Estimating the Degradation Rate of Photovoltaic Arrays Using a Two Component Nonlinear Model

Christopher Gotwalt
JMP Division, SAS Institute

Introduction

Modeling the degradation rate of the output of photovoltaic (PV) arrays over time is challenging because the degradation path can be clearly nonlinear, especially early in the life of the array. Identifying a nonlinear model for PV data is made more complicated because large solar seasonal effects mask the degradation path.

We model PV array output degradation data collected over 6 years and supplied to us by Dr. Dirk Jordan of NREL. We use the estimated degradation model to obtain the rate of degradation. The model fits very well, and modeling only the 1st 12 months of data leads to very similar results. This suggests that the same approach can be used to obtain earlier estimates of the life of arrays in general.

Initial Model

We proposed an exponential decay model for the degradation component. An cursory analysis suggested that a transformation on time would be needed. To accommodate this , a power parameter on time was added. An empirical seasonal model that was motivated as a two term sine series with unknown amplitudes and phase was also proposed.

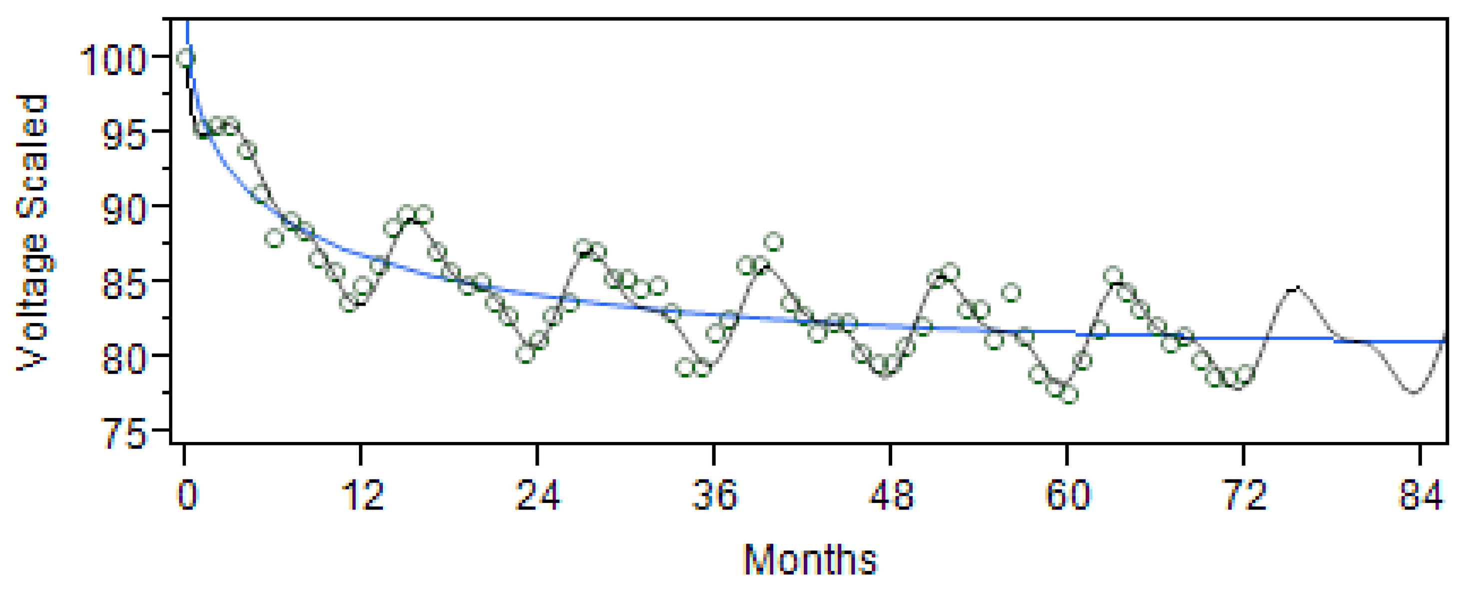
We use nonlinear least squares with a structural seasonal component rather than a nonlinear model with a seasonal ARIMA errors because our approach is easier in that it can be done using standard statistical software, and because a structural seasonal model will lead to more accurate predictions if it is close to correct.

