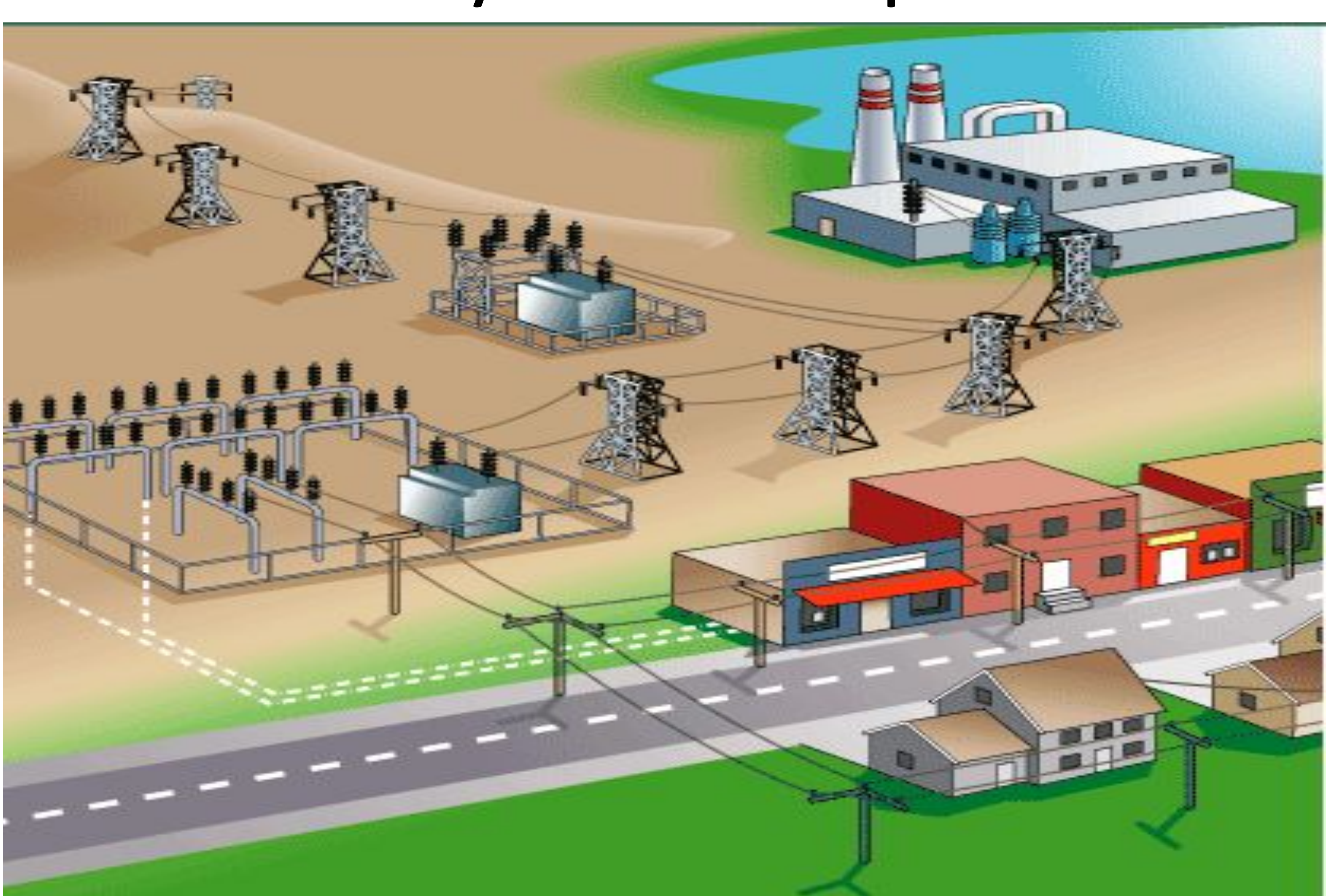
# Introduction

In power system studies, a load generally refers to the total power demand at a particular substation. Accurate representation of dynamic responses of loads are critical for system controls and stability. Phasor measurement unit (PMU) data is relatively new technology for collecting close to real-time (60 samples/sec) data at different locations on a power grid. Here, we describe the development of a dynamic load model using single-line-to-ground fault (SLG) PMU data. The proposed model is in transfer function form and the model parameters are estimated using the Least Squares method. Then, the model is validated using PMU fault data from line-to-line-to-line (LLL) and line-to-line (LL) events. Preliminary results show that the model captures the system dynamics, but more work is needed in order to capture the dynamics with greater accuracy.

