LOAD MODELLING IN STUDIES OF POWER SYSTEM DAMPING

I.A. Hiskens, MIEEE J.V. Milanović
Department of Electrical and Computer Engineering
The University of Newcastle, Newcastle, NSW, 2308, Australia

Abstract

This paper considers the significance of load voltage dynamics in studies of power system damping. A generic model of dynamic loads is used to investigate the influence of active and reactive power dynamics on the damping of oscillations in a multimachine power system. The interaction between the load and the power system is explored in terms of load and system transfer functions. It is shown that the power system transfer function is composed of a static part and a dynamic part. The static part is derived from the power flow Jacobian. The investigations indicate that load voltage dynamics can significantly influence the damping of modal oscillations. Static load models can give quite misleading predictions of damping when loads actually exhibit dynamic behaviour.

Keywords: load dynamics, electromechanical oscillations, system damping

1 Introduction

Electromechanical oscillations inevitably occur in multimachine power systems. They result from the rotors of machines oscillating with respect to one another. Oscillation energy is exchanged between machines through the transmission system [1]. Oscillations are classed as local mode if they occur between a single machine, or sometimes a small group of machines, and the rest of the system. Typical local mode frequencies range from 0.7 to 2.0Hz [2, 3]. Oscillations can also occur between large groups of machines. They are referred to as interarea oscillations, and typically have a frequency in the range of 0.1 to 0.8Hz [2, 3].

However sustained oscillations are undesirable. They can lead to fatigue of machine shafts, and can cause excessive wear of mechanical actuators of machine controllers. Also, oscillations make system operation more difficult. Therefore it is desirable that oscillations are well damped. Unfortunately, as systems become more heavily loaded in response to economic and environmental pressures, damping tends to reduce.

95 WM 111-5 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the 1995 IEEE/PES Winter Meeting, January 29, to February 2, 1995, New York, NY. Manuscript submitted August 1, 1994; made available for printing January 3, 1995.

It is important that the frequency and damping of oscillations can be accurately predicted. The feasibility of some projects may be critically dependent on the level of damping of particular modes. For example, an interconnection of two large power systems may be unworkable if oscillations between the two systems could not be adequately damped [4]. If predictions of damping were optimistic, the project could proceed, but then not meet expectations due to the poorly damped oscillations. Further, accurate prediction of damping is essential in the tuning of stabilizing control loops of generators and FACTS devices [5, 6, 7, 8].

However many power utilities have recently found that predictions of damping are optimistic when compared with actual system behaviour, e.g., [9]. In general many factors may contribute to the inaccuracy of the predictions. In this paper we focus on one factor that can have a significant effect on the accuracy of system studies, namely load modelling. The importance of load modelling is well documented [10-17]. Yet accurate modelling of loads is a difficult task [18, 19]. It is therefore important that the sensitivity of system behaviour to changes in load response be clearly understood. This paper considers that sensitivity, in terms of the link between system damping and the dynamic response of loads.

The structure of paper is as follows. Section 2 provides some background ideas on the analysis of load-system interaction, and on a generic dynamic load model. The transfer function of the power system is considered in Section 3. In Section 4, the influence on damping of real and reactive power dynamic loads is explored. Results in this section highlight the inadequacy of static load models. The effects of load dynamics on local and interarea modes of a well tuned multimachine power system are also explored.

2 Background

2.1 Load-system interaction

Load-system interaction can be conveniently analysed by decomposing the power system into a feedback system such as shown in Figure 1 [20]. (This figure shows a real power disturbance ΔP. In general the ideas remain valid whether the disturbance is real or reactive power, or a combination of both. Sections 3 and 4 consider this further.) The load provides a feedback path, and so has the potential to alter the overall system behaviour. Depending on load and system parameters, this feedback may improve damping. But a deterioration in damping is also possible.

Consider some sinusoidal variation in bus power ΔP. A variation in the bus voltage ΔV will result. The magnitude of that variation, and its phase relative to ΔP, will depend on the transfer function of the power system. This

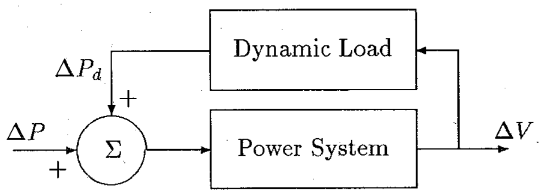

Figure 1: Load - power system interaction.

is considered further in Section 3. But ΔV will induce, through the load, some variation ΔP_d. The magnitude of this ΔP_d, and its phase relative to ΔV, are given by the transfer function of the load. Section 2.2 discusses that transfer function.

If the load variation ΔP_d happened to be in phase, or nearly so, with the original disturbance ΔP, then the load would serve to reinforce oscillations, with a corresponding reduction in damping. One could also envisage situations where the load fed back a ΔP_d which was out of phase with the original disturbance ΔP. In that case the load would cause an improvement in damping. Of course the exact effects depend on the gains of the system and the load at the oscillation frequency of interest. However it was shown in [21] that for a weak power system, this feedback due to load dynamics could reduce damping to the point where instability occurred.

