Effect of Load Model on Damping of Oscillations in Power Systems

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Abstract: Power system dynamic stability is closely associated with load model and damping of oscillations is affected by load model. In this regard, investigation of load model on system dynamic stability is useful. Application of a practical load model can lead to more suitable results in power system simulations. In this paper, different load models are investigated and some of them are simulated and compared. The results show the great effect of load model on power system stability and performance.
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1. Introduction

Load models have always been an important issue in power system analysis and performance and many different researches have been presented to show effect of load models in power systems [1-9]. The aggregate characteristic of the load depends on the characteristics of its individual components. A rough estimate of the aggregate characteristic, viewed from the medium-voltage side (the secondary of the feeder transformer), can be obtained by summing the individual load characteristics. Figure 1 shows two examples of load characteristics obtained by this technique. Figure 1(a) shows an industrial load characteristic with a predominance of heavily loaded induction motors and discharge lighting. Near the nominal operating point (voltage Vn), the P(V) curve is flat while the Q(V) curve is steeper with a positive slope. As the voltage decreases, the Q(V) curve becomes flatter and even rises due to the increased reactive power demand of the stalled motors. When the voltage drops below about 0.7 per unit, the P(V) and Q(V) curves rapidly decrease due to tripping of the induction motors and extinguishing of the discharge lighting. Figure 1(b) shows an example of a residential/commercial load that is dominated by traditional bulb lighting and heating. Near the nominal voltage both the P(V) and Q(V) curves are quite steep. Again the real and reactive power demand drops rapidly at about 0.7 per unit. As the induction motor's stall voltage is now below the dropout voltage, dropout is not preceded by an increase in the reactive power demand. The curves shown in Figure 1 can only give an indication of the kind of shape a load voltage characteristic may have. They cannot be treated in a general manner because the characteristic of a particular load may be quite different. For example, reactive power compensation can cause the Q(V) curve to be flatter near the nominal voltage. Also relatively small, non-utility generation embedded in the load area will significantly affect the load characteristic. There is also a difference in the characteristic as seen from the primary and secondary sides of the feeder transformer. Firstly, the real and reactive power loss in the transformer must be added to the load demand. Secondly, the feeder transformer is usually equipped with an on-load tap changer to help control the voltage in the distribution network and this also affects the characteristic as illustrated in Figure 1. In Figure 1 the middle dashed bold line represents the load voltage characteristic at the nominal transformation ratio. Tap changing is controlled in discrete steps so that if the transformers tap setting is changed, the voltage characteristic moves to the left or right in discrete steps as shown by the dotted lines. The extreme left and right characteristics represent the tap-changer limits. A dead zone is also present in the regulator in order to prevent any tap changes if the voltage variations are within limits. The resulting voltage characteristic is shown by the bold line and is quite flat within the regulation range, as can be seen by sketching an average line through the resulting characteristic.

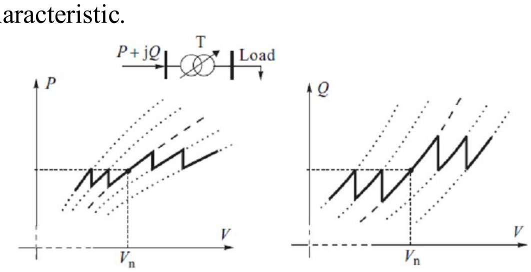

Figure 1: Influence of a tap-changing transformer on the voltage characteristic of a composite load [10]

2. Load Models

The last subsection described how the real and reactive power of particular types of load depends on the load voltage but did not explain how these could be represented by a mathematical model. Since all power system analysis programs, for example load flow or dynamic simulation, require such a load model, this subsection describes some of the most popular models currently in use.

2.1. Constant Power/Current/Impedance

The simplest load models assume one of the following features [10]:

- a constant power demand (P)
- a constant current demand (I)
- a constant impedance (Z).