# Power System Components



# Model

- This system can be modeled in the continuous time domain or the discrete time domain.
- Given the nature of the data, we start with the discrete time domain model. We follow the norms of modeling by starting with a simple linear model. Specifically, a temporal multivariate linear regression model for real power $P(t)$ and another one for reactive power $Q(t)$:

$$P(t) = c_0 \cdot P(t-1) + c_1 \cdot V(t) + c_2 \cdot V(t-1)$$

and

$$Q(t) = c_5 \cdot Q(t-1) + c_6 \cdot V(t) + c_7 \cdot V(t-1)$$

, where $c_0$ through $c_7$ are the model parameters.

- Another way to model the system is by considering time a continuous variable. A simple linear model for the change in real power $\Delta P$ and the change in reactive power $\Delta Q$ is then given by the following first-order transfer functions:

$$\Delta P = \frac{a_1 \cdot s + a_2}{s + a_0} \cdot \Delta V \quad \text{and} \quad \Delta Q = \frac{b_1 \cdot s + b_2}{s + b_0} \cdot \Delta V$$

,where $a_0,$ $a_1,$ $a_2,$ $b_0,$ $b_1,$ and $b_2$ are all model parameters. $\Delta V$ is the change in voltage and s represents the Laplace domain.

# Method of Least Squares

- The parameters P=[$c_{0,}$ $c_{1,}$ $c_2$] of the discrete time equation $P\,(t)$ are estimated using phasor measurement unit (PMU) data in the following form:

$$X = \begin{pmatrix} P_0 & V_1 & V_0 \\ P_1 & V_2 & V_1 \\ \vdots & \vdots & \vdots \\ P_t & V_{t+1} & V_t \end{pmatrix} \text{and} \quad Y = \begin{pmatrix} P_1 \\ P_2 \\ \vdots \\ P_{t+1} \end{pmatrix}.$$

- The Least Squares method is then used to estimate the parameters P=($X^T$*X)$^{-1}$*$X^T$*Y.
- Now that we have the fitted $P\,(t)$ model, we can derive the continuous $\Delta P$ model.
  - Using the Z-transform on $P\,(t)$ we get:

$$P(Z) = \frac{c_1 \cdot Z + c_2}{Z + c_0} \cdot V(Z)$$

  , where *Z* is an arbitrary complex number and this is now the discrete frequency domain.
  - Finally, applying the bilinear transform

$$Z = \frac{1 + s \cdot T \cdot 0.5}{1 - s \cdot T \cdot 0.5}$$

  on P(Z) we get the continuous time model:

$$\Delta P = \frac{a_1 \cdot s + a_2}{s + a_0} \cdot \Delta V$$

- The same process is repeated for the discrete time equation $Q(t)$ and we arrive at:

$$\Delta Q = \frac{b_1 \cdot s + b_2}{s + b_0} \cdot \Delta V$$

# $P\ (t)$ and $Q(t)$ for SLG Data

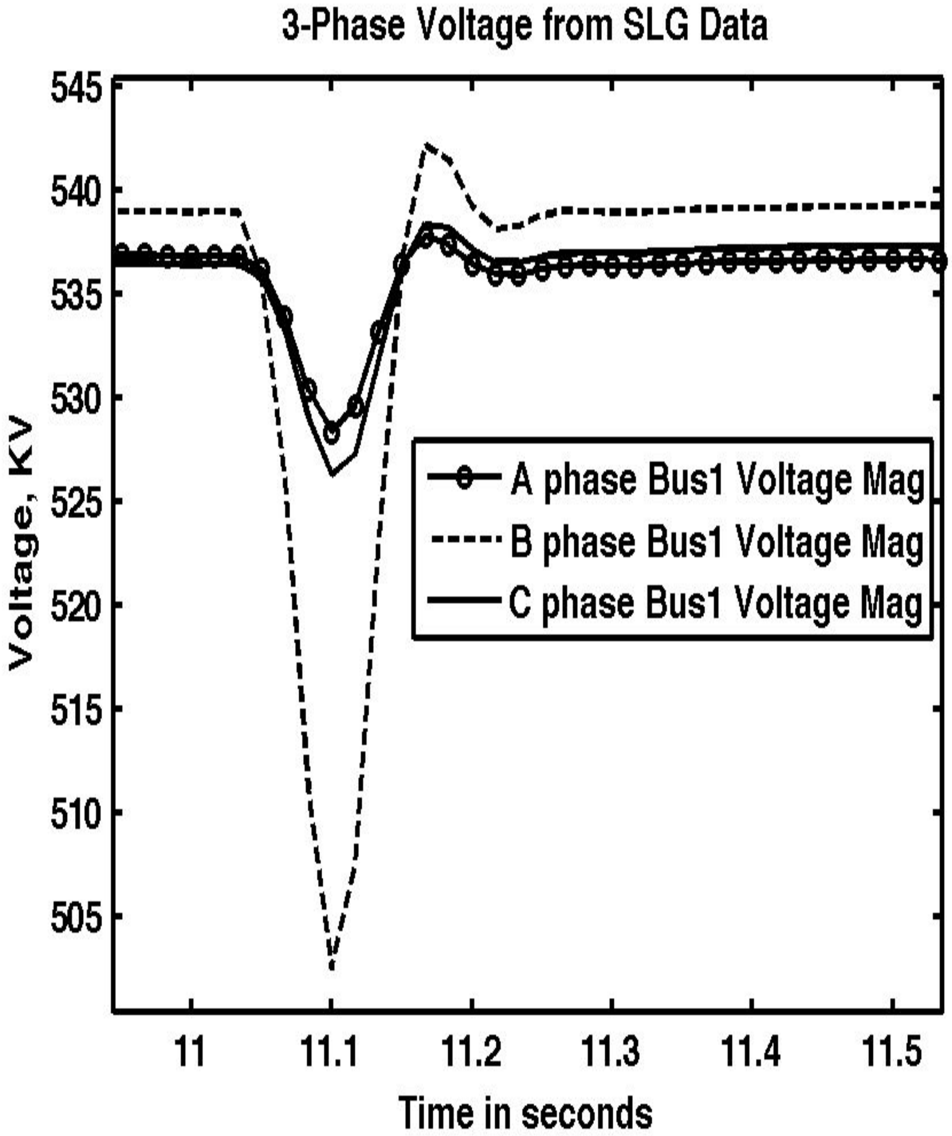



Figure 1: SLG observed 3-Phase voltage data.

