LOCATING DYNAMIC LOADS WHICH SIGNIFICANTLY INFLUENCE DAMPING

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Abstract

The paper proposes a techniques for locating loads where dynamics have a significant influence on the damping of power system inter-area oscillations. A feedback interpretation of load dynamics underlies this technique. It is shown that eigenvalue sensitivity and residues can be used to provide the desired information. This approach is applicable for the analysis of large systems. Use of these ideas allows limited resources to be devoted to obtaining good models of important loads, rather than trying to obtain adequate models of many extra loads.

Keywords: dynamic loads, damping, eigenvalue sensitivity, residues

1 Introduction

The accurate prediction of power system dynamic behaviour is vital as power systems become more interconnected and as security margins decrease. It is important that system planners and operators have confidence in results obtained from analysis tools. The development of an understanding of the dynamic behaviour of a particular power system is generally based upon such results. If the results are incorrect, that understanding may be flawed, and subsequent decisions may be incorrect.

There have however been frequent reports of instances where the difference between predictions and actual behaviour has been quite significant, e.g., [5, 10]. In many cases, differences can be reduced by carefully testing (and accurately identifying the parameters of) major system components such as generators and their associated control loops. However loads can also have quite a dramatic effect on system behaviour [5, 13, 18]. Unfortunately though the testing of loads is not such a straightforward proposition.

Often modelled loads represent an aggregation of many diverse consumers [9]. The composition of the aggregate load continually varies, so it is only really meaningful to formulate a statistical description of that load. Producing useful statistics can involve enormous resources, in terms of equipment, people and time. It is therefore often not viable, even for moderately sized systems, to produce accurate load models for all loads. As a way of overcoming these problems, this paper proposes a technique for identifying loads which have a particularly significant influence on dynamic behaviour. This allows resources to be focussed where they are most needed. The aim has been to develop a technique suitable for large systems.

Previous papers [8, 14] have demonstrated that the dynamic response of loads can greatly influence the damping of electromechanical modes, and in particular inter-area modes. It has been shown that ignoring dynamics, and treating loads as statically dependent on voltage, can result in quite misleading predictions of damping. It is therefore important to identify loads which should be modelled as dynamic, as against those loads where a static representation would suffice. This is a subset of the overall problem of identifying significant loads. But it is nonetheless an important issue. It therefore forms the focus of this paper.

Load dynamics can be thought of as a feedback mechanism which influences system behaviour. This is shown diagrammatically in Figure 1, and is discussed further in Section 2.2. This representation motivates the use of linear system ideas which have proved useful in control design. In particular, residues and eigenvalue sensitivities have been used extensively in determining the most effective locations for siting power system stabilizers (PSSs). This is a similar problem to that of finding locations where load dynamics have the greatest effect. Therefore, in this paper we propose the use of these ideas/techniques for locating dynamic loads which significantly influence damping.

The results obtained using residue and sensitivity ideas are only valid for small parameter perturbations. However it is argued in Section 2 and demonstrated in the example of Section 5 that the results provide valuable information. Further, these techniques allow for fast scanning of all loads in large systems. (Having identified significant loads, other analysis techniques which are suitable for large parameter perturbations [8] could be used for more detailed investigations. Such techniques are more computationally intensive though, so are not generally suited to the problem of scanning all loads of large systems.) Another feature of the procedure based on residue and sensitivity ideas is that it effectively allows a decoupling of a load's location from the actual load at that location. It is therefore possible to identify significant locations in a power system (even though the load there may be relatively small), as well as significant loads. This is discussed further in Section 3.

The paper is organized as follows. Section 2 provides some background material on dynamic load modelling. Section 3 then establishes an analytical framework for investigating load effects. Based on that material, a proce-

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dure is developed in Section 4 for determining significant loads. This procedure is illustrated using the 150 bus example of Section 5. Conclusions are given in Section 6.

