THE INFLUENCE OF VOLTAGE VARIATIONS ON ESTIMATED LOAD PARAMETERS

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I. INTRODUCTION

The importance of load models in power system stability studies has long been recognized [1-8]. Currently, there is an increasing interest in developing appropriate load models for various power system studies. Several dynamic load models have been proposed [9-13] and used in small-disturbance, transient stability and voltage stability studies [2-4, 12,16]. Different ranges of parameters were also recommended for the different types of load [8,12].

There are mainly two approaches of developing load models – the component based approach and measurement based approach [5]. The former is based on the prior knowledge of the composition of loads and the corresponding specific models of its main components. This paper deals with the later one which involves placing sensors and recording equipment at various load buses within the system. Measurement based approach has the advantage of direct measurement of actual load behaviours resulting from system disturbances (either artificially created by altering control components such as on-load tap changing transformers, or naturally occurring such as lightning strikes and short circuits). The recorded data can yield load models directly in the form needed for existing computer program inputs.

A load model is the mathematical description of the relationship between the voltage and the real power and reactive power of the bus. A system disturbance is needed for the model development (usually a voltage step change). The majority of the load models proposed in the past was developed assuming an ideal voltage step [9-13]. In realistic system measurements, bus voltage however is not an ideal step. It varies, and the magnitude of its variation is influenced by the system impedance. In an extended ended distribution system in particular voltage may experience variations to a great extent [13,15]. As a consequence of voltage variation, recorded real and reactive power will also vary.

As the load model and its parameters are estimated from the measurements they depend on the measured quantities. This paper investigates the influence of voltage variations on the estimated model parameters for the different load models.

The software package PSCAD/EMTDC has been utilised to perform the required simulation studies. The use of PSCAD/EMTDC in initial load modeling exercises can only be seen to be beneficial in the long term as many problems associated with the gathering of the information and performing of field tests can be isolated and hopefully solved before expensive and time consuming field work begins.

II. LOAD MODEL

A large variety of load models have been proposed in the past for modelling power system loads. Some of them have been recommended by the IEEE load modeling task force[1]. Three of those models were used for the analysis presented here.

A. Generic Dynamic Load Model

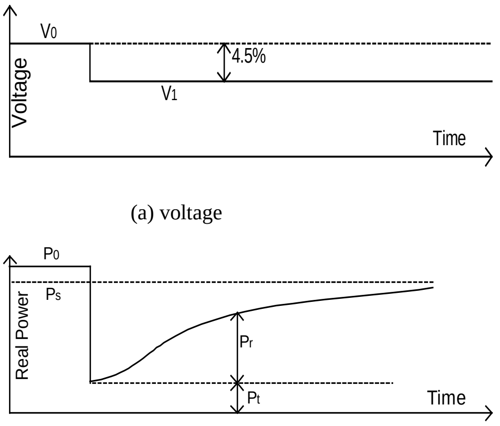
Fig. 1 shows the general form of the dynamic response of an aggregate load to a step change in voltage. A voltage step produces a transient jump of power followed by recovery to a steady state. A number of generic dynamic load models have been proposed to model this aggregate load behaviour [9-12]. The generic non-linear dynamic load model was originally proposed in [9]. The mathematical form of the load model is:

$$\begin{aligned} &T_p \dot{x}_p + x_p = N_p(V) \\ &N_p(V) := P_s(V) - P_t(V) \\ &P_d(V) = x_p + P_t(V) \end{aligned} \tag{1}$$

where x_p is the state variable that describes the transient process of load recovery. P_t and P_s are transient and steady state non-linear characteristics of the load, respectively and P_d is the total load demand. Generally, non-linear load characteristics $P_s(V)$ and $P_t(V)$ may adopt the following forms [9]

$$P_s = P_0 (\frac{V}{V_0})^{\alpha_s}$$
$$P_t = P_0 (\frac{V}{V_0})^{\alpha_t} \quad (2)$$

where P_0 and V_0 are pre-disturbance values of real power and bus voltage respectively, and α_s and α_t are steady state and transient voltage exponents. Reactive power recovery can be modelled in the same way except that the steady state and transient voltage exponents in this case would be denoted by β_s and β_t respectively.