Complete Data Model Fit

We fit the model using the nonlinear regression tools in JMP9 software. The parameter estimates and confidence intervals are below. The power parameter on time in the decay component is consistent with one half, which we assumed for the rest of the analysis. Notably a_2=.5*a_1 is also consistent with the data, though we did not take advantage of this later. Removing the second sine term of the seasonal model seriously degrades the fit and led to residuals with a large seasonal effect remaining. The model had an R^2 of .9, indicating an excellent fit.

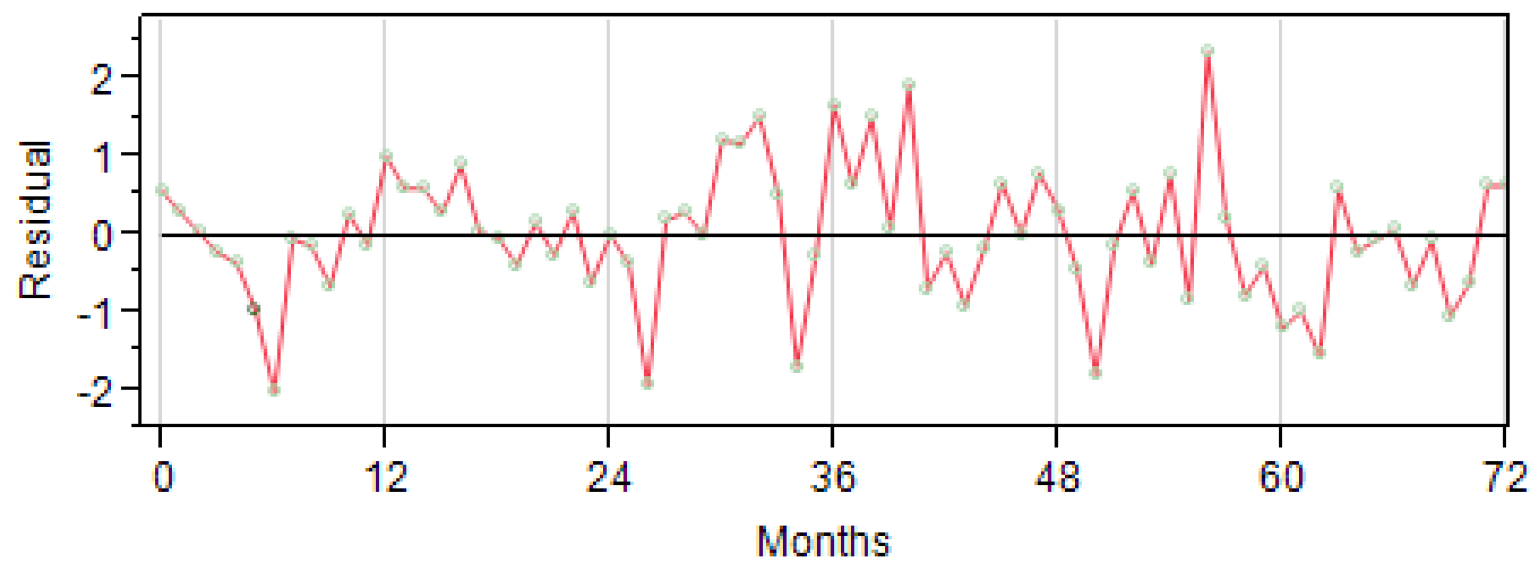
$$\begin{aligned} V(T) &= D(T) + S(T) \\ D(T) &= 80.2 + 22.2e^{-.35\sqrt{T}} \\ S(T) &= 2.7\sin(\frac{\pi}{6}(T-1.3)) + 1.3\sin(\frac{\pi}{3}(T-1.3))) \\ \dot{D}(T) &= 3.9T^{-\frac{1}{2}}e^{-.35\sqrt{T}} \end{aligned}$$

Six Years of PV Array Voltage Data



Green dots represent the monthly voltage measurements. Black line is the overall model, D(T)+S(T), blue line is D(T). Both lines fit to complete data.