2 Background

2.1 Load modelling

We wish to identify locations where static load models do not adequately describe load behaviour, i.e., where load dynamics cannot be ignored. The first step is to establish generic models which are appropriate for describing static and dynamic load behaviour. The models need to be generic because loads are usually an aggregation of many devices. The aggregate load therefore generally does not behave like any one component, but rather as a combination of all the individual component responses. Further, generic load models are only useful if their parameters can be identified from measurements.

A generally accepted static load model for real power is given by,

$$P_d = P_o(V/V_o)^{n_p} \tag{1}$$

where P_d is the real power load demand. A similar equation describes reactive power demand. (Throughout the analysis we shall focus on real power loads. However reactive power loads, and combinations of real and reactive power loads can be treated similarly [8].) The static load representation establishes a fixed relationship between voltage and demand. However loads often respond dynamically to bus voltage changes. At a step change in voltage, demand will generally initially undergo a step change according to a relationship similar to (1). Load will then often recover back to some steady state value, see for example [7, 19]. A model which captures this form of behaviour was proposed in [7] as,

$$\begin{aligned} T_p\dot{x}_p &= P_s(V) - P_d &(2)\\ P_d &= x_p + P_t(V) &(3)\end{aligned}$$

where $P_t(V)$ describes the initial transient response of the load, and $P_s(V)$ gives the steady state load behaviour. It is convenient to formulate these functions as,

$$\begin{aligned} P_s(V) &= P_o(V/V_o)^{n_{ps}} &(4)\\ P_t(V) &= P_o(V/V_o)^{n_{pt}} &(5)\end{aligned}$$

The time constant T_p describes the rate of recovery of the load. Note that as $T_p \rightarrow 0$, load behaviour approaches $P_d = P_s(V)$. With $T_p = 0$, (2) has the same form as the static load representation (1), but with n_{ps} replacing n_p. Therefore the parameter T_p captures an essential difference between static and dynamic loads. The sensitivity of system behaviour to variations of T_p away from zero reflects, to a large extent, the significance of dynamic load effects, i.e., a low sensitivity would indicate that a static representation was adequate whereas a high sensitivity would indicate that load dynamics played an important role. We shall therefore use a sensitivity-based framework for identifying important dynamic loads. This is further justified by the fact that for inter-area modes, loads with time constants around 0.3-0.5sec have the largest influence on system damping [15].

Note that the dynamic load model (2),(3) was originally proposed for modelling slower load behaviour relevant for voltage collapse studies. However it is just as appropriate for describing faster load dynamics. Because we are investigating the effects of loads on system damping, i.e., a small disturbance phenomenon, we shall linearize the dynamic load model. This gives,

$$\begin{aligned} \Delta P_d &= (P_o/V_o)\frac{(n_{pt}T_p s + n_{ps})}{(T_p s+1)}\Delta V &(6)\\ &= (P_o/V_o)n_{pt}\frac{(T_p s + \frac{n_{ps}}{n_{pt}})}{(T_p s+1)}\Delta V &(7)\\ &= L(s,T_p)\Delta V &(8)\end{aligned}$$

2.2 Feedback interpretation of loads

The load equations, (1) for static loads and (2),(3) for dynamic loads, couple into the overall power system model via the power balance equations. For real power we have,

$$0 = P_d + P_l(\theta, V) \tag{9}$$

where $P_l(\theta, V)$ is the total power received from the system. A similar equation applies for reactive power. Linearizing this equation yields,

$$0 = \Delta P_d + \frac{\partial P_l}{\partial \theta}\Delta\theta + \frac{\partial P_l}{\partial V}\Delta V \tag{10}$$

where $\frac{\partial P_l}{\partial \theta}$, $\frac{\partial P_l}{\partial V}$ are elements of the power flow Jacobian.