(a) voltage

(b) load response

Fig. 1. Dynamic response of the aggregate load to voltage step

The block diagram representation of the load model (1) is shown in Fig. 2.

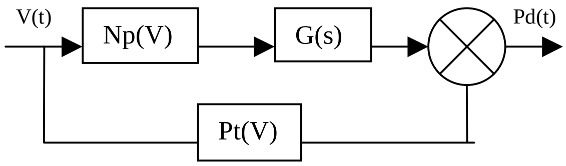


Fig. 2. Block diagram of generic load model 1

Where

$$G(s) = 1/(T_p s + 1) \quad (3)$$

The same block diagram representation of Fig. 2 can be used to describe higher order dynamic loads. In that case the transfer function G(s) has a higher order form. To illustrate this assume that the load response has the form shown in Fig. 3, then the transfer function G(s) is of second order form.

$$G(s) = \frac{b_1 s + b_0}{s^2 + a_1 s + a_0} \quad (4)$$

The complete mathematical model of the load is

$$\ddot{x}_p + a_1 \dot{x}_p + a_0 x_p = b_1 \dot{N}_p(V) + b_0 N_p(V)$$
$$N_p(V) := P_s(V) - P_t(V) \quad (5)$$
$$P_d(V) = x_p + P_t(V)$$

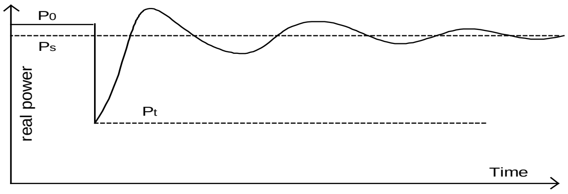


Fig. 3. Second-order response of the load to a voltage step

B. Generic Adaptive Load Model

In [12], typical exponential load recovery following step in voltage was modelled by a generic adaptive model. This model is slightly different from the one proposed in[10]. The block diagram of the load model is shown in Fig. 4.

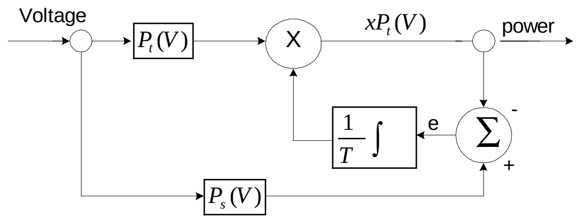


Fig. 4. Block diagram of generic load model 2

In this model, x is the state variable. The voltage functions $P_t(V)$ and $P_s(V)$ have the same meaning as previously discussed. T is the recovery process time constant. The mathematical description of the load model is given by:

$$T(dx/dt) = P_s(V) - P, P = xP_t(V) \quad (6)$$

Where P_s and P_t are defined by (2).

C. Input-Output Transfer Function Load Model

Probably the most convenient load model from the point of view of parameter identification is the I/O TF load model. This model however, doesn't have any physical meaning or correlation with the actual physical processes.

The load model can be conveniently represented as a black box, input-output transfer function model as shown in Fig. 5.

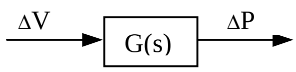


Fig. 5. Block diagram of input –output transfer function model

Transfer function G(s) is of the general form:

$$G(s) = K \frac{s^2 + b_1 s + b_0}{s^2 + a_1 s + a_0} \quad (7)$$

Where K is the gain constant.

For the first-order form of the load model, G(s) may have the first order form. G(s) may generally have different forms of polynomials depending on the coefficients in numerator and denominator of (7).