Note that the view of load-system interaction given by Figure 1 is useful for analysing the effects due to a single load. Power systems in general have many loads though. The other loads which are not of immediate interest are treated as part of the system. Their effects are included in the transfer function of the power system, i.e., the feedforward block in Figure 1.

2.2 Generic dynamic load model structure and parameters

In response to a step change in voltage, loads will generally undergo a step change in real and reactive power demand. The load will then recover, over some time, to a steady state value which may be different from its predisturbance value. Important characteristics of this dynamic behaviour are the initial step change, the final value, and the rate of load recovery. A generic model which captures these characteristics was proposed in [22, 23]. That model can be expressed for real power as,

$$T_p \dot{x}_p = P_s(V) - P_d \quad (1)$$

$$x_p = P_d - P_t(V) \quad (2)$$

A similar model can be used for reactive power load. The functions $P_t(V), P_s(V)$ define the initial step response, and the final value of power demand respectively. A convenient form for these functions is

$$P_s(V) = P_o(V/V_o)^{n_{ps}} \quad (3)$$

$$P_t(V) = P_o(V/V_o)^{n_{pt}} \quad (4)$$

where V_o, P_o are the nominal voltage and the corresponding real power demand respectively, and n_{ps}, n_{pt} are the steady state and transient voltage indices. Reactive power functions $Q_s(V), Q_t(V)$ can be defined similarly, but with voltage indices n_{qs}, n_{qt} respectively. The time constants T_p, T_q describe the rate of recovery of the real and reactive power loads.

The steady state and transient voltage indices are generally in the ranges [10, 12, 18, 23, 24, 25]:

$$0 \le n_{ps} \le 3$$
$$0 \le n_{qs} \le 7$$
$$1.5 \le n_{pt} \le 2.5$$
$$4 \le n_{qt} \le 7$$

Time constants T_p, T_q depend on the type of load being modelled. For industrial, agricultural and air conditioning loads, consisting predominantly of induction motors [11, 18, 19, 25], T_p, T_q are in the range of 0.02s to a few seconds. This depends on the proportion of induction motors in the total combined load. For industrial plants such as aluminium smelters [26], or power plant auxiliary power systems [27], the time constants are in the range of 0.1s to 0.5s. For tap-changers and other such control devices they are in the range of minutes, and for heating load they may range up to hours [23].

In [20], the load model (1),(2) was linearized to give the dynamic load transfer function of Figure 1. The linearized model has the form of a lead/lag block, with the lead/lag time constants dependent on the load parameters. It was shown that if $n_{pt} > n_{ps}$ ($n_{qt} > n_{qs}$), which is the normal situation, then the phase shift through the real (reactive) load was always positive. The dependence on load parameters of the gain and phase shift of the load transfer function was discussed in [20].

3 The Power System Transfer Function

In establishing the transfer function for the power system, we first notice that the power system model has the differential-algebraic form

$$\dot{x} = f(x,y) \quad (5)$$

$$0 = g(x,y) \quad (6)$$

where the differential equations describe the dynamics of generators, their controllers, FACTS devices, and dynamic loads, and the algebraic equations describe the real and reactive power balance at buses in the network. The algebraic equations are effectively the power flow equations, modified to account for interfacing with dynamic devices. For example, the real power balance equation at a dynamic load would follow from (2) as

$$x_p + P_t(V) - P_l(\theta, V) = 0 \quad (7)$$

where $P_l(\theta, V)$ gives the real power flow into the load bus from the network.

The dynamic state variables x consist of generator states, e.g., internal angle, speed deviation and fluxes, states of machine and FACTS controllers, and dynamic load state variables, i.e., x_p, x_q. The algebraic variables y are the voltage magnitude and angle at all buses in the network.

Linearizing these equations about an operating point gives

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \quad (8)$$

From Figure 1 it can be seen that we are interested in the behaviour of the bus voltage ΔV for changes in bus powers $\Delta P, \Delta Q$. The power demand changes are inputs to the system (8). Also, ΔV is an element of Δy. So the *linearized* system becomes

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} f_x & f_y \\ g_x & g_y \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ e_1 & e_2 \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{9}$$

$$\Delta V = \begin{bmatrix} 0 & e_3^t \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{10}$$

where e_1, e_2, e_3 are column vectors which are all zeros, except for a '1' in the appropriate place. In e_1, e_2, the 1 corresponds to the real and reactive power balance equations respectively of the bus of interest. For e_3, the 1 corresponds to the voltage at the bus of interest.