Consider a bus in the power system where we wish to investigate the effect of the load. In particular, we are interested in how changes in real power ΔP_d affect the bus voltage ΔV. Equation (10) is part of a differential-algebraic description of the complete system. Manipulation of this system description yields the state space representation [8],

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + b\Delta P_d &(11)\\ \Delta V &= c^t\Delta x + d\Delta P_d &(12)\end{aligned}$$

where x is the vector of state variables, such as generator states, FACTS devices, and load states of *other* loads (not the particular load of interest). Taking Laplace transforms, we obtain the power system transfer function,

$$\begin{aligned} \Delta V &= \left(c^t(sI-A)^{-1}b + d\right)\Delta P_d &(13)\\ &= S(s)\Delta P_d &(14)\end{aligned}$$

So we see from (14) that changes in power demand ΔP_d produce changes in voltage ΔV. But from (8) we have that changes in voltage ΔV produce changes in load ΔP_d. Therefore together the system $S(s)$ and the load $L(s, T_p)$ have the feedback structure shown in Figure 1. Note however that the time constant of interest T_p is a parameter of the feedback (load) transfer function $L(s, T_p)$ only.

3 Eigenvalues, residues and sensitivities

The power system transfer function $S(s)$, i.e., the open-loop system with no load feedback, can be formulated in a partial fractions expansion as,

$$S(s) = \frac{R_1}{(s-\lambda_1)} + \frac{R_2}{(s-\lambda_2)} + \ldots + \frac{R_n}{(s-\lambda_n)} = \sum_{i=1}^{n}\frac{R_i}{(s-\lambda_i)} \tag{15}$$

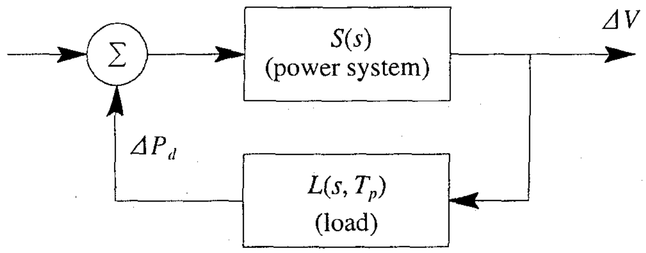

Figure 1: Feedback interpretation of load

where the λ_i are the eigenvalues of the A matrix in the state space representation (11),(12). The coefficients R_i are the residues [6] associated with distinct eigenvalues λ_i. For the single input single output system (11),(12), the residues can be calculated from,

$$R_i = w_i^t b c^t v_i \tag{16}$$

where w_i^t and v_i are the left and right eigenvectors associated with λ_i, normalized such that $w_i^t v_i = 1$.

Consider the feedback system of Figure 1. If we assume for now that $L(s, T_p) = 0$ for $T_p = 0$ (we will discuss this assumption later), then the sensitivity of eigenvalue λ_i to an incremental change in parameter T_p is given by [1, 17],

$$D\lambda_i = \frac{\partial \lambda_i}{\partial T_p} = R_i \frac{\partial L(\lambda_i, T_p)}{\partial T_p} \tag{17}$$

Now λ_i and R_i are an eigenvalue and residue of the open-loop system. However under the assumption $L(s, 0) = 0$, and for small variations ΔT_p, the eigenvalue variation $\Delta\lambda_i$ effectively gives the sensitivity of the closed loop eigenvalue. So (17) provides information on the variation of the damping of a system mode for small changes (away from zero) in the load time constant T_p. As discussed earlier, static loads correspond to $T_p = 0$, whilst for dynamic loads $T_p > 0$. Therefore (17) effectively describes the sensitivity of a system mode to the inclusion of load dynamics.

In establishing (17) we made the assumption that $L(s, 0) = 0$, i.e., that the load feedback was zero when $T_p = 0$. Referring to (6), we see that condition is only strictly satisfied for $n_{ps} = 0$, i.e., when the load dynamics restore the demand back to its predisturbance value at steady state. Whilst that is not exactly the case is general, many loads do return to near their predisturbance values, implying that n_{ps} is small. In fact, it can be seen from (7) that provided (n_{ps}/n_{pt}) is small then $L(s, 0) \approx 0$, i.e., our earlier assumption is closely approximated. Many different types of loads, from motors [4] to aluminium smelters [3], have $n_{ps} << n_{pt}$. We conclude that the error introduced into (17) by this assumption can be neglected [16, 20].