The real power P has been used to illustrate load models above. For the reactive power Q, the models have the similar form.

III. CASE STUDY

A. Model of the System

Load response tests in a simple power system shown in Fig. 6 are simulated in PSCAD. The system is operating at the rated condition with transformers T1 and T2 operating at different taps. A step change is formed by tripping out transformer T1 having initially a higher tap.

The load is composed of 80% induction motor load and 20% static load. Static load is represented as combination of resistance and reactance. The induction motor is modelled by the 5^{th} order model. The induction motor used in simulation is 800hp, 2300V single cage motor operating with constant torque.

The variations in load bus voltage were simulated by using different system impedance, Z.

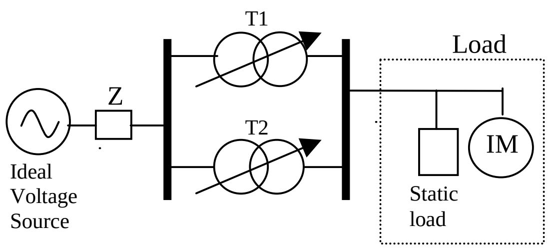
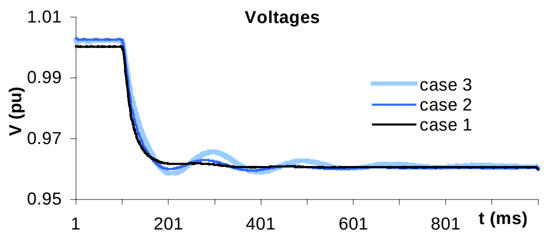


Fig. 6 Simple power system used for load test simulation

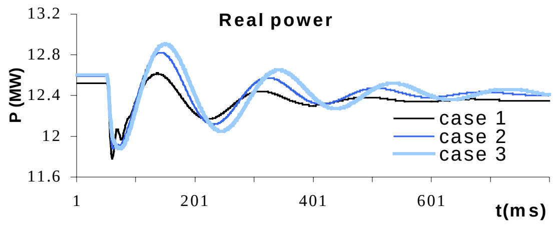
B. Cases Considered

Test results of three case studies with different system impedances are shown in Fig. 7. Fig. 7(a) shows the load bus voltage response, Fig. 7(b) shows the load real power and Fig. 7(c) load reactive power responses. The value of system impedance of case 3 was two times that of the case 2. The system impedance of case 1 has the smallest value, half the one of the case 2.

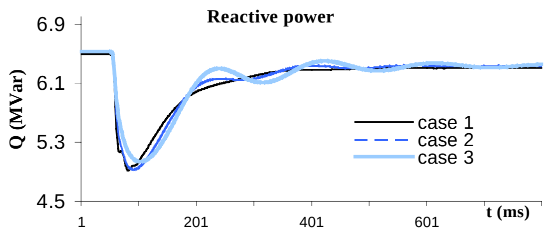
From Fig. 7 it can be seen that the load responses of real and reactive power following the voltage step are closely related to the voltage. For case 1 the reactive power response can be considered as an ideal first order exponential recovery. For case 3 however, the reactive power response of the same load is different. The real power responses in all three cases are qualitatively the same.



(a) Voltage steps of different variations



(b) Real power dynamic responses



(c) Reactive power dynamic responses

Fig. 7 Load responses under voltage steps

C. Influence on Parameters of Generic Dynamic Load Model

To investigate the influences of voltage variations on load model parameters, firstly, the results of case 1 are used to develop the load model. The developed model is then applied to case 3 for model verification. Secondly, load model parameters were estimated based on case 3 results, and then applied to case 1 for the verification. By doing this we can assess the robustness of the developed load model.

The simulated load response results shown in the Fig. 7 were used in MATLAB. The second-order form of load model was used for real power G(s) parameter estimation and a first-order form for the reactive power. The output error (OE) method was used for the load model parameter estimation. The parameters of the load model for real power and reactive power are included in Table 1 and Table 2 respectively.