If g_y is nonsingular, then we see from (9) that

$$\Delta y = -g_y^{-1} g_x \Delta x - g_y^{-1} [e_1\ e_2] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{11}$$

So, from (9)

$$\begin{aligned} \Delta\dot{x} &= f_x \Delta x + f_y \Delta y & (12) \\ &= (f_x - f_y g_y^{-1} g_x)\Delta x - f_y g_y^{-1} [e_1\ e_2] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} & (13) \\ &= A\Delta x + B \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} & (14) \end{aligned}$$

Also, from (10)

$$\begin{aligned} \Delta V &= e_3^t \Delta y & (15) \\ &= -e_3^t g_y^{-1} g_x \Delta x - e_3^t g_y^{-1} [e_1\ e_2] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} & (16) \\ &= C\Delta x + D \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} & (17) \end{aligned}$$

The transfer function between the inputs $\Delta P, \Delta Q$ and the output ΔV is obtained in the usual way using Laplace transforms

$$\begin{aligned} G(s) &= [G_1(s)\ G_2(s)] & (18) \\ &= C(sI - A)^{-1} B + D & (19) \end{aligned}$$

Note that it consists of two terms. The first term describes the dynamic aspects of the response of ΔV to $\Delta P, \Delta Q$. The bus power disturbance will excite dynamic devices such as generators. Their response will cause ΔV to vary. The second term provides a direct connection between the inputs $\Delta P, \Delta Q$ and the output ΔV. It can be seen from (16),(17) that the elements of $D = [d_1\ d_2]$ are just particular elements of g_y. But g_y is the modified power flow Jacobian. So d_1 will be the element of the inverse Jacobian corresponding to $\frac{\partial V}{\partial P}$. Similarly, d_2 will be the element corresponding to $\frac{\partial V}{\partial Q}$.

The transfer function (19) clearly shows the difference between the static voltage-power sensitivities obtained from power flow studies, and the voltage-power sensitivities which occur when dynamics are included.

The transfer function (19) was established for independent inputs $\Delta P, \Delta Q$. However it is also useful to consider disturbances where ΔP and ΔQ are coupled via a constant power factor. Let $\Delta P = \Delta S \cos\phi$ and $\Delta Q = \Delta S \sin\phi$, i.e., the load has a power factor of $\cos\phi$.

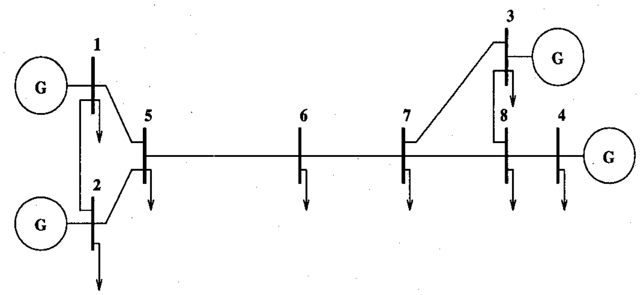

Figure 2: Four-machine eight-bus system

The transfer function between the power disturbance ΔS and the voltage ΔV is given by

$$\begin{aligned} \Delta V &= G(s) \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} & (20) \\ &= [G_1(s)\ G_2(s)] \begin{bmatrix} \cos\phi \\ \sin\phi \end{bmatrix} \Delta S & (21) \\ &= (G_1(s)\cos\phi + G_2(s)\sin\phi)\Delta S & (22) \end{aligned}$$

The system is now single input single output.

4 Effects of Load Models on Damping

In this section we shall look at a number of cases which demonstrate in various ways the importance of correct load modelling. The system of Figure 2 will be used to illustrate the ideas.

4.1 Real and reactive power load dynamics

The influence of unity power factor loads on damping was demonstrated in [20]. It is interesting to extend those ideas to loads which are not unity power factor. The first step in that extension is to look at the system transfer function for power disturbances ΔS which have differing power factors. The transfer function (22) can be used.

Consider the eight bus example of Figure 2. The system transfer functions, as seen from buses 5 and 6, are shown in Figures 3 and 4 respectively. These figures show the magnitude of the Bode plot for varying power factor. It can be seen from Figure 3 that at bus 5, the system is much more sensitive to real power disturbances ($\cos\phi = 1$) than to reactive power disturbances ($\cos\phi = 0$). However Figure 4 shows that at bus 6, the system is more sensitive to reactive power than to real power disturbances. These observations are reflected in Figure 5, where the variation in damping with load time constant is shown. Each root locus of Figure 5 shows the movement of the interarea mode of the eight bus example as the load time constant is increased from zero. (Note that a time constant of zero corresponds to a static voltage dependent load model.) In the cases where both real and reactive loads are dynamic, a constant power factor has been assumed. For bus 5 the power factor used was 0.91. A value of 0.93 was used for bus 6.

Referring to Figure 5, we shall focus on the root loci for bus 5. If real power load is modelled as dynamic, then the system is always better damped than with a static