We shall now consider the use of (17) for quantifying the effects of load dynamics on damping. The sensitivity $D\lambda_i$ gives the change in the mode λ_i for a small variation of T_p away from zero. It reflects the change in λ_i as the load moves from a static to a dynamic representation. The sensitivity $D\lambda_i$ is a complex number. If its real part is negative, then damping is improved by the change from a static to a dynamic load representation. (The eigenvalue moves further to the left.) If its real part is positive, the change in load modelling leads to a deterioration in damping. The magnitude of $D\lambda_i$ gives a measure of how sensitive the mode is to load modelling. A high value of $D\lambda_i$ would flag the load as having a significant effect on the mode, whereas a small value would indicate the load was likely to have an insignificant effect. This information would identify loads which were worthy of further, more detailed, investigation, and those that were not.

Note that the sensitivity $D\lambda_i$ is a function of both the residue R_i and the load sensitivity $\frac{\partial L}{\partial T_p}$. The residue reflects the behaviour of the open-loop power system, whereas $\frac{\partial L}{\partial T_p}$ describes load behaviour. Therefore $D\lambda_i$ is influenced by both the load and its location. In particular, the size of the load will be factored into $D\lambda_i$. This may lead to situations where a large load at a relatively insensitive location has a larger sensitivity $D\lambda_i$ than a smaller load at a more important location. It may therefore be desirable to decouple the location from the load. A discussion of the way in which this can be achieved follows.

The eigenvalue sensitivity formulation (17) has been used for siting and tuning PSSs [2, 11]. From (17), it can be seen that as the magnitude of the residue R_i increases, the sensitivity of the eigenvalue to parameter changes increases. In the PSS context, this provides information on locations where the effectiveness of PSSs would be maximized. Similar ideas can be used for dynamic loads. A large residue magnitude for a particular location and mode would indicate that the mode was quite sensitive to a change in T_p, and hence to load dynamics. A small residue would indicate that the mode was quite insentitive to load dynamics at that location. Recall that the residues are calculated for the open-loop system, i.e., the power system 'seen' by the load. They are (effectively) independent of the actual load at that location. (There is however a secondary dependence on the load magnitude because the loads are coupled in through the power flow equations (9).) Therefore residue magnitudes provide a measure of the significance, in terms of the influence of loads on particular modes, of load locations. Note that residues can (and in practice do) show that a location may be significant for one mode but insignificant for a different mode.

In designing controllers such as PSSs, the residue phase angle ($\arg R_i$) has also proved to be useful [1, 11, 17]. To achieve maximum damping, the phase shift through the feedback controller, at the frequency of the mode of interest, should be,

$$\arg H(j\omega_i) = 180^o - \arg R_i \tag{18}$$

With this phase shift, the change in the eigenvalue λ_i after closure of the feedback loop will be in the 180^o direction, i.e., in the negative real direction [11]. This maximizes damping.

These ideas are again useful in interpreting the effects of load dynamics. When $n_{ps} < n_{pt}$, which is normal for loads, the load transfer function $L(s, T_p)$ always has positive phase shift [8]. Therefore if the residue lies in the first or second quadrant, then the load phase shift will move the sensitivity $D\lambda_i$ towards 180^o. The load will therefore tend to improve damping. (With the real part of $D\lambda_i$ negative, λ_i will move further to the left as T_p increases from zero.) However if the residue lies in the third or fourth quadrant, then the load phase shift will move the sensitivity away from 180^o toward 360^o. The load in this case will tend to reduce damping.