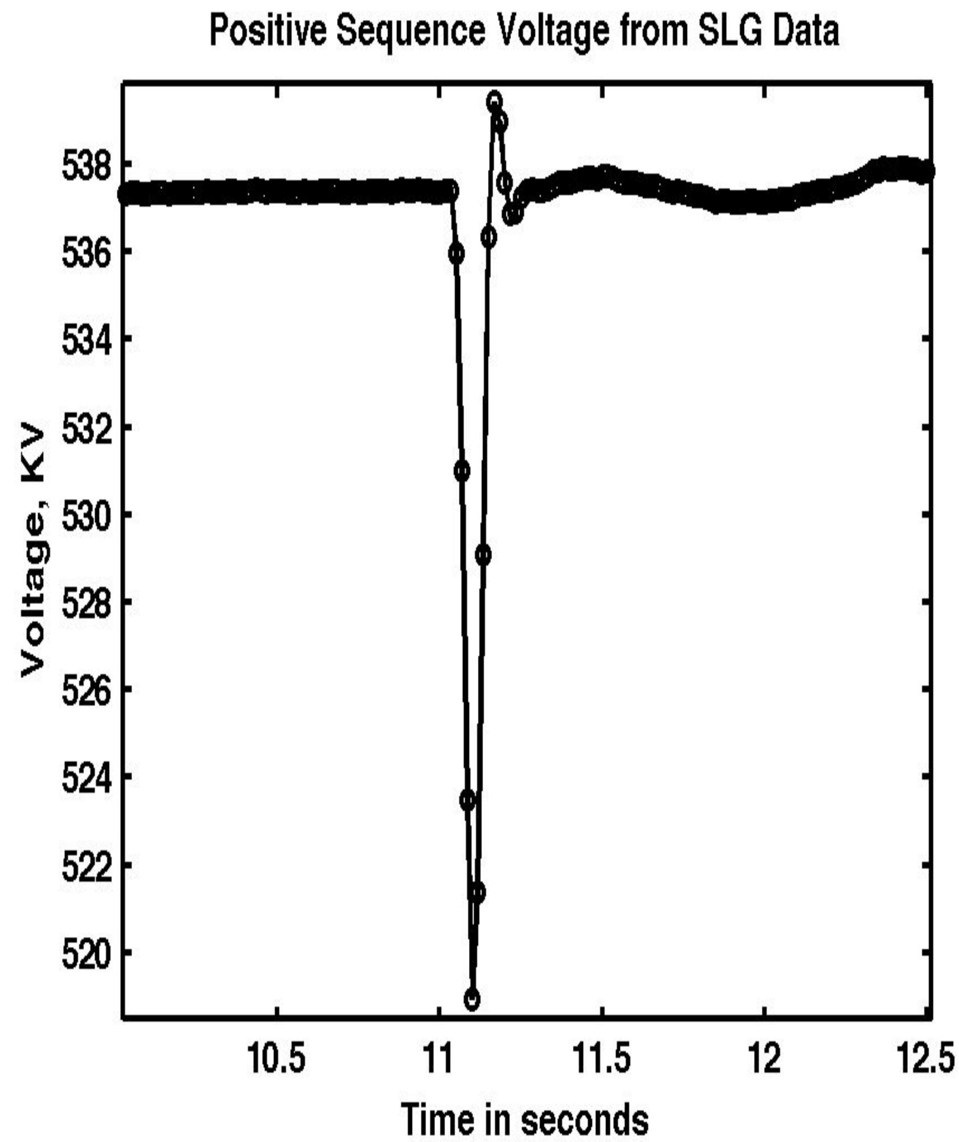



Figure 2: SLG observed positive sequence voltage data .

