DETERMINATION OF STATIC LOAD MODELS FROM LTC AND CAPACITOR SWITCHING TESTS

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Abstract: This article investigates the characteristics of a pure residential load through field tests. Staged voltage perturbations by station transformer tap-changing are induced both with and without switching ON the feeder shunt capacitors. Sudden voltage deviations by capacitor switching are attempted. Static load parameters are derived from the recorded load response to voltage variations. It is found that the load real and reactive powers can be respectively approximated by a linear and a quadratic function of voltage.

Keywords: Static load models, residential load characteristics, induced voltage disturbances.

I. INTRODUCTION

load modeling received significant attention over the past two decades because of its important representation in power system dynamic performance, and the significant impact of load-voltage dependency on voltage stability [1]-[3]. Load models are developed by either the component-base approach (which requires detailed information on load composition, load mixture, and component characteristics [4]-[5]), or by the field-test approach where the load parameters are derived from staged tests (such as changing substation transformer taps and switching capacitor banks or actual system transients [6]-[7]).

During the summer of 1998, Nevada Power Company conducted a number of field tests in an effort to determine the characteristics of feeder loads consisting of residential, commercial, and light industrial customers. A summary of the results of this study is reported in Ref. [8]. This paper presents more details on the load characteristics of one of the residential feeders tested. After a brief review of the field test procedure, the article analyses the recorded load response due three voltage disturbances; namely, LTC tap changing without feeder capacitors, feeder capacitor switching, and LTC tap changing with feeder capacitors. Much of the collected data is corrupted by natural load fluctuations that occurred during the induced changes in voltage. The load parameters are then derived from non-corrupted data using simple polynomial curve fitting techniques.

II. TEST PROCEDURE

The procedure followed during load testing is based the one described in Ref. [3] where some of the important factors that may corrupt the load response to staged voltage disturbances (i.e., the natural fluctuation of the load and the automatic switching of shunt capacitors along the feeder) were considered. To limit such effects, pre-disturbance monitoring was conducted few days before the testing date to determine the best half-hour time window near peak load where the fluctuations are minimal, and testing was conducted both with and without the fixed and switched capacitors along the feeder. A sophisticated power measuring instrument capable of recording and storing all currents, voltages, system frequency, active and reactive powers for a sufficient length of time with a high sampling rate was used for data acquisition.

The residential feeder under study is among 10 feeders that are supplied by two 138/12.47 kV station transformers operated in parallel, each is equipped with 32 taps. The following set of tests were conducted:

- **Test A: voltage disturbance by LTC tap movement with capacitors OFF**. With the feeder capacitors switched OFF, sudden voltage changes on the secondary side of the station transformers were induced by simultaneous and rapid tap movement on both station transformers. The taps are then moved back to their original position several minutes later.
- **Test B: voltage disturbance by capacitor switching**. In here, capacitors are switched on one bank at a time while the station transformer tap mechanism is disabled.
- **Test C: voltage disturbance by LTC tap movement with capacitors ON**. This test is the same as Test A, except that the feeder capacitors are energized.

The test procedure showing detailed steps and fall-back procedures in case some unexpected events take place was approved by management, and coordination with the company's dispatch center was confirmed prior to testing. The tests on the residential feeder under study were conducted between 2:00pm and 4:00pm on September 9, 1998 (the local temperature was 100° F). The results of these tests are described in the following section.

III. TEST RESULTS

The power consumed by the load varies with both the voltage and frequency, but this study analyzes only the effect of sudden voltage variations. The system frequency was measured in case there may be the possibility of concurrent frequency deviations that may have contributed to the feeder power consumption. In such cases, the data is considered invalid and should not be used for the derivation of load parameters. Figures 1-3 displays the variation in a) system frequency, b) feeder voltage, c) feeder active power, and d) feeder reactive power, during Tests A, B, and C, respectively. Note that frequency deviation during each of the three tests is small (less than 0.1%), hence its effect can be ignored.

In Test A, the station transformers were originally tapped out after switching off the feeder capacitors. The voltage was rapidly reduced to the minimum allowed value by dropping the taps from +16 to 0. Ten minutes later, the taps were raised to +8, then to +16 six minutes later. A false voltage reading above the allowed limit at the feeder end caused the interruption while raising the transformer taps. Fig. 1(c) and 1(d) show that the impact on reactive power is much more significant than on real power, and the load was fairly constant during the first step voltage. Consequently, the resulting changes in P and Q are considered to be valid and considered to be caused solely by the voltage deviation. However, the load was continuously rising at a rate of (160 kW/min, and 40 kVar/min) during the second and third step voltages. In here, the change in power is attributed to both voltage and load change, hence cannot be used to determine the load parameters.

