Estimation of PCS UtiliData AdaptiVolt™ System Performance using Observed Energy Demand Profiles

Problem statement

- Estimate the period conserved energy, normalized for ambient temperature, for a distribution feeder circuit controlled by the AdaptiVolt™ CVR system.
- Estimate the Conservation Voltage Reduction factor (CVR) for the feeder circuit.

Available data

- Recordings of energy consumption and end of line voltages shall be captured for the subject feeder circuit, with measurements sampled at uniform intervals. Suitable sample intervals range from 5 seconds to 15 minutes.
- During the testing period, AdaptiVolt™ shall be alternately engaged and disengaged on successive days at 12:00 AM local time.
- Ambient temperature data for the region served by the subject distribution feeder shall be sampled at uniform intervals not to exceed 1-hour. National Weather Service observations may be used if integrated temperature measurement is not available.

Sampling & preparation (per feeder)

- Demand profile (energy consumption) data are captured and stored for 24 hour periods with the corresponding end-of-line voltage data.
- The load profile data are summed and the voltage data are averaged to 1-hour intervals.
- Thus each daily record comprises three uniformly sampled time series, with a sampling interval of 1 hour:

integrated demand profile in kilowatt-hours	kWh
circuit RMS voltage in Volts	V
ambient temperature	°F or °C

- Holidays, weekends, and any days with missing data are excluded from this analysis; a minimum of 10 days of valid data for each CVR system operating state is required.

Model Formulation (per feeder)

A two component additive model is postulated for these data, as follows.

(1) A background load profile, independent of temperature.
This component comprises a linear term depending on the circuit voltage, from which the CVR evolves, and a stochastic component arising from customer activity. The stochastic component is assumed to be a linear stationary random process.

(2) A piece-wise linear dependence on temperature, mutually independent for each sampling interval. This component is used to estimate load profiles for the 'typical' temperature profile. Three distinct temperature 'zones' are considered: heating, for temperatures below 65°F; neutral, for temperatures between 65°F and 70°F; cooling, for temperatures above 70°F.

Analysis Procedure (per distribution feeder)

(1) The demand profile time series are arranged into two ensembles, one for the CVR system engaged loads and one for the CVR system disengaged loads.

(2) The end of line voltage time series are arranged into two ensembles, one for the CVR system engaged loads and one for the CVR system disengaged loads.

(3) The ambient temperature time series are arranged into two ensembles, one for the CVR system engaged loads and one for the CVR system disengaged loads.

(4) The vectors of ensemble average end-of-line voltages are estimated using either an L_1 median procedure or MCD robust regression.

(5) The vectors of energy demand and ambient temperature are sorted by the temperature observation, into three temperature zones as follows:

- observations below 65°F, termed the heating zone,
- observations between 65°F and 70°F inclusive, termed the neutral zone,
- observations above 70°F, termed the cooling zone.

(6) Linear models for energy demand as a function of temperature are estimated for each zone, of temperature-sorted observations in step (5), and the cooling to heating ratio of their slopes is computed as the cooling zone slope divided by the heating zone slope.
The neutral zone is defined to be that region in which the energy demand does not depend on the ambient temperature; thus the linear model in this zone is a constant.
In both the heating and cooling zones, the linear model coefficients are estimated using MCD robust regression. In the neutral zone, the demand is the L_1 median of the neutral zone observations.

(7) The explanatory variable representing temperature for estimation purposes is the deviation of the ambient temperatures from the neutral zone temperatures in which the deviations above the neutral zone temperatures are multipied by the slope ratio computed in step (6).

(8) The vectors of linear terms for temperature dependence of the loads are estimated by MCD robust regression of energy against the temperature variable in step (7).

(9) The temperature profile for the 'average' day is estimated from the ensemble of hourly temperature data using either an L_1 median procedure or MCD robust regression.

(10) The expected demand profiles, one each for the CVR system engaged and disengaged, are computed by applying the 'average' day temperature profile to the temperature model for each CVR system state.

(11) The difference between the expected load profiles represents the conservation profile, which is compared to the difference between the end-of-line voltage profiles to estimate a vector of CVR factors.

(12) The per-feeder scalar CVR factor is the mean of the CVR vector, weighted by the CVR system disengaged demand profile.