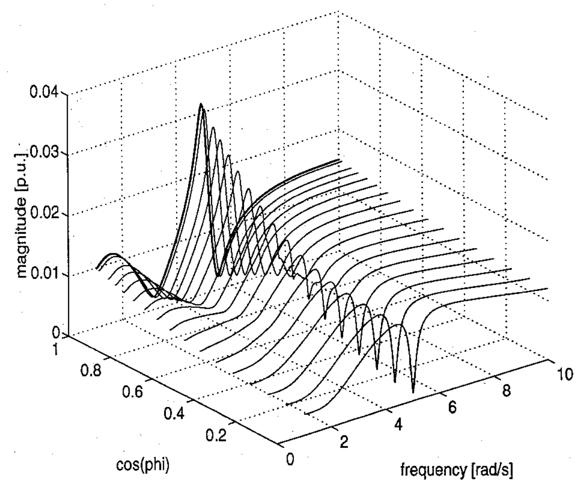

Figure 3: Magnitude of Bode plots for bus 5 for different power factors

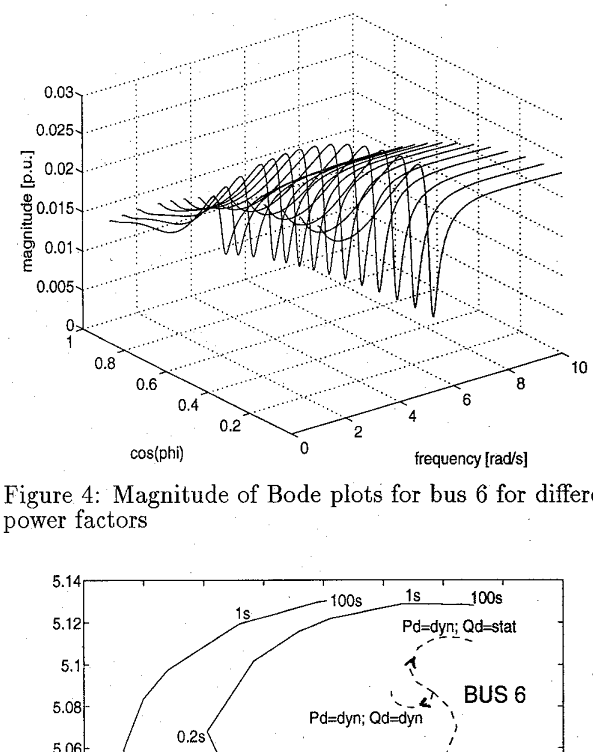

Figure 4: Magnitude of Bode plots for bus 6 for different power factors

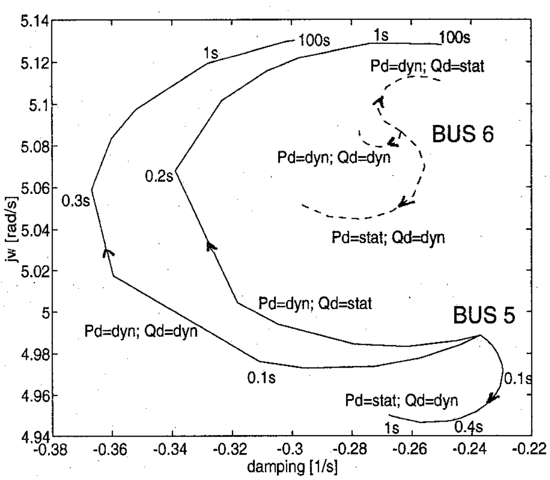

Figure 5: Root loci of the interarea mode for varying load time constants

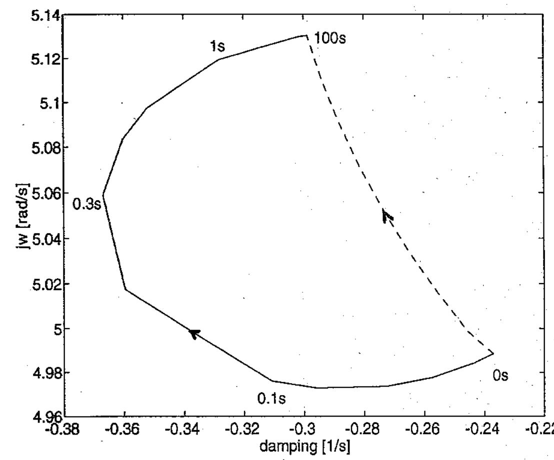

Figure 6: Root loci for variation of dynamic and static load parameters

real power load. This is independent of whether reactive power is modelled as static, or modelled as dynamic with a constant power factor. However if real power is modelled as static, and reactive power as dynamic, then for small time constants, system damping deteriorates. For larger time constants, damping improves. Similar analysis can be undertaken of the root loci for bus 6.

These results highlight the fact that care must be taken in modelling loads.

4.2 Static versus dynamic load modelling

The solid line in Figure 6 shows the movement of the interarea mode as the real and reactive power time constants of the dynamic load at bus 5 are varied simultaneously. It was pointed out in [20] that when the load time constants T_p, T_q were very small, the load effectively behaved as a static load, with indices n_{ps}, n_{qs}. When T_p, T_q were very large, the load again behaved as a static load, but this time with indices n_{pt}, n_{qt}.

It is interesting therefore to consider the influence on the interarea mode of treating the load at bus 5 as static, and varying the indices from n_{ps}, n_{qs} to n_{pt}, n_{qt}. This is shown in Figure 6 as a dashed curve.

As predicted, the two curves start and finish at the same points. However they trace out significantly different paths. It can be seen that dynamic loads with time constants in the range from 0.1s to a few seconds cannot be adequately described by a static representation. Note that this range of time constants corresponds to most dynamic loads, e.g., industrial, agricultural and air conditioning loads.