During Test B, the three capacitor banks (each rated at 1.2 Mvar), along the feeder were switched on at 4 min, 17.5 min and 23 min as can be seen in Figure 2(d). Simultaneous switching of these banks was not possible due to crew limitation and physical distance between the capacitor banks. Feeder capacitor switching resulted in small rise in voltage (less than 1%) as seen in Fig. 2(b) and changes in real power that are too small to distinguish from the natural load fluctuation. Therefore, the collected data during this test cannot be used for determining the load parameters. Note that other events during the half-hour monitoring period caused additional jumps in voltage. These sudden voltage deviations are likely due to automatic capacitors switchings on adjacent feeders. The feeder power factor improved from 89% to near 100% when all the capacitors are turned on.

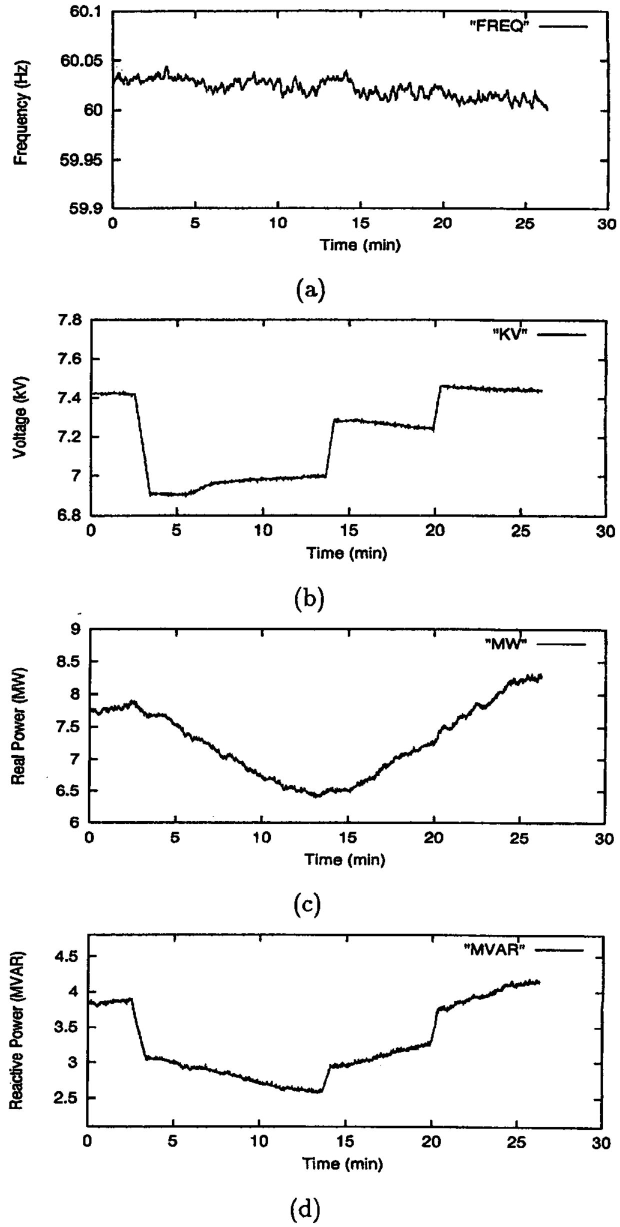


Figure 1: Test A - Feeder Response to Voltage Variation with Capacitors OFF, a) System Frequency, b) Feeder Voltage, c) Feeder Real Power, d) Feeder Reactive Power.

With all feeder capacitors locked on, the induced voltage dip by LTC tap change resulted in a leading power factor as shown in the graphs of Fig. 3 that correspond to Test C. Also note that the load was fairly steady during the drop in voltage between 4-5 min., and during the voltage rise between 11.5-13 min. Hence, the data collected during these time periods will be of acceptable for deriving the feeder load parameters. The voltage drop at the 20 min. mark induced by tap switching to restore the voltage to its initial value occurred while the load was rising, and it is too small to consider.