4 A procedure for determining significant loads

To assess the influence of a particular load on damping, that load is treated in the feedback form shown in Figure 1. Then, for the corresponding open-loop system (the power system 'seen' by that load), eigenvalues and the associated left and right eigenvectors can be determined from the system A matrix. This can be done by calculating all eigenvalues and eigenvectors of the system or only those connected with particular electromechanical modes. Calculation of all eigenvalues and eigenvectors is time consuming and impractical for very large power systems, so various iterative techniques have been developed to determine only those modes of interest [12]. After determining the left (w_i) and right (v_i) eigenvectors associated with the relevant inter-area modes, they are normalized in order to satisfy $w_i^t v_i = 1$. By applying (16), the residues associated with desired open-loop eigenvalues can be determined. Once these residues have been calculated, the sensitivities can be quickly found using (17).

The above procedure can be built into a loop which scans through all loads calculating the residues and sensitivities for modes of interest. Their magnitudes identify significant locations and loads respectively. The phase angles indicate whether load dynamics cause an improvement or a deterioration in the damping of the various modes. On the basis of this information the load modelling efforts could be directed to those loads which have the maximum effect.

Each load 'sees' a slightly different power system, so residues need to be recalculated for each load bus of interest. This involves different b and c vectors, and a recalculation of the relevant system eigenvalues and eigenvectors. The shift in eigenstructure between loads is however quite small, so the recalculation can be performed extremely efficiently using an iterative technique [12].

It should be noted that the sensitivity information obtained from this procedure is only valid for small parameter changes. Therefore, whilst it is useful as an indicator of load significance, it doesn't guarantee any particular trend for large parameter variations. Having identified important loads, more detailed investigations would generally be required to determine global trends.

5 Example

To illustrate the method explained in the previous section, a 150 bus power system consisting of 10 equivalent generators (with associated AVR, PSS and governors), 87 loads and 1 SVC, connected by 289 lines and transformers was used. (This system was motivated by an Australian state system.) With all loads modelled statically, the system has two inter-area modes, with frequencies of 0.31Hz and 1.05Hz. Tables 1 and 2 give load magnitudes ($P+jQ$), modal eigenvalues (λ), residues (R), residue magnitudes ($|R|$) and eigenvalue sensitivities (Sens.) for a number of representative loads. In Table 2, the first row for each bus corresponds to the 0.31Hz mode, while the second row corresponds to the 1.05Hz mode.

In Figure 2 the root loci for the loads that have the largest (B14) and smallest (B24) effect on the inter-area mode with frequency of 1.05Hz are given. (The loci correspond to variation of load time constants from 0s to 100s. The arrows indicate the direction of increasing time constant. They were obtained using large parameter variation techniques.) Agreement between predictions based on sensitivities and residue magnitudes and phases, and the actual root loci behaviour can be seen by comparing the loci with the values given in Table 2. The root locus of the 1.05Hz mode when loads at the five most sensitive locations were modelled as dynamic is also given in Figure 2.

Bus	(P+jQ)(p.u.)
B01	4.0100+j1.8270
B02	2.6327+j2.3545
B06	1.1412+j0.7278
B14	0.7919+j0.5159
B24	0.5159+j0.4482

Table 1: Bus loads

Bus	λ	R	$\lvert R\rvert$	Sens.
B01	-0.1592+j2.0022	0.0062-j0.0047	0.0078	+0.1523
	-0.6358+j6.5020	0.0023+j0.0139	0.0141	-1.6490
B02	-0.1457+j1.9223	0.0011+j0.0047	0.0048	-0.1633
	-0.5896+j6.6161	-0.0037-j0.0064	0.0074	+0.7786
B06	-0.1499+j1.9656	0.0062-j0.0038	0.0073	+0.0397
	-0.5925+j6.5810	0.0019+j0.0161	0.0162	-0.6572
B14	-0.1489+j1.9500	0.0015-j0.0002	0.0015	+0.0007
	-0.7102+j6.6995	0.0472-j0.0855	0.0977	+2.4062
B24	-0.1427+j1.9459	-0.0008+j0.0004	0.0009	-0.0025
	-0.5895+j6.5867	-0.0034+j0.0037	0.0050	-0.0775