4.3 Sensitivity of damping to load parameters

The accurate modelling of loads is a difficult task for a number of reasons, including [18, 19]: large number of diverse load components, ownership and location of load devices in customer facilities that are not directly accessible to the electricity utility, changing load composition with time of day and week, seasons and weather, lack of precise information on the composition of loads, and uncertainties regarding the characteristics of many load components.

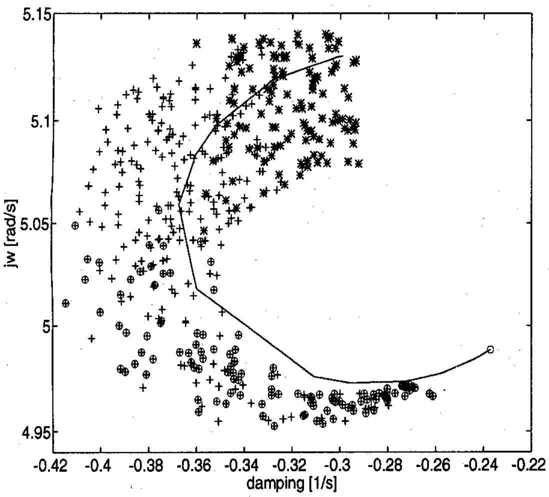

Figure 7: System damping when load parameters randomly chosen for bus 5

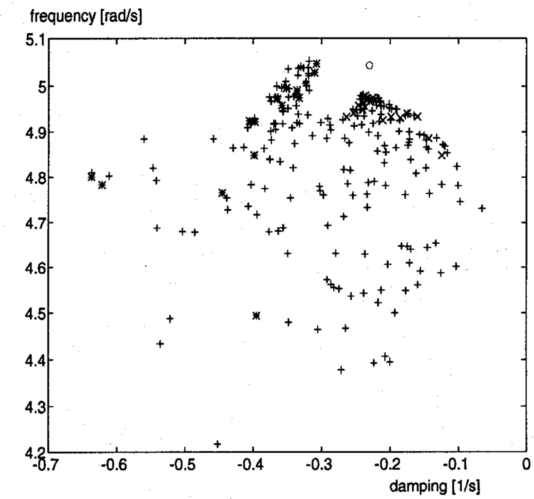

Figure 8: System damping when load parameters randomly chosen for non-generator load buses

In the root loci of Figures 5 and 6, we have seen the variation in damping when the load time constant is varied. Also of interest is the effect when the other load parameters $n_{ps}, n_{pt}, n_{qs}, n_{qt}$ are varied as well. This is shown in Figure 7 for the interarea mode. The solid curve is the same as that shown in Figure 6. It corresponds to load parameters $n_{ps} = 0.1, n_{pt} = 2.4, n_{qs} = 2, n_{qt} = 5$. The scattered points in the figure were obtained by randomly varying T_p, T_q, n_{pt}, n_{qt} simultaneously. The following ranges were used:

$$0 \leq T_p, T_q \leq 50$$
$$1.5 \leq n_{pt} \leq 2.5$$
$$2 \leq n_{qt} \leq 5$$

The encircled plus signs correspond to $0 \leq T_p, T_q \leq 0.1$, the plus signs to $0.1 \leq T_p, T_q \leq 1.0$, and the asterisks to $1.0 \leq T_p, T_q \leq 50$. The steady state voltage exponents n_{ps}, n_{qs} were left unchanged.

Notice that the static load representation, given by the point at the start of the curve, is not near the region covered by the random points. Further, comparing Figures 6 and 7, we see that the dashed curve of Figure 6 which corresponds to variation of the static load model, lies in a region devoid of random points. This is further confirmation that the static load model can give misleading results.

In producing Figure 7, only the load parameters at bus 5 were varied. Figure 8 shows results when the parameters for dynamic loads at the non-generator buses of the example system were randomly varied. The same parameter ranges were used as above. In the figure, the small circle shows the location of the interarea mode when loads were represented statically. All other points correspond to dynamic loads. Notice that the dynamic load points cover quite a wide area. But the static load point does not lie in the covered region. Depending on load parameters, it is possible to have very good damping or very poor damping. In fact it is possible to obtain points that lie in the right half plane, i.e., values of load parameters which cause the system to be unstable. Optimization techniques, similar to those developed for coordinated tuning of controllers, could be used to determine the values of load parameters which give the worst or best damping.

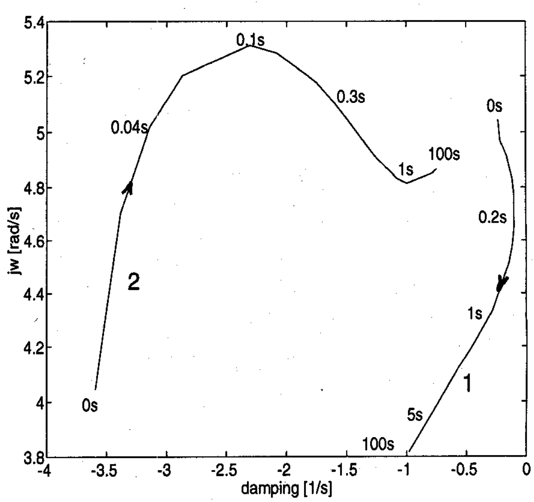

Figure 9: Root loci for the two least damped modes

4.4 Effects on multiple modes

Until now we have only considered the influence of dynamic loads on a single mode. The ideas extend naturally to multiple modes though. Figure 9 shows the root loci for the two least damped modes of the eight bus system. In this case the loads at all non-generator buses were modelled as dynamic. The time constants of the bus 5 load were varied to give the curves.