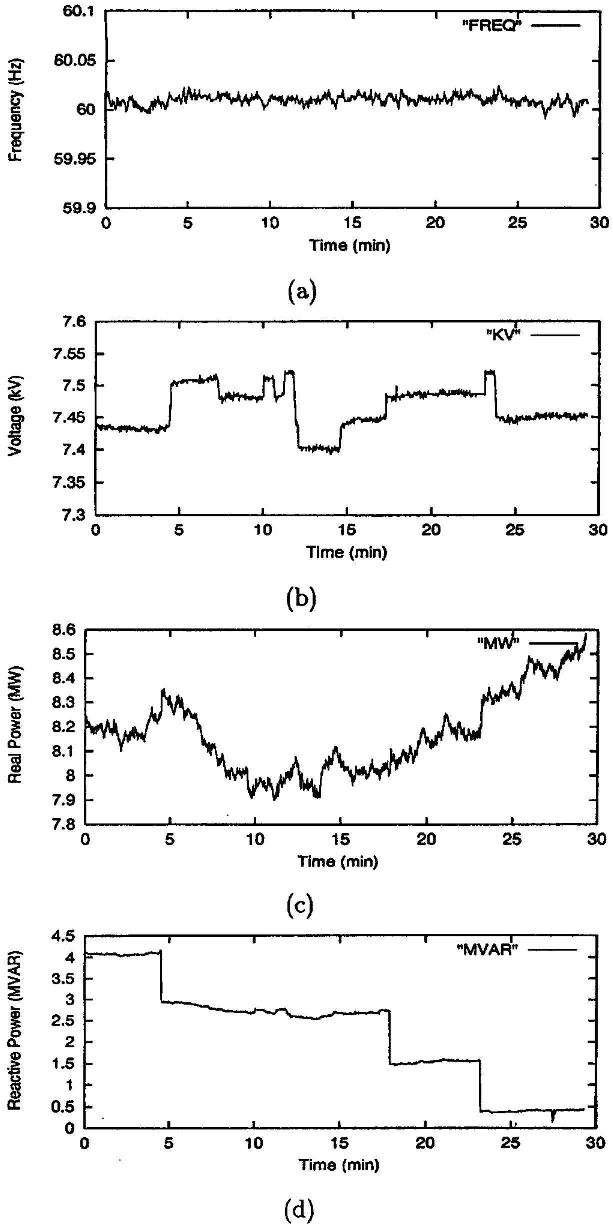


Figure 2: Test B - Feeder Response to Capacitor Switching, a) System Frequency, b) Feeder Voltage, c) Feeder Real Power, d) Feeder Reactive Power.

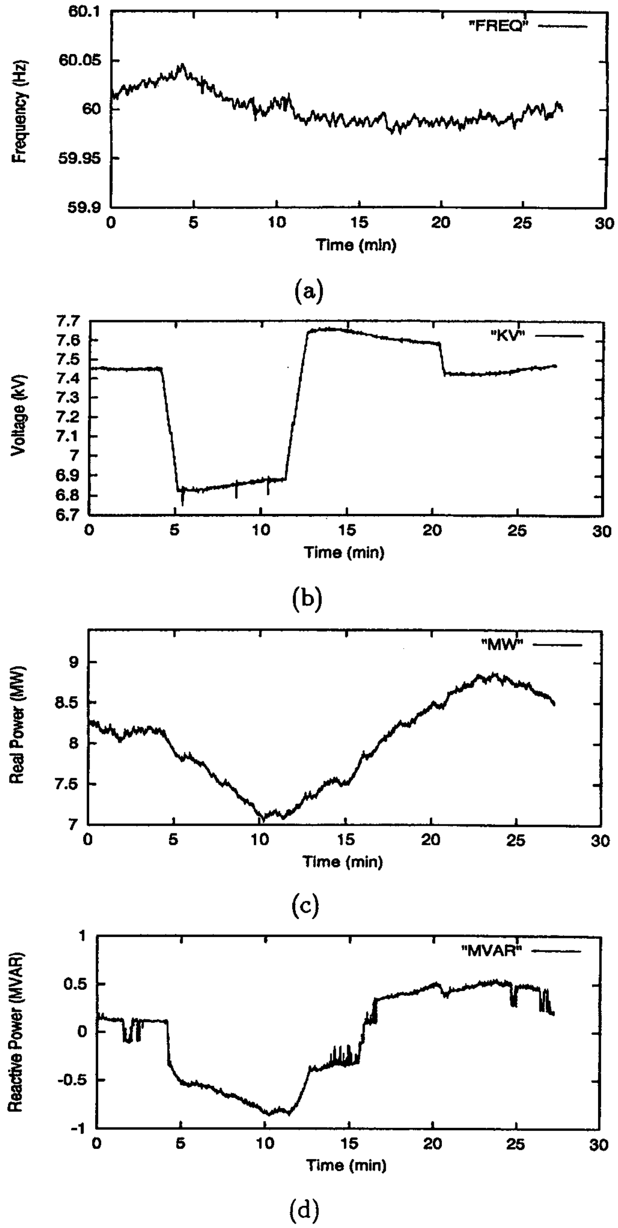


Figure 3: Test C - Feeder Response to Voltage Variation with Capacitors ON. a) System Frequency, b) Feeder Voltage, c) Feeder Real Power, d) Feeder Reactive Power.