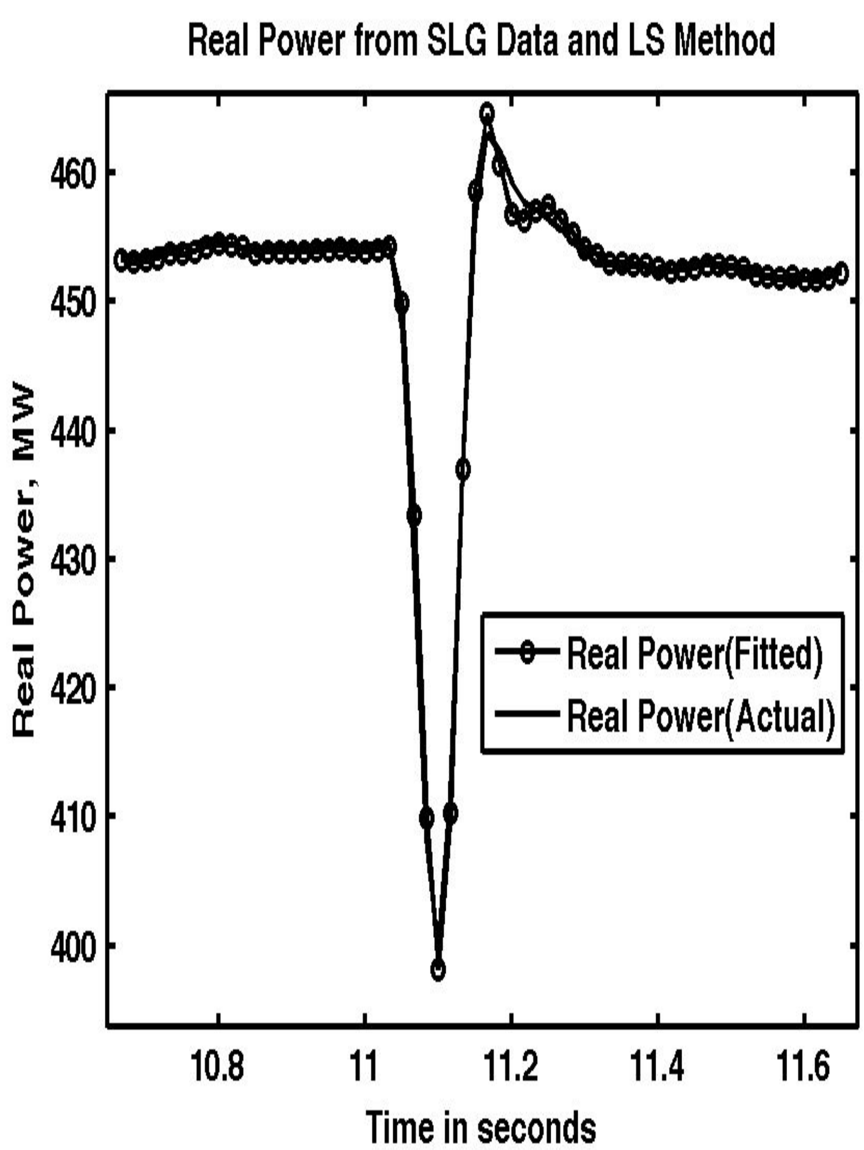



Figure 3: SLG real power model tested using SLG data.

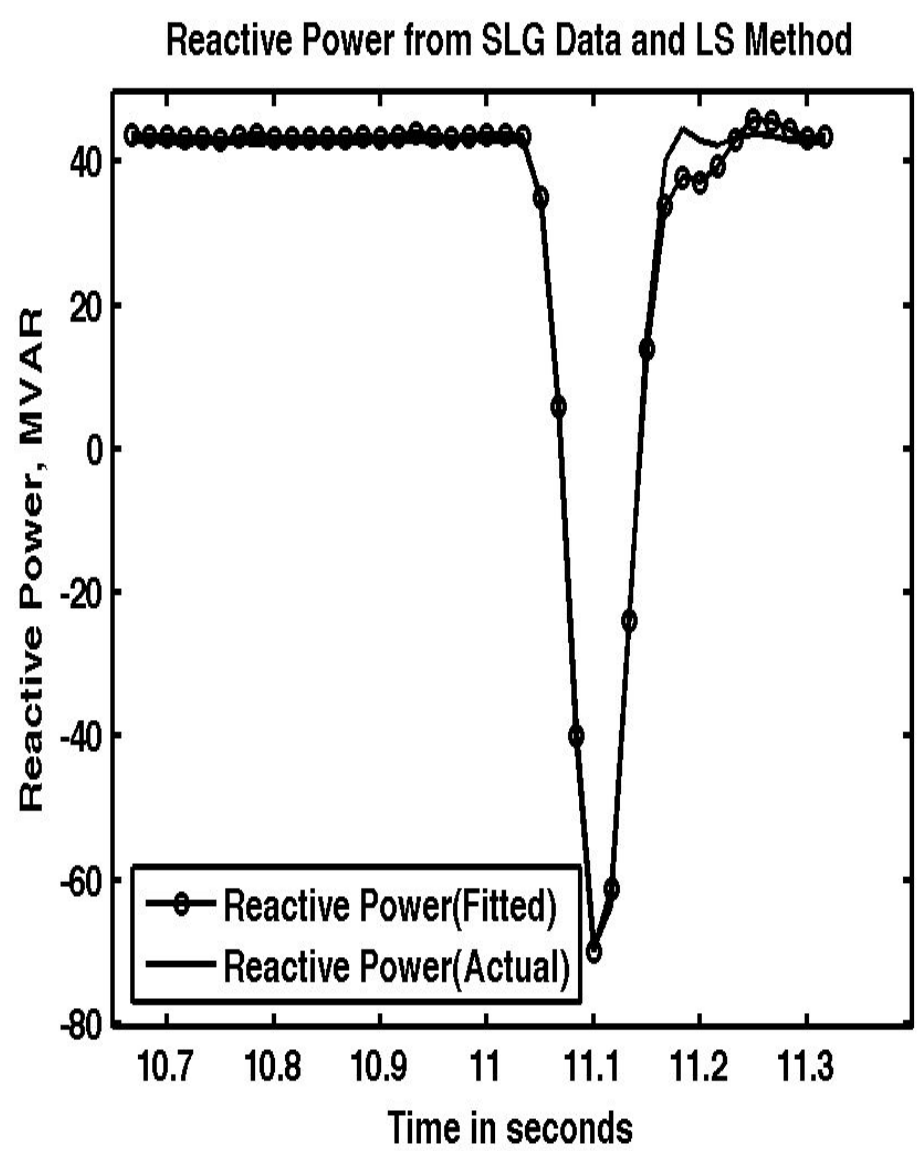