As the load time constant was increased, the interarea mode (labelled 1) became slightly worse damped, then damping improved. But the damping of the local mode (labelled 2) steadily decreased. In fact, for time constants greater than 1.5s, mode 2 became the least damped mode. Also, it was found that the participation of generators in those modes changed as the time constant increased. For small time constants, mode 1 had strong participation from generators 2 and 3, but for large time constants, the mode predominantly involved generators 1 and 2. Mode 2 though involved generators 1 and 2 for small time constants, but generators 1,2 and 3 for large time constants.

5 Conclusions

The paper has demonstrated the need for accurate modelling of loads. A static representation of loads that exhibit dynamic behaviour can give quite misleading results.

The influence of non-unity power factor loads has been explored in the paper. Depending on system conditions, the dynamic behaviour of the reactive part of loads can be more significant than the real power part.

The significance of load model uncertainty was considered. To do this, load parameters were randomly varied, with damping being determined for each set of parameters. This study indicated that the calculated values of damping could be quite wide spread.

It was shown that dynamic load models could not only affect the damping of electromechanical modes, but could also have an influence on which generators participated in the mode. As load parameters vary, this participation can also vary.

References

[1] E.V. Larsen, et. al., "Applying power system stabilisers", *IEEE Trans. Power Apparatus and Systems*, Vol. 100, 1981, pp. 3010-3046.

[2] G.C. Verghese, et. al., "Selective modal analysis with applications to electric power systems, Part II: The dynamic stability problem", *IEEE Trans. Power Apparatus and Systems*, Vol. 101, No. 9, 1982, pp. 3126-3134.

[3] M. Klein, et. el., "A fundamental study of inter-area oscillations in power systems", *IEEE Trans. Power Systems*, Vol. 6, No. 3, 1991, pp. 914-921.

[4] T. George, et. al., "Options for an interconnection between the power systems of Queensland and New South Wales", *1993 CIGRÉ Regional Meeting, South-East Asia and Western Pacific*, Paper No. 7.4, Gold Coast, Australia, October 1993.

[5] A. Roman-Messina and B.J. Cory, "Enhancement of dynamic stability by coordinated control of static VAR compensators", *Int. Journal of Electrical Power and Energy Systems*, Vol. 15, No. 2, 1993, pp. 85-93.

[6] L. Wang, "A comparative study of damping schemes on damping generator oscillations", *IEEE Trans. Power Systems*, Vol. 8, No. 2, 1993, pp. 613-619.

[7] H.F. Wang, et. al., "Stabilization of power systems by governor-turbine control", *Int. Journal of Electric Power and Energy Systems*, Vol. 15, No. 6, 1993, pp. 351-361.

[8] M. Noroozian, "Damping of power system oscillations by controllable components, II - study of a multi-mode system", *PFC Project*, Dept. of Electric Power Systems, Royal Institute of Technology, Stockholm, August 1993.

[9] B.R. Korte, A. Manglick and J.W. Howarth, "Interconnection damping performance tests on the South-east Australian power grid", *Colloquium of CIGRÉ Study Committee 38*, Paper No. 3.7, Florianópolis, Brazil, September, 1993.

[10] R.H. Craven and M.R. Michael, "Load representations in the dynamic simulation of the Queensland power system", *Journal of Electrical and Electronics Engineering*, Vol. 3, No. 1, 1983, pp. 1-7.

[11] M.H. Kent, et. al., "Dynamic modelling of loads in stability studies", *IEEE Trans. Power Apparatus and Systems*, Vol. 88, No. 5, 1969, pp. 756-763.

[12] N.D. Rao and S.C. Tripathy, "Effects of load characteristics and voltage-regulator speed-stabilizing signal on power system dynamic stability", *Proceedings IEE*, Vol. 124, No. 7, 1977, pp. 613-618.

[13] W. Mauricio and A. Semlyen, "Effect of load characteristics on the dynamic stability of power systes", *IEEE Trans. Power Apparatus and Systems*, Vol. 91, 1972, pp. 2295-2304.

[14] C-J. Lin, et. al., "Dynamic load models in power systems using the measurement approach", *IEEE Trans. Power Systems*, Vol. 8, No. 1, 1993, pp. 309-315.

[15] W.W. Price, et. al., "Load modelling for power flow and transient stability computer studies", *IEEE Trans. Power Systems*, Vol. 3, No. 1, 1988, pp. 180-187.

[16] E. Welfonder, H. Weber and B. Hall, "Investigations of the frequency and voltage dependence of load part systems using a digital self-acting measuring and identification system", *IEEE Trans. Power Systems*, Vol. 4, No. 1, 1989, pp. 19-25.

[17] I.V. Zhezhelenko and V.P. Stepanov, "Development of methods for calculating electrical loads", *Electrical Technology*, No. 1, 1993, pp. 75-89.