IV. LOAD PARAMETERS

The widely used load characteristic known as the ZIP model, i.e., sum of constant impedance (Z), constant current (I) and constant power (P), expresses the load real and reactive powers as a second order polynomial of voltage:

$$P = P_0(a_0 + a_1\frac{V}{V_0} + a_2(\frac{V}{V_0})^2), \qquad (1)$$

$$Q = Q_0(b_0 + b_1\frac{V}{V_0} + b_2(\frac{V}{V_0})^2). \qquad (2)$$

where the constants

$$a_0 + a_1 + a_2 = b_0 + b_1 + b_2 = 1, \qquad (3)$$

and P_0, Q_0, V_0 are the initial real power, reactive power and voltage prior to the voltage disturbance.

In cases where the powers appear to be linear with voltage, the third term in Eqns. (1)-(2), i.e., the constant impedance term, is dropped out and the static load model reduces to

$$P = P_0(a_0 + a_1\frac{V}{V_0}), \qquad (4)$$

$$Q = Q_0(b_0 + b_1\frac{V}{V_0}). \qquad (5)$$

It is important to point out that the ZIP model is unrealistic for low voltages, and that when load parameters are obtained from measurements, some of them may assume negative values [9].

In order to derive the load parameters of the residential feeder under study. a simplified feeder model shown in Fig. 4 is considered. In this model, the distributed shunt capacitors are lumped into one node, the net effect of distribution transformer impedances are lumped as part of the load load active and reactive powers, and the effect of feeder series impedance is ignored.

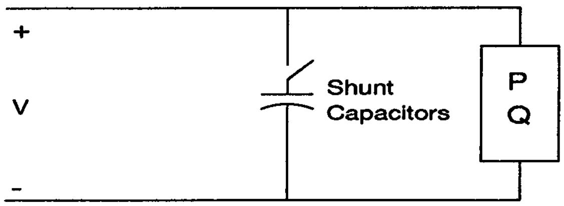
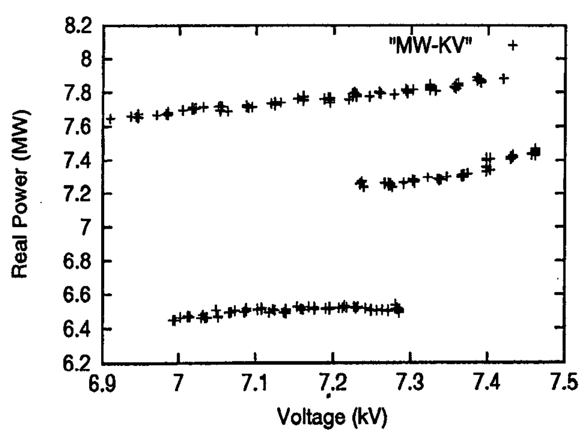
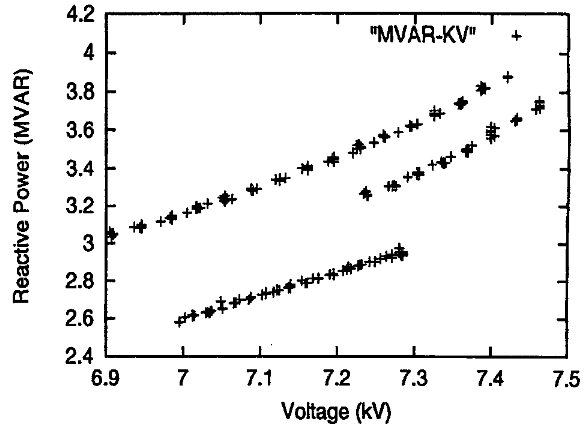


Fig. 4: Simplified Feeder Model.