Table 1 Estimated model parameters for real power

	a_1	a_0	b_1	b_0	α_s	α_t
Case 1	15.5	1418	30.8	1396	0.32	1.51
Case 3	14.5	1582	82	1523	0.30	1.4

Table 2 Estimated model parameters for reactive power

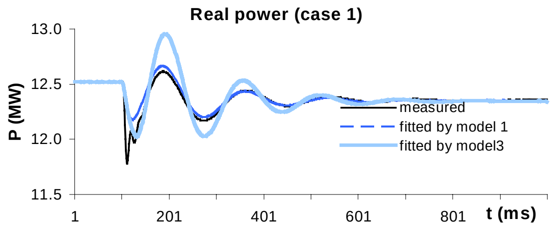
	a_0	b_0	β_s	β_t
Case 1	16.5	16.5	0.72	6.87
Case 3	20.1	20.1	0.72	6.15

From Tables 1 and 2 it can be seen that the estimated model parameters are significantly different.

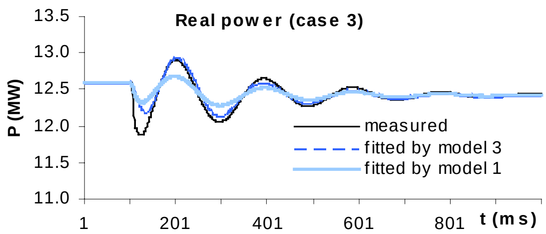
Fig. 8 shows the comparison of simulated and fitted real power responses using load parameters estimated for different cases. Fig. 8(a) refers to case 1, i.e., simulated responses of case 1 are compared with the responses of the load model whose parameters were fitted based on simulated responses of case 1 and case 3 respectively. Fig. 8(b) refers to case 3, i.e., simulated response of case 3 is compared with the responses of the load models whose parameters were fitted based on responses of case 3 and case 1 respectively. It can be seen from these figures that there is quite good agreement between simulated and fitted responses developed for the same case. There is however a significant difference if the model developed for one case is compared with simulated responses of the model fitted from different case.

Fig. 9 gives the comparison of measured and fitted reactive power responses. It can be seen that the agreement between simulated and fitted responses is quite good in all examined cases.

For both real and reactive power, errors occur during the initial period of time after a voltage step. This is the effect of delayed voltage drop caused by transducer delay [19].

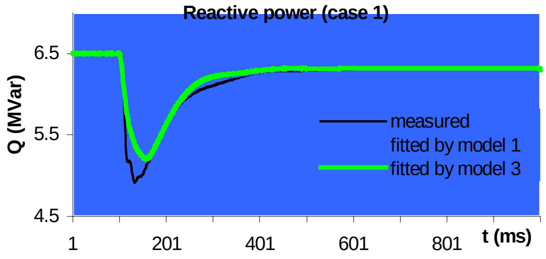


(a) . Comparison of measured and fitted real power for case 1 using different models

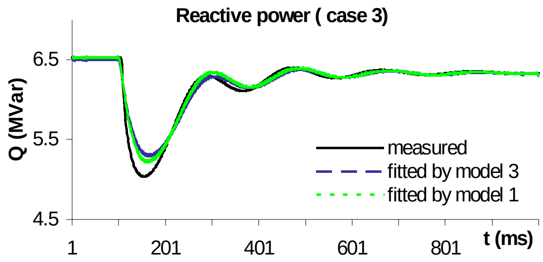


(b) . Comparison of measured and fitted real power for case 3 using different models

Fig. 8. Comparison of measured and fitted real power using different models



(a). Comparison of measured and fitted reactive power for case 1 using different models



(b). Comparison of measured and fitted reactive power for case 3 using different models

Fig. 9. Comparison of measured and fitted reactive power using different models

Based on the results shown in Fig. 8 and 9, it can be concluded that the second order generic dynamic load model is not robust. While reactive power response (i.e., first order model) is not affected by voltage variations, real power response (i.e., second order model) is quite influenced by it.