[18] IEEE Task Force Report, "Load representation for dynamic performance analysis", *IEEE Trans. Power Systems*, Vol. 8, No. 2, 1993, pp. 472-482.

[19] C. Concordia and S. Ihara, "Load representation in power system stability studies", *IEEE Trans. Power Apparatus and Systems*, Vol. 101, No. 4, 1982, pp. 969-977.

[20] J.V. Milanović and I.A. Hiskens, "Effects of load dynamics on power system damping", *IEEE PES Summer Meeting*, Paper No. 94 SM 578-5 PWRS, San Francisco, 1994.

[21] J.V. Milanović and I.A. Hiskens, "The effects of dynamic load on steady state stability of synchronous generator", *Proc. Int. Conference on Electrical Machines ICEM'94*, Paris, France, September 1994.

[22] D.J. Hill, "Nonlinear dynamic load models with recovery for voltage stability studies", *IEEE Trans. Power Systems*, Vol. 8, No. 1, 1993, pp. 166-176.

[23] D. Karlsson and D.J. Hill, "Modeling and identification of nonlinear dynamic loads in power systems", *IEEE Trans. Power Systems*, Vol. 9, No. 1, 1994, pp. 157-166.

[24] S.A.Y. Sabir and D.C. Lee, "Dynamic load models derived from data acquired during system transients", *IEEE Trans. Power Apparatus and Systems*, Vol. 101, No. 9, 1982, pp. 3365-3372.

[25] CIGRÉ Task Force 38.02.05, "Load modelling and dynamics", *Electra*, No. 130, May 1990, pp. 122-141.

[26] C.P. Arnold, K.S. Turner and J. Arrillaga, "Modelling rectifier loads for a multi-machine transient-stability programme", *IEEE Trans. Power Apparatus and Systems*, Vol. 99, No. 1, 1980, pp. 78-85.

[27] C. Shackshaft, O.C. Symons and J.G. Hadwick, "General-purpose model for power-system loads", *Proceedings IEE*, Vol. 124, No. 8, 1977, pp. 715-723.

Ian A. Hiskens (S'77,M'80) received the B.Eng.(Elec.) degree and the B.App.Sc.(Math.) degree from the Capricornia Institute of Advanced Education, Rockhampton, Australia in 1980 and 1983 respectively. He received the Ph.D. degree from the University of Newcastle, Australia in 1990. He worked in the Queensland Electricity Supply Industry from 1980 to 1992. Dr Hiskens is currently a Senior Lecturer in the Dept. of Electrical and Computer Engineering at the University of Newcastle. His major research interests lie in the area of power system analysis, in particular system dynamics and control, security, and numerical techniques. Other research interests include nonlinear systems and control.

Jovica V. Milanović received Dipl.Ing.(Elec.) and M.E.(Elec.) degree from the University of Belgrade, Yugoslavia, in 1987 and 1991 respectively. One year he worked with "Energoproject-MDD" Co. in Belgrade as an engineer in designing power plants and substations. In 1988 he joined the Faculty of Electrical Engineering of the University of Belgrade, Yugoslavia, first as associate teaching assistant and then as teaching assistant at the Dept. of Power Converters and Drives. Since March 1993 Mr Milanović has been with the University of Newcastle, Australia, as a PhD student at the Dept. of Electrical and Computer Engineering. His major research interests includes synchronous machine and power system transients, control and stability.

DISCUSSION

D.M. VINOD KUMAR (Department of Electrical Engineering, Regional Engineering College, Warangal, INDIA) :

The authors' are to be congratulated for their paper which presents the load modelling studies for the power system damping. The paper is well written.

The modelling of the loads is complicated as the load composition were known exactly, it would be impractical to represent each individual component as there are usually several such components in the total load suplied by a power system [A].

The purpose of constructing load models is to obtain an accurate mathematical representation of loads to be incorporated in system stability and dynamic analysis

Artificial Neural Networks (ANN) approximation theorems were applied to ANN based load modelling problem with the knowledge of error bounds, and the results of ANN model load dynamics are accurate [B].

Hence authors' can make use of AI based (such as ANNs etc.,) dynamic load modelling for power system damping to over come misleading results of the classical load modelling.

REFERENCES

[A] P.Kundur, "Power System Stability and Control", McGraw-Hill, Inc 1994.

[B] B.Y.Ku, R.J. Thomas, C.Y.Chiou and C.J. Lin, "Power system dynamic load modelling using Artificial Neural Networks", IEEE Trans. on Power Systems, Vol. 9, No. 4, November, 1994, pp. 1868-1874.

Manuscript received February 27, 1995.