A constant power model is voltage invariant and allows loads with a stiff voltage characteristics $k_{PV} \approx k_{QV} \approx 0$ to be represented. This model is often used in load flow calculations, but is generally unsatisfactory for other types of analysis, like transient stability analysis, in the presence of large voltage variations. The constant current model gives a load demand that hangs linearly with voltage $k_{PV} \approx 1$ and is a reasonable representation of the real power demand of a mix of resistive and motor devices. When modeling the load by a constant impedance the load power changes proportionally to the voltage squared $k_{PV} \approx k_{QV} \approx 2$ and represents some lighting loads well but does not model stiff loads at all well. To obtain a more general voltage characteristic the benefits of each of these characteristics can be combined by using the so-called polynomial or ZIP model consisting of the sum of the constant impedance (Z), constant current (I) and constant power (P) terms [10]:

$$P = P_0\left[a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right]$$

$$Q = Q_0\left[a_4\left(\frac{V}{V_0}\right)^2 + a_5\left(\frac{V}{V_0}\right) + a_6\right]$$

where, V_0, P_0 and Q_0 are normally taken as the values at the initial operating conditions. The parameters of this polynomial model are the coefficients (a_1 to a_6) and the power factor of the load. In the absence of any detailed information on the load composition, the real power is usually represented by the constant current model while the reactive power is represented by constant impedance.

2.2. Exponential Load Model

In this model the power is related to the voltage by [10]:

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p} \quad \text{and} \quad Q = Q_0\left(\frac{V}{V_0}\right)^{n_q}$$

where, n_p and n_q are the parameters of the model. Note that by setting the parameters to 0, 1, 2, the load can be represented by constant power, constant current or constant impedance, respectively. The slope of the characteristics given by equation depends on the parameters n_p and n_q. By linearizing these characteristics it can be shown that n_p and n_q are equal to the voltage sensitivities.

2.3. Piecewise Approximation

None of the models described so far will correctly model the rapid drop in load that occurs when the voltage drops below about 0.7 per unit. This can be remedied by using a two-tier representation with the exponential, or polynomial, model being used for voltages close to rated and the constant impedance model being used at voltages below 0.3–0.7 per unit. Figure 2 shows an example of such an approximation [10].

2.4. Frequency-Dependent Load Model

Frequency dependence is usually represented by multiplying either a polynomial or an exponential load model by a factor $(1 + a_f(f - f_0))$ where f is the actual frequency, f_0 is the rated frequency and a_f is the model frequency sensitivity parameter. Using the exponential model this gives [10]:

$$P = P(V)\left[1 + k_{Pf}\frac{\Delta f}{f_0}\right]$$

$$Q = Q(V)\left[1 + k_{Qf}\frac{\Delta f}{f_0})\right]$$

where, P(V) and Q(V) represent any type of the voltage characteristic and k_{Pf}, k_{Qf} are the frequency sensitivity parameters, $f = f - f_0$.

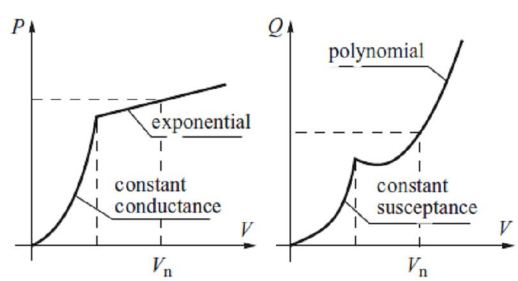

Figure 2: Example of a two-tier approximation of the voltage characteristics [10]

3. Load Model and Stability

Figure 3 shows a simple model of power system. Following relation can be driven form the figure [10]:

$$\left(\frac{EV}{X}\right)^2 = [P_L(V)]^2 + \left[Q_L(V) + \frac{V^2}{X}\right]^2$$

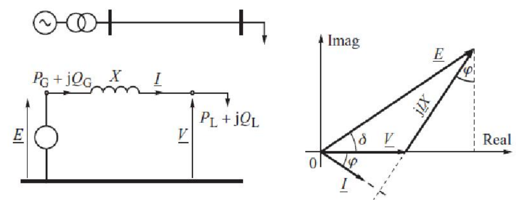

Figure 3: simple power system model [10]