Table 2: Residues and sensitivities for some representative load buses

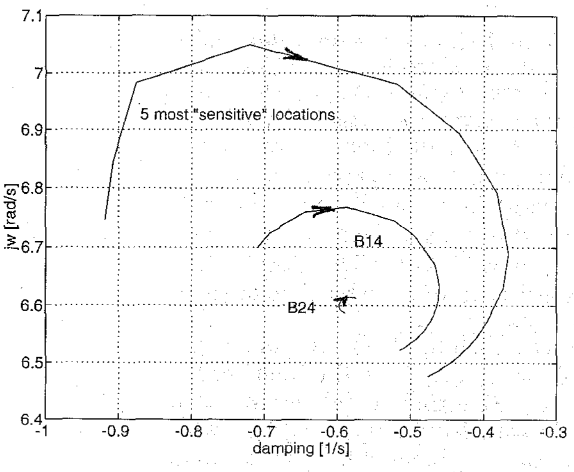

Figure 2: Root loci of 1.05Hz mode

In Figure 3, root loci are given for the loads that have the largest (B01) and smallest (B24) effects on the inter-area mode with frequency of 0.31Hz. Also shown is the root locus for the case where loads at the five most sensitive locations were modelled as dynamic. The arrows again denote the direction of movement of a mode as the time constants of the dynamic loads were varied from 0s to 100s.

The root loci in Figures 2 and 3, and the predictions of eigenvalue behaviour given by residues and sensitivities in Table 2, show complete agreement. All root loci initially move in accordance with predictions based on residue phase angles and sensitivities. For residue phase angles which are smaller than 180° initial movement is to

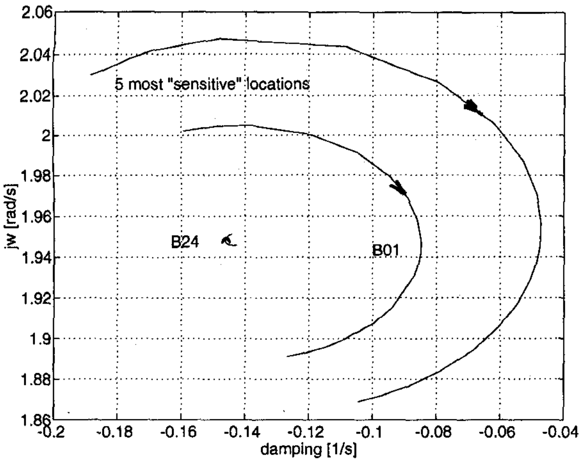

Figure 3: Root loci of 0.31Hz mode

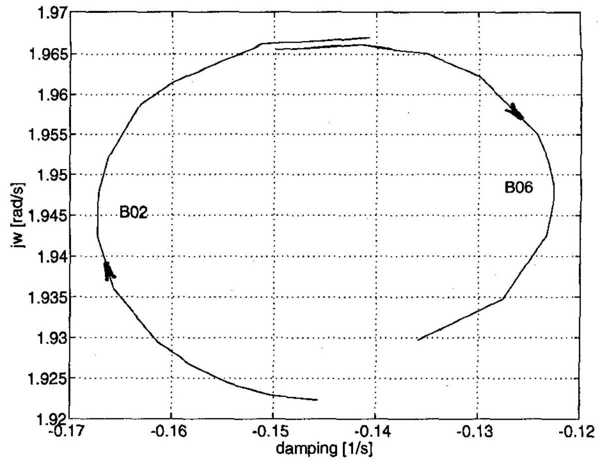

Figure 4: Root loci of 0.31Hz mode

the left, i.e., an increase in damping. In these cases sensitivities are negative. For residue phase angles larger than 180^o, initial movement is to the right, i.e., a decrease in damping. In these cases sensitivities are positive.