D. Influences On Adaptive Generic Load Model

For the adaptive generic load model only a first order form is available. Because of this only reactive power responses shown in Fig. 7 were considered.

Firstly, case 1 was idealized and the parameter T was calculated as suggested in [12]. Then the model was applied to case 1 and case 3 for verification. The estimated time constant T was 0.42s.

Fig. 10 gives the voltages used for parameter estimation. Fig. 11 shows the fitness of the model for ideal case. Fig. 12 illustrates the comparison of measured result and fitted result when applying the model to case 1. Fig. 13 illustrates the comparison of the responses for case 3. For both cases the fit is good except the errors occurred during the initial period after a voltage step [19].

The big influence of voltage variation on the parameters of this model is due to the difficulty to determine the recovery time constant. It is suppose to be calculated from an ideal first order recovery response [12].

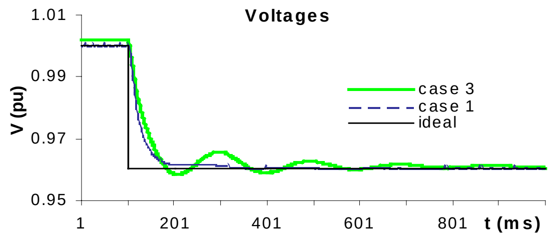


Fig. 10 Votages used for load model development

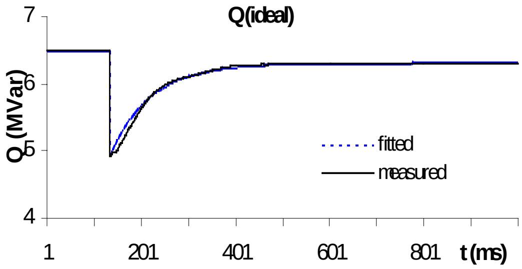


Fig. 11 Comparison of measured and fitted reactive power for ideal case

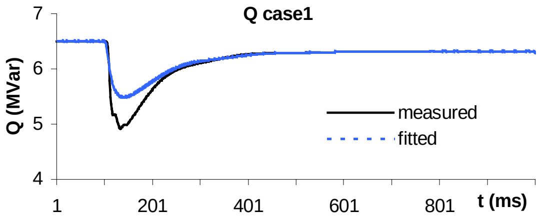


Fig. 12 Comparison of measured and fitted reactive power for case 1

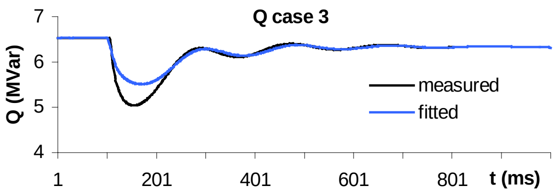


Fig. 13 Comparison of measured and fitted reactive power for case 3

E. Influences On Input-Output Transfer Function Load Model

Variations ΔV, ΔP and ΔQ are calculated from the original data for V, P and Q, and then applied to model parameter estimation algorithm. The model parameters are included in Tables 3 and 4 for real power and reactive power, respectively.

Table 3 Gp(s) model parameters (real power)

	K	a_1	a_0	b_1	b_0
Case 1	29	25	1775	6.3	265
Case 2	41	14	1554	-1.5	175

Table 4 Gq(s) model parameters (reactive power)

	K	a_0	b_0
Case 1	65.7	16.5	1.14
Case 2	67	17	1.2

Fig. 14 shows the ΔV used for input of parameter estimation. Fig. 15 illustrates the comparison of fitted results for the real power. Fig. 16 gives the comparison of fitted results for reactive power. Similar behaviour can be obtained in this case as in the case of real power responses of generic dynamic load model.