Comments on the proposed procedure

Available data

We acknowledge that the observations of the ambient temperature may lack suitable resolution with respect to location in some cases, since it is believed that the subject terrain contributes to the significant local variation in ambient temperature and wind velocity. We also acknowledge that the estimate of the expected daily temperature profile could also be improved upon.

We expect that the variance in the estimates of temperature dependence parameters will thus be larger than the best achievable variance associated with estimates using spatially detailed temperature observations. However, this defect in the observations does not undermine the physical suitability of the proposed linear dependence of energy consumption on temperature.

We note here that the magnitude of the temperature dependence will depend on whether the principal utility loading for environment control is heating or cooling; it is expected that cooling will require more energy per unit temperature compensation, entirely as a result of the inferior energy conversion efficiency of cooling equipment.

Model formulation

The principal objective of the present analysis is to estimate the magnitude of conserved energy resulting from a small reduction in the delivered voltages. Ideally, this estimate would be made by adjusting the delivered voltage and observing the response of the connected load, under conditions in which every important characteristic of the load was identical before and after the voltage adjustment. This test condition is in no way achievable in practice.

The alternative, of course, is to attempt such an estimate by identifying a physically suitable model of the load process, such that the behavior of the load process can be evaluated under identical simulated conditions. In the present case, models for the standard load process and the reduced voltage load process are estimated, and their outputs compared for a simulated representative temperature input.

We acknowledge without reservation that we lack sufficient data to identify some expected dependencies in the load process model. For example, the available observations clearly show that the 'weekday' load process differs from the 'weekend' load process; however, clear identification of the difference between the 'Tuesday' and 'Friday' load processes, known to exist in practice in some utility load distributions, cannot be identified with confidence from the small number of available observations.

The load process, characterized by the so-called load profile, is inherently cyclostationary with a natural period of one day. Since the objective here is not the explicit identification of the load profile, we are not interested in cyclic autocorrelation or any other temporal statistics of any order that exploit the periodicity of the load data. I repeat, we make no attempt to formulate or identify a time domain model for the load profile and thus have no use whatever for temporal measures for parameter estimation.

However, we do exploit the cyclic behavior of the load for the alignment of the members of the process ensemble, including only those cycles (weekdays) that are expected to originate from the same load process dynamics, which in turn behave according to the previously stated properties. Samples taken at different times are assumed to be independent (in the sense of De Moirve), so that the resulting estimates of temperature dependence are easily computed using only observations for each time interval.

Comments on the proposed procedure - continuation

Forecasting

The proposed model may be applied to the problem of forecasting conservation if specific constraints are met and known limitations are observed.

- The present formulation excludes daylight duration and other expected seasonal variables. Thus any forecast for a given season must use estimation results from that season in prior years.
- The ambient temperature formulation is not well suited for extrapolation, so that the daily temperature profile in the forecast interval is bounded by temperature profile observations in the estimation reference interval.
- The present formulation easily accomodates load growth on a given feeder circuit under the broad assumption that such growth is demographically similar, such that the stochastic behavior of the load is second order stationary.

Exemplary References

The literature on the subject of time series analysis is extensive; we cite here a few references which are generally well regarded by experts in the field.

Fundamentals

Parzen, E.: Stochastic Processes
SIAM 1999, ISBN 0898714419

Gold, B., Rader, C.M., Oppenheim, A.V., Stockham, T.G.: Digital Processing of Signals
McGraw-Hill 1969

Wiener, N.: Extrapolation, Interpolation, and Smoothing of Stationary Time Series
Wiley 1949

Statistics and Estimation

Box, G.E.P, Jenkins, G.M.: Time Series Analysis, Forecasting and Control
Holden-Day 1976, ISBN 0816211043

Bendat, J.S., Piersol, A.G.: Random Data Analysis and Measurement Procedures
Wiley 1971, ISBN 047106470X

Rousseeuw, P.J., Leroy, A.M.: Robust Regression and Outlier Detection
Wiley 1987, ISBN 0471852333

Engineering

Himmelblau, D.M., Bischoff, K.B.: Process Analysis by Statistical Methods
Wiley 1969

Helstrom, C.W.: Statistical Theory of Signal Detection
Pergamon Press 1975, ISBN 0080132650