The magnitude of the residue provides an indication of the sensitivity of the load's location. However the overall effect on damping is due both to the sensitivity of the location and the size of the load at that location. To illustrate this, consider the 0.31Hz mode and buses B02 and B06. Comparing residue magnitudes and sensitivities for loads at buses B02 and B06, given in Table 2, one can conclude that the location of load B06 is almost twice as sensitive. However the load at B02 is much larger than that at B06. From Table 2, it can be seen that the sensitivity of the mode to dynamics of the load at B02 is higher, so the resulting effect is that the system is more sensitive to load dynamics at B02. This can be seen by comparing the sizes of the corresponding root loci in Figure 4. The arrows again denote the direction of movement of the mode when the time constants of the dynamic loads were varied from 0s to 100s. Note that the results of Table 2 indicate that the 0.31Hz mode will be a little more sensitive to load dynamics at B02 than at B06. The camparative sizes of the loci of Figure 4 reflect that result.

Figure 5 illustrates the significance of appropriate load modelling, and especially modelling based on residue and sensitivities predictions. It can be seen that for a large disturbance, in this case a single-phase-to-ground fault, the power system experiences different damping depending on the type of load dynamics. In producing the results shown in Figure 5, the 21 most influential of the 87 loads were modelled as dynamic. The results show that the power system with those loads modelled as dynamic can be more (load time constants, T=10s) or less (load time constants, T=0.3s) damped than the power system with all loads modelled as static (load time constants, T=0s). The damping of the system clearly depends on the dynamics of its loads.

As a comparison, Figure 6 shows the same case, but with the 21 least influential loads (as predicted by the procedure of Section 4) modelled as dynamic. It is clear that load dynamics have little effect in this case. Figures 5 and 6 highlight the importance of identifying loads which have a significant influence on system dynamics, and the need for correct modelling of those significant loads.

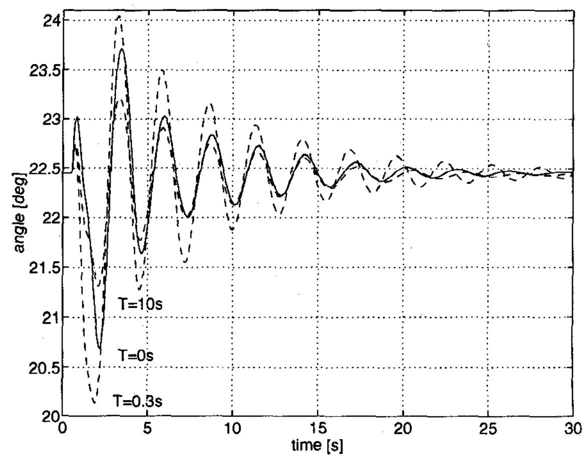

Figure 5: Dynamic response for different load dynamics - most influential loads

6 Conclusions

Dynamic behaviour of loads can have a significant influence on the damping of inter-area oscillations of power systems. Ignoring load dynamics, by treating loads as statically dependent on voltage, can lead to errors in damping predictions. But not all loads influence system behaviour to any great extent. Therefore it is important to be able to identify loads and locations which are significant. Then the resources required for producing better load models can be focussed where they are most needed.

The dynamic behaviour of loads can be thought of as a feedback mechanism which influences system damping. This representation motivates the use of linear systems ideas. It is shown in the paper that residues and eigenvalue sensitivities can be used to identify locations where load modelling is important, and loads which have a significant influence on damping. Even though these techniques are strictly only valid for small parameter variations, a 150 bus example illustrates that the ideas reliably provide useful information.