Notice that the fitting during the initial period of time after voltage drop is better than in the case of the generic load model discussed above for both, real and reactive power. It can be concluded that the input-output transfer function model is not influenced by the delay introduced by transducers.

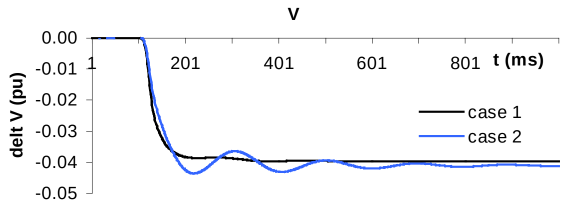
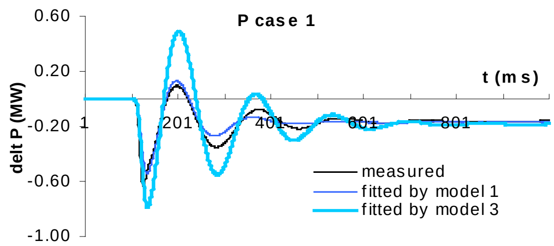
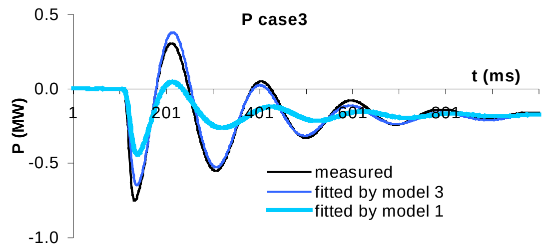


Fig. 14 .Delta voltage used for input-output transfer function model development

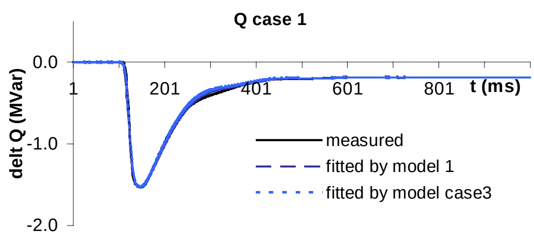


(a) Comparison of measured and fitted Δ P for case 1

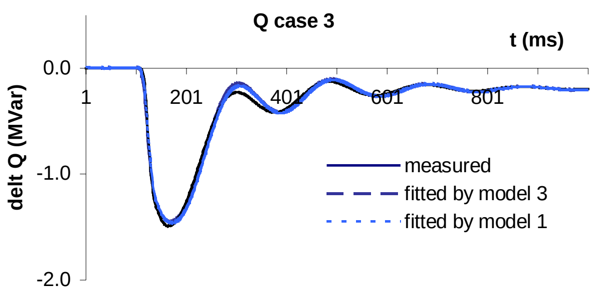


(b) Comparison of measured and fitted Δ P for case 3

Fig. 15 Comparison of measured and fitted ΔP



(a) Comparison of measured and fitted ΔQ for case 1



(b) Comparison of measured and fitted ΔQ for case 3

Fig. 16 Comparison of measured and fitted ΔQ

IV. SUMMARY

The paper investigated the influence of voltage variations on estimated load model parameters. Three different load model structures have been used for the analysis. Parameters of first and second order model were estimated using output error method. Simulated load responses obtained from load models developed in SIMULINK were compared with simulated measured load responses generated in PSCAD/EMTDC. Several conclusion can be summarized as follows:

1. For the same load, the load model parameters for the real power are different if the load bus voltage variations are different. That means that the load model of real power developed from one system may not be valid for another system even though the load is the same.

2. For the same load, the load model parameters for the reactive power do not change as much as real power. The model developed in one system can be used for another system. Variations in the reactive power response may affect the parameter estimation in the case of adaptive generic load model.

In summary, first order load models are more robust and can be used in different systems once developed. Higher order load models are more influenced by operating conditions and system parameters.

V. ACKNOWLEDGEMENT

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