Residuals



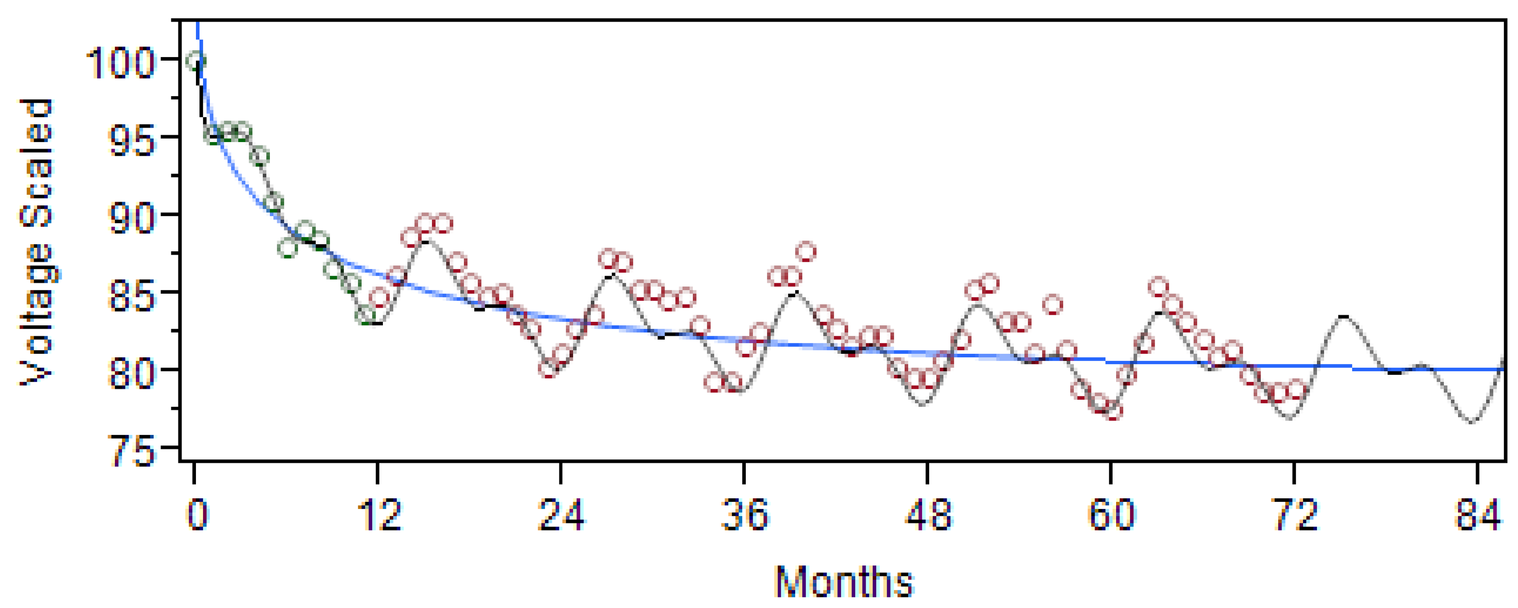
Residuals have no evidence of a trend or seasonality. This is evidence of a good model.

First Year of Data Model Fit

Because the model fit to the complete data was excellent, we sought to find how early one could obtain reasonably accurate estimates of the degradation path and rate. For this dataset, one year of data appeared to be enough, as can be seen by comparing the model coefficients below to the ones from the complete data fit to the lower left.