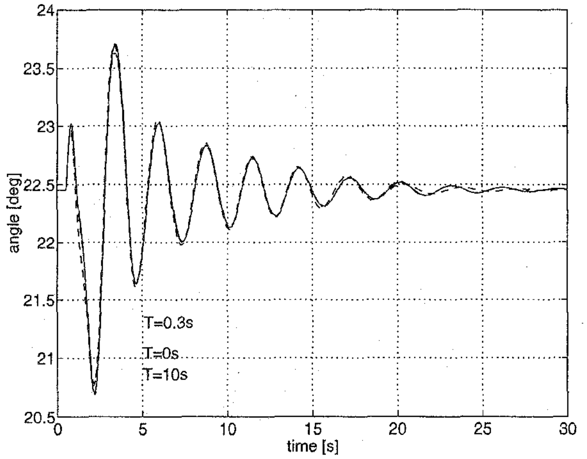

Figure 6: Dynamic response for different load dynamics - least influential loads

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Discussion

Y. Liang and C.O. Nwankpa(Drexel University, Philadelphia, PA 19104): The authors are to be commended for having systematically developed an approach for locating dynamic loads which significantly influence power system damping. Based on locating results, both labor and time can be saved in modeling dynamic loads which usually involves measurement device installation and data recording. The proposed method is simple and straightforward to implement. Concerning the details of this paper, we have some comments and questions presented below.

The appropriateness of a dynamic load model depends on which study it is applied to. In different power system studies, different load models should be employed. This is mainly because of the interested time interval of study and the interested state variable oscillation frequency. In particular, when system oscillation frequency is considered, selection of the load model will depend on the interested mode. In this paper, the authors chose the nonlinear dynamic load model from [D1] for all the modes under investigation. Have the authors verified that this load model is suitable to their interested mode of oscillation damping study?

According to our observations[D2][D3], the load recovery after a step voltage disturbance exhibited oscillation immediately following the disturbance, which suggests that higher order model may be used, if this early stage behavior is important to the application. Having examined the oscillation damping modes, we find that they are in the range of 1-3 seconds compared to most of the dynamic load recovery behaviors whose time constants range from tens of seconds to minutes[D2,D3]. This implies that higher order dynamic load model is a better choice to capture the early stage oscillation behaviors. This idea was justified in [D4]. Where the first order dynamic load model[D4] was first applied and found not to be accurate enough. A second order dynamic load model was then applied which yielded satisfactory results. We would the authors' comments on whether or not this has been observed by them in their studies and how is it addressed by their methodology.

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I.A. Hiskens and J.V. Milanović: We wish to thank the discussers for their thoughtful comments and questions.

We agree that the appropriateness of a load model is dependent upon the study in which it is applied. Certainly, the load model which we have used was originally developed to capture longer term load recovery, such as occurs with heating load [D1]. However it is a generic model which is valid whenever load responds to a voltage step by undergoing an initial step change followed by an exponential form of recovery. Many different types of loads exhibit that form of response, including loads with quite small time constants, e.g., $T_p, T_q \approx 0.1 - 0.4$sec. It is these loads which have an influence on the damping of electromechanical oscillations, as verified in [8,14].

The techniques proposed in the paper were motivated by the feedback interpretation of the load influence, as illustrated in Figure 1. The paper used the (linearized) recovery load model. However the methodology is effectively independent of that particular load model.

The higher order dynamics of slower recovery loads could influence the damping of electromechanical oscillations. We have not studied such cases where the higher order dynamics were important. However the ideas in the paper extend naturally to those situations. The higher order dynamics are modelled by a higher order load transfer function [C1]. In the analysis of damping, the load model is linearized, yielding a higher order linear transfer function. Because of the linearity of the small disturbance model, the methodology of the paper remains valid. It may however become necessary to check the sensitivity of oscillatory modes to extra parameters, i.e., to produce sensitivities of the form (17) for a number of parameters. These parameters could presumably be the time constants associated with the recovery dynamics and the higher order dynamics. This is not difficult to do, as the major computational burden is in determining the residues R_i. The load transfer function derivatives $\frac{\partial L(\lambda_i,\eta)}{\partial \eta}$, where η is a parameter vector, involve little extra computation.

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