Estimation of PCS UtiliData AdaptiVolt™ System Performance - continuation

Formulation Details for the Heating Zone only – per distribution feeder basis

Observables

$s=0$	AVC system state indicator: system disengaged
$s=1$	AVC system state indicator: system engaged
p_s	number of samples (time series records) in ensemble s
x_{si}	daily cycle index, the ensemble axes $1 \le i \le p_s$
t_j	sample time index, the time axis $1 \le j \le n$
$T(t_j, x_{si})$	ambient temperature surface
$v_s(t_j, x_{si})$	end of line voltage surfaces
$E_s(t_j, x_{si}, T_{ji}, v_{sji})$	energy consumption (load profile) response surfaces

Model Components

$P(x)$	stochastic component of load profiles
T_R	heating zone reference temperature (== 65°F)
$T_R - T$	heating comfort temperature
$\beta_s(t_j)$	linear slopes, energy vs temperature
$w_s(t_j)$	estimated load profiles at reference temperature

Statistics

$\overline{v}_s(t_j)$	ensemble 'median' voltage profiles
$T_m(t_j)$	ensemble (combined off & on) median comfort temperature profile
$W_s(t_j)$	estimated load profiles at ensemble median temperature

Results

η	conservation factor

Estimation of PCS UtiliData AdaptiVolt™ System Performance - continuation

Formulation Details... - continuation

Salient Assumptions

$n = 24$	number of hourly samples per one daily period
$P(x)$	stochastic component of load profile zero mean, wide-sense stationary, unknown probability density
	deterministic component of load profile is linear in end of line voltage over the voltage interval of interest
β	probability structure of the energy/temperature slopes is unknown, thus robust regression procedures are indicated
$P(x_a \mid x_b) = P(x_a)$	The 'random' component of observations at any given times a, b are mutually independent.

Formulation

$$E_s(t, x, T, v) = w_s(t)[1 + P(x)] + [T_R - T(t, x_s)]\beta_s(t)$$

where $s = 0$ AVC system disengaged
$s = 1$ AVC system engaged

Analysis

Manually segregate daily profiles on the basis of ambient temperature, since we expect that the temperature dependence of the load profile will differ when heating or cooling for comfort.

Form ensembles of daily profiles on the basis of AVC system state.

Perform MCD robust regression on the ensemble axis for energy consumption against comfort temperature for each ensemble, estimating:
$w_s(t_j)$ and $\beta_s(t_j)$ for $s = 0{,}1$ and $1 \le j \le n$.

Formulas for Minimum Covariance Determinant (MCD) robust regression can be found in:
Rousseeuw, P.J., and Leroy, A.M.: "Robust Regression and Outlier Detection", Wiley, 1987.

Formulation Details... - continuation

Analysis - continuation

Compute the L_1 location estimate of the end-of-line voltage observations $v_s(t_j, x_i)$, estimating the <u>expected</u> voltage profiles $\bar{v}_s(t_j)$ for $s = 0{,}1$ and $1 \le j \le n$:

$$\bar{v}_s(t_j) = \min \sum_{i=1}^{p_s} \left| \bar{v}_s(t_j) - v_s(t_j, x_{si}) \right|$$

Compute the L_1 location estimate of the ambient temperature observations $T(t_j, x_i)$, estimating the <u>expected</u> comfort temperature profile $T_m(t_j)$ for $1 \le j \le n$.

$$T_m(t_j) = \min \sum_{i=1}^{p} \left| T_m(t_j) - T(t_j, x_i) \right|$$

, where $p = p_0 + p_1$

Compute the <u>expected</u> load profiles (energy consumption time series for a one day period), so that each load process (AVC system engaged or disengaged) is evaluated with the same comfort temperature input:

$$W_s(t_j) = w_s(t_j) + [T_R - T_m(t_j)]\beta_s(t_j)$$

Compute the CVR factor, thus normalized for comfort temperature:

$$\eta = 100 \frac{\sum_j [W_0(t_j) - W_1(t_j)]}{\frac{1}{n}[\sum_j W_0(t_j)][\sum_j \bar{v}_0(t_j) - \sum_j \bar{v}_1(t_j)]} ,$$

which has physical units of percent energy consumption difference per volt difference. This quantity may of course be expressed in other relevant scales without altering the above algorithm, such as percent energy consumption difference per percent voltage difference.

This procedure should be repeated for observations under cooling for comfort conditions, since the energy/temperature slopes are expected to be greater by a factor of 2.0 to 3.0 .