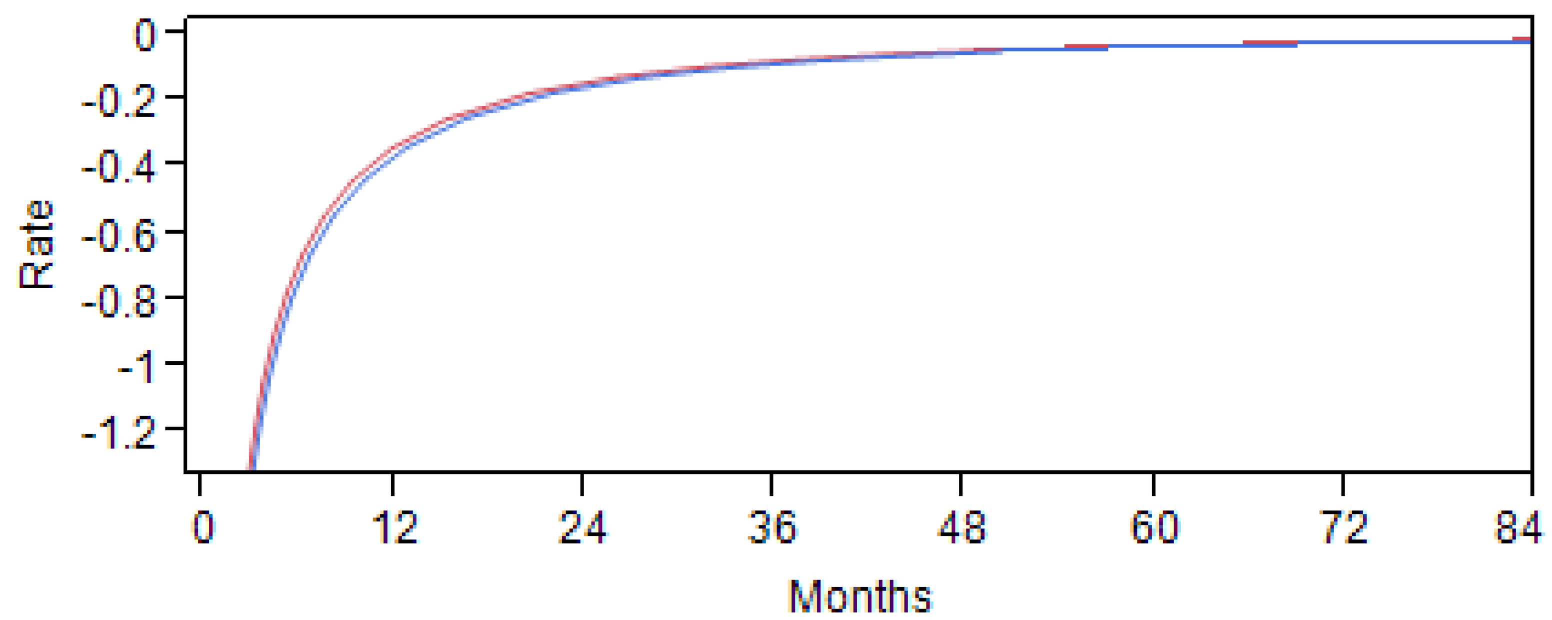
$$\begin{aligned} V(T) &= D(T) + S(T) \\ D(T) &= 79.2 + 23.8e^{-.35\sqrt{T}} \\ S(T) &= 2.2\sin(\frac{\pi}{6}(T-1.3)) + 1.6\sin(\frac{\pi}{3}(T-1.3))) \\ \dot{D}(T) &= 4.2T^{-\frac{1}{2}}e^{-.35\sqrt{T}} \end{aligned}$$

One Year of PV Array Voltage Data



Overall and degradation model fit to only the 1st year of data (green dots). Note how well the fit to the first year predicts the next five years of data.

Comparing the Rate Estimates



Red line is the 72 month rate estimate, blue line is the 12 month estimate. The rate function estimates are quite similar.

Conclusions

The two component model yields an excellent fit to the data, even when only using the first year's worth of data. This suggests that this exponential decay model in the square root of time with a two term trigonometric seasonal model can be used to obtain early, yet accurate estimates of the life of PV arrays.