactions on Power Apparatus and Systems*, 85(12):1234–1247.