The P-V and Q-V curves corresponding to Test A (i.e., Fig. 4 with capacitors switched OFF) and Test C (i.e. Fig. 4 with capacitors switched ON) are shown in Fig. 5 and 6, respectively. Each figure shows three curves that represent that change in power and reactive power with voltage during the three induced voltages steps. Based on the observations described in the previous section, some of these curves do not accurately represent the load response to a voltage change because of the concurrent variation in the load itself. Only the top curve of Fig. 5 and the two bottom curves of Fig. 6 are valid for the calculation of load parameters. These curves indicate that the real power varies linearly with voltage (Eqn. (4)), while the reactive power varies quadratically with voltage (Eqn. (2)).

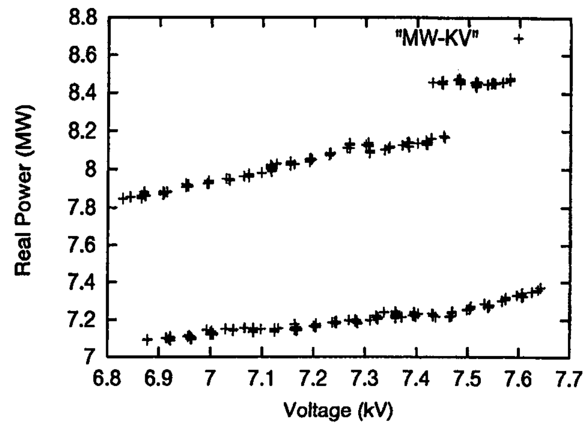


(a)

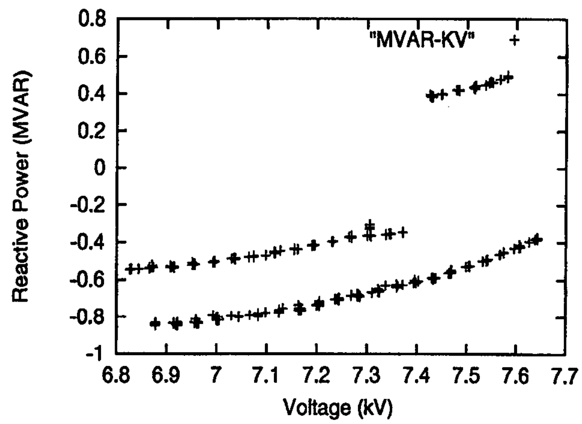


(b)

Figure 5: (a) P-Q and b) Q-V curves With Capacitors Switched OFF.



(a)



(b)

Figure 6: (a) P-Q and b) Q-V curves With Capacitors Switched ON.

The real and reactive power parameters a_i and b_i can be found by simple curve fitting algorithms. These parameters derived from Tests A and C can then be compared for validation purposes. But before doing so, the reactive power expression for Test C needs to be modified to account for the present of the switched capacitors. In Test C, the measured reactive power is a sum of load and capacitor powers, i.e.,

$$Q = Q_L + Q_C, \tag{6}$$

where

$$Q_c = -Q_{Cn}(\frac{V}{V_n})^2. \tag{7}$$

Herein, Q_{Cn} and V_n are the total capacitor size (3.6 Mvar) and nominal voltage (7.2 kV), respectively. Substituting (7) and (2) into (6) yields,

$$Q = Q_0(b_0 + b_1\frac{V}{V_0} + b_2'(\frac{V}{V_0})^2). \tag{8}$$

where

$$b_2' = b_2 - \frac{Q_{Cn}}{Q_0}(\frac{V_0}{V_n})^2. \tag{9}$$

Table 1 shows the ZIP load model coefficients calculated from the recorded data of Tests A and C. The difference, which is within ±10% is primarily due to the unsteady load and the simplified feeder model in Fig. 4.

TABLE I: ZIP MODEL COEFFICIENTS

	Test A	Test C	% Error
a_0	0.55	0.51	-7.2%
a_1	0.45	0.49	+8.9%
b_0	9.2	9.5	+3.2%
b_1	-20.4	-21.4	-4.9%
b_2	12.2	13.2	+8.2%

V. CONCLUSION

This paper analyzed the response of a pure residential load to small induced voltage deviations by station transformer tap changing and feeder capacitor switching. Capacitor switching caused voltage deviations that are too small to induce noticeable changes in real power. ZIP load model parameters are derived from the recorded changes in active and reactive power due to LTC tap switching, after selecting the data uncorrupted by the natural fluctuations of the load. The parameters are calculated for cases where the feeder capacitors are switched ON and OFF. The results are found acceptable as they vary within ± 10%, and the difference is due to the unsteady load and the simplified feeder model.

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