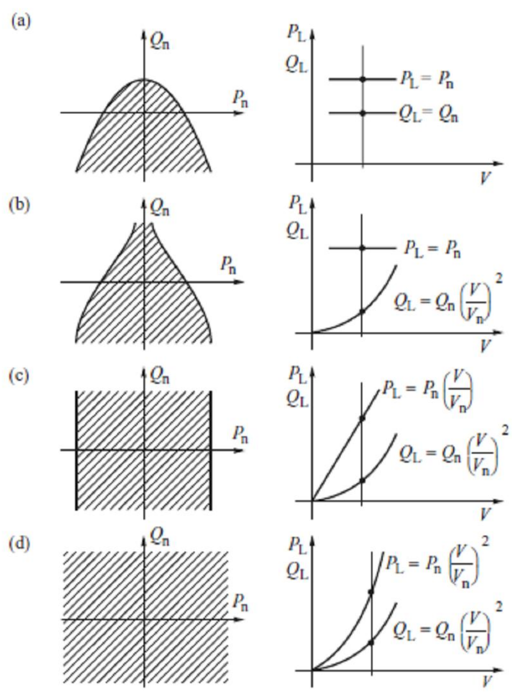

Figure 4: Dependence of the network solution area on the shape of the load characteristics [10]

For the more general case the power demand will depend on the voltage as described by the voltage characteristics $P_L(V)$ and $Q_L(V)$. The possible solutions to above equation will not now be bounded by a simple parabola, as for $P_L(V) = Pn$, $Q_L(V) = Qn$, but the shape of the solution area will vary depending on the actual voltage characteristics as shown in Figure 4. In general the less stiff the load, the more open the solution area. For the constant load discussed above, the solution area corresponds to a parabola, Figure 4(a). If the reactive power characteristic is a square function of the voltage, $Q_L(V)=(V/Vn)^2Qn$, then the solution area opens up from the top, Figure 4(b), so that for Pn = 0 there is no limit on Qn. If the real power characteristic is linear $PL(V) = (V/Vn)^2Pn$ as in Figure 4(c), then the solution area is bounded by two parallel, vertical lines. If both real and reactive power characteristics are square functions of the voltage, $PL(V)=(V/Vn)^2Pn$ and $QL(V)=(V/Vn)^2Qn$, then there are no limits on the values of Pn and Qn as shown in Figure 4(d). Consider again the characteristics of Figure 4(d) where there are no limits on the real and reactive power. This can be proved by expressing [10]:

$$P_L(V) = P_n\left(\frac{V}{V_n}\right)^2 = \frac{P_n}{V_n^2}V^2 = G_n V^2$$

$$Q_L(V) = Q_n\left(\frac{V}{V_n}\right)^2 = \frac{Q_n}{V_n^2}V^2 = B_n V^2$$

4. Simulation results

In order to show effect of turbine governing systems on stability, a typical power system is considered as test case. The turbine governing systems parameters are changed to show effect of them on stability. Figure 3 shows the test system and its data are given in [11]. Two load models are considered as follows:

Case 1: ZIP load model
Case 2: Constant P-Q load model

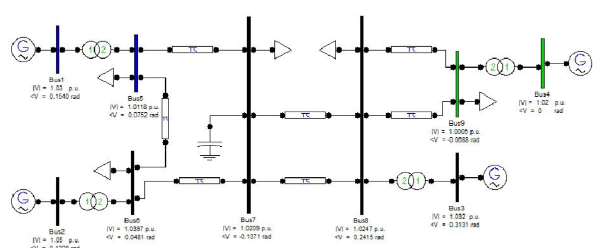

Figure 5: IEEE 9-bus System Dynamic Benchmark[11]

The simulation results are carried out by applying three disturbances as follows:

Disturbance 1: 6-cycles three phase short circuit in bus 6
Disturbance 2: 8 cycles three phase short circuit in bus 6

The simulation results are depicted in Figures 6-13. It is clearly seen that the load model has a great effect on responses and constant PQ model is the worst case model in power systems. The results show that PQ model is instable in some conditions such as Figures 10-13, where the ZIP model is stable. Therefore the results show effectiveness of load model in power system analysis.