Y. Liang and C. Nwankpa (ECE Department, Drexel University, Philadelphia, PA):

The authors should be commended for having clearly shown both theoretical and numerical effects of different load models on power system damping. The result of this paper indicates that dynamic load models should be applied in studies on power system damping. It is obvious that the degree of this effect depends on the parameters of the model. It is interesting to note in Figure 5 of the paper that the time constant of the dynamic load model which has the most significant damping effect on the system oscillation is around 0.3 seconds which is relatively close to the period of the system oscillation (about 1.1 seconds). Is this coincidence? In other words, is this true in most other cases? We don't believe this to be coincidence. This is because load models with time constants significantly less or greater than the system oscillation period have minimal interactive effect on system oscillations and vice versa. If the authors agree or disagree with our point, is there theoretical explanations based on the closed loop transfer function of Figure 1? Finally, we would like to ask if the authors have thought about the effect of reverse reactive power recovery on system oscillation? We think this is an important question, since the reverse reactive power recovery occurs in heavily compensated power systems[1].

[1] S. G. Casper, C. O. Nwankpa, R. Fischl, A. DeVito and S. C. Readinger, "On Substation Tests for Load Modeling", Proceedngs of the 26th Annual *North American Power Symposium*, Manhatten Kansas, September 26-27, 1994.

Manuscript received March 7, 1995.

I.A. Hiskens, J.V. Milanović. We wish to thank the discussers for their kind comments and interesting discussions. We will provide a separate response to each discussion.

Y. Liang and C.O. Nwankpa

We agree with the discussers that the load time constant which has greatest effect on damping and the period of the system oscillation will generally be of the same order of magnitude. As mentioned in the paper, if the time constant is much smaller than the system oscillation period then the load will effectively behave as a static load, with indices given by the steady state characteristics, i.e., n_{ps}, n_{qs}. In response to the slow voltage changes caused by the system oscillations, the load will recover back to its steady state characteristic very quickly. So it will appear as a static load. Similarly, if the load time constant is much greater than the system oscillation period, then the load will respond very slowly to voltage deviations. So it will appear as a static load with indices n_{pt}, n_{qt} given by the transient characteristics.

The relationship can be explained further by referring to Figure 3 of [A], which is given here as Figure A. This figure plots gain and phase for the linearized dynamic load model for various load parameters. Interaction between the system and the load is generally dependent on there being significant gain and phase shift through the load at the system modal frequency. It can be seen from Figure A that as the frequency of interest (i.e., the modal frequency) increases, the time constant which gives maximum phase shift at that frequency decreases. Note though that it is a combination of gain and phase shift that dictates the overall effect.

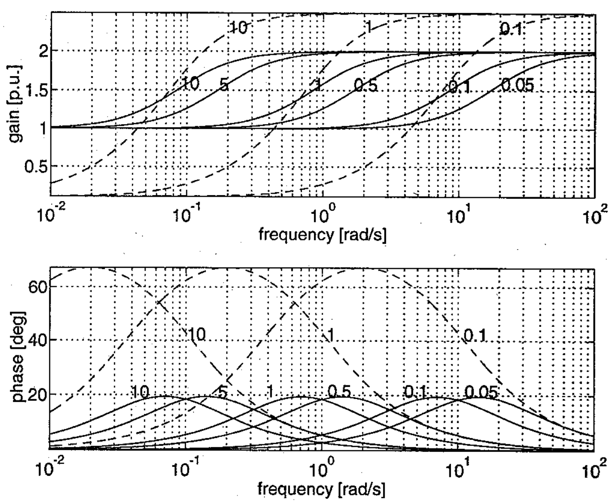

Figure A: Bode plots of dynamic load for different time constants, T_p. Dashed line - $n_{pt}/n_{ps} = 25$, solid line - $n_{pt}/n_{ps} = 2$.

We have not explored in any detail the effects of reverse reactive power recovery on system electromechanical oscillations. However we believe the effects could be very interesting. From [20], the linearized load model for reactive power is given by,

$$\Delta Q_d = (Q_o/V_o)\frac{(n_{qt}T_q s + n_{qs})}{(T_q s + 1)}\,\Delta V \qquad (1)$$

It can be seen from (1) that if n_{qt} or n_{qs} was less than zero, indicating transient reverse behaviour or steady state reverse recovery respectively, then the load model would be non-minimum phase, i.e., would have a right half plane zero. Such systems can exhibit complicated and quite non-intuitive behaviour. In a different line of work, we have found that for load systems, reverse recovery can lead to sustained oscillations, i.e., stable limit cycles. Further work is certainly required to explore the effects on electromechanical oscillations.

If both n_{qs} and n_{qt} were negative, then from (1), there would be an additional 180^0 phase shift through the load. It would appear that load - system interaction would be similar to 'normal' behaviour, but with the additional load phase shift.

D.M. Vinod Kumar

Artificial neural networks appear to provide a method of modelling the dynamic behaviour of loads. Other more traditional approaches, based on system identification techniques, can also provide useful models. In all cases, the models are only as good as the available data, and the statistics describing those data.

One important observation is that loads at certain locations within a power system may have more of an influence on electromechanical oscillations than loads at other locations. Figure 5 of the paper illustrates this. In that case, BUS5 is a much more significant location than BUS6. It is therefore important to identify the more significant loads and locations within a system, and devote most resources to modelling them.

[A] J.V. Milanović and I.A. Hiskens, "The influence of load dynamics on power system oscillations", *Proc. Electrical Engineering Congress*, Sydney, Australia, November 1994.

Manuscript received May 2, 1995.