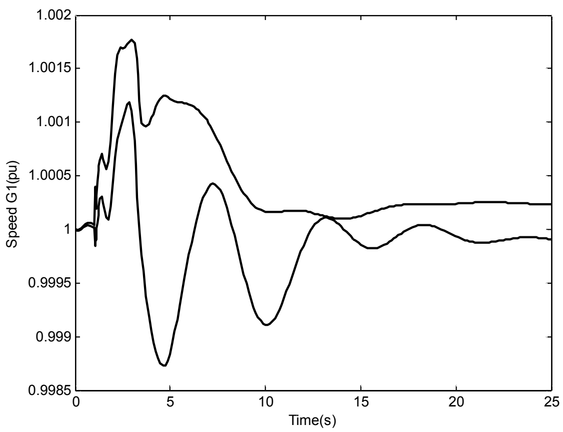

Figure 6: Speed G_1 following disturbance 1 (solid: case 1, dashed: case 2)

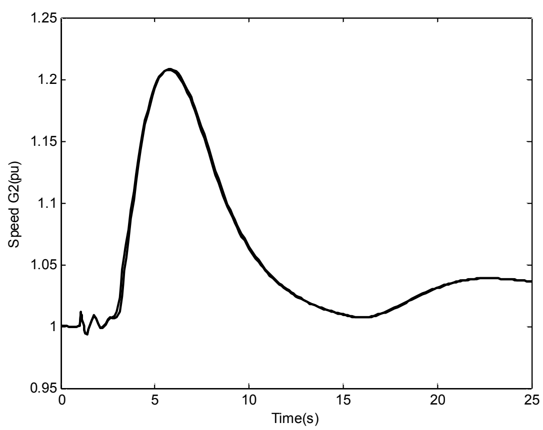

Figure 7: Speed G_2 following disturbance 1 (solid: case 1, dashed: case 2)

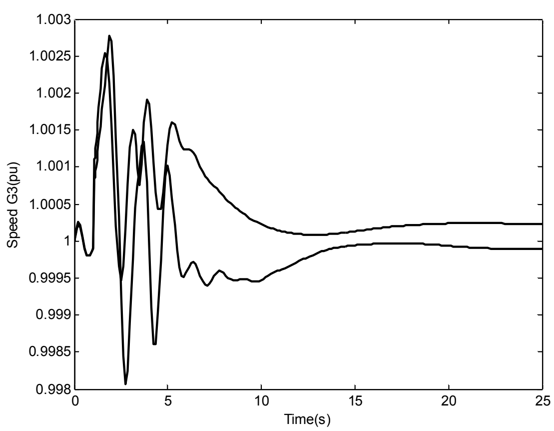

Figure 8: Speed G_3 following disturbance 1 (solid: case 1, dashed: case 2)

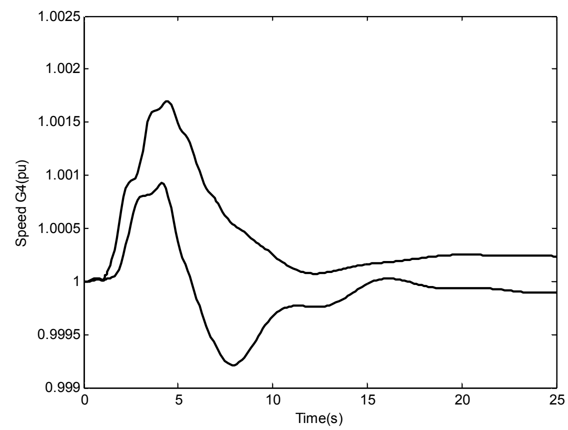

Figure 9: Speed G_4 following disturbance 1 (solid: case 1, dashed: case 2)

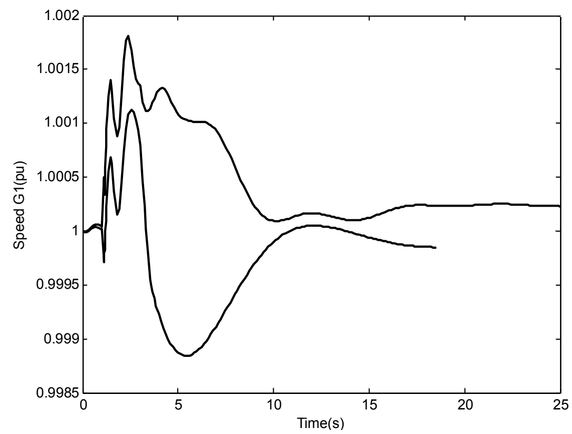

Figure 10: Speed G_1 following disturbance 2 (solid: case 1, dashed: case 2)

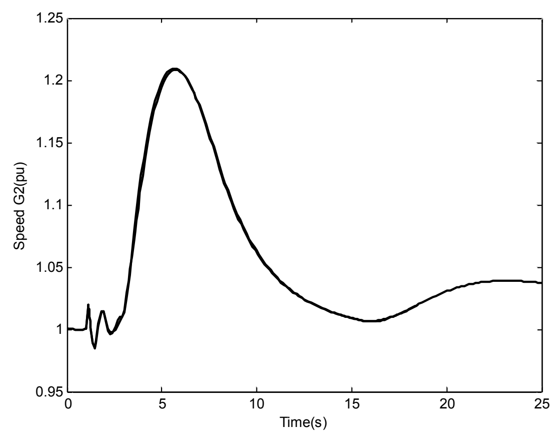

Figure 11: Speed G_2 following disturbance 2 (solid: case 1, dashed: case 2)

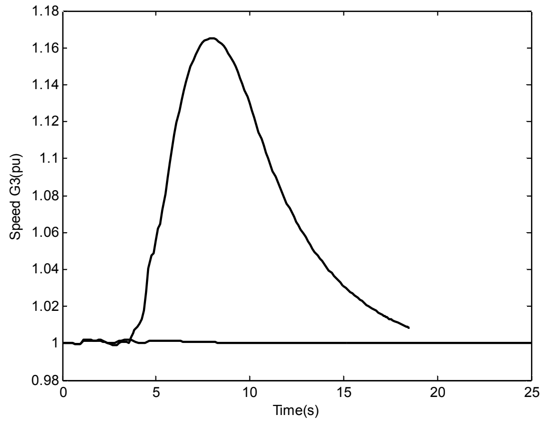

Figure 12: Speed G_3 following disturbance 2 (solid: case 1, dashed: case 2)

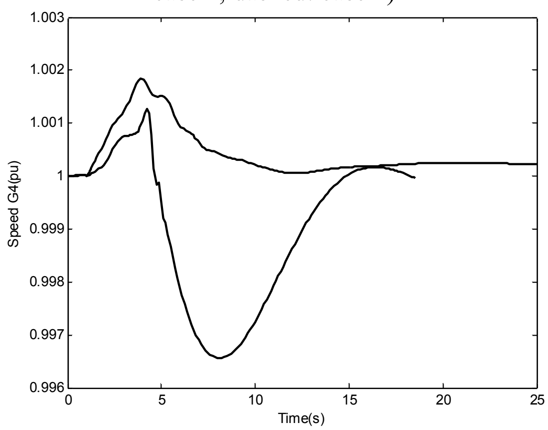

Figure 13: Speed G_4 following disturbance 2 (solid: case 1, dashed: case 2)

5. Conclusion

In this paper, different loading models were defined and analyzed. The difference between two load models was investigated and results showed that the PQ load model is the worst case model in power system. A typical power system with different loading models was considered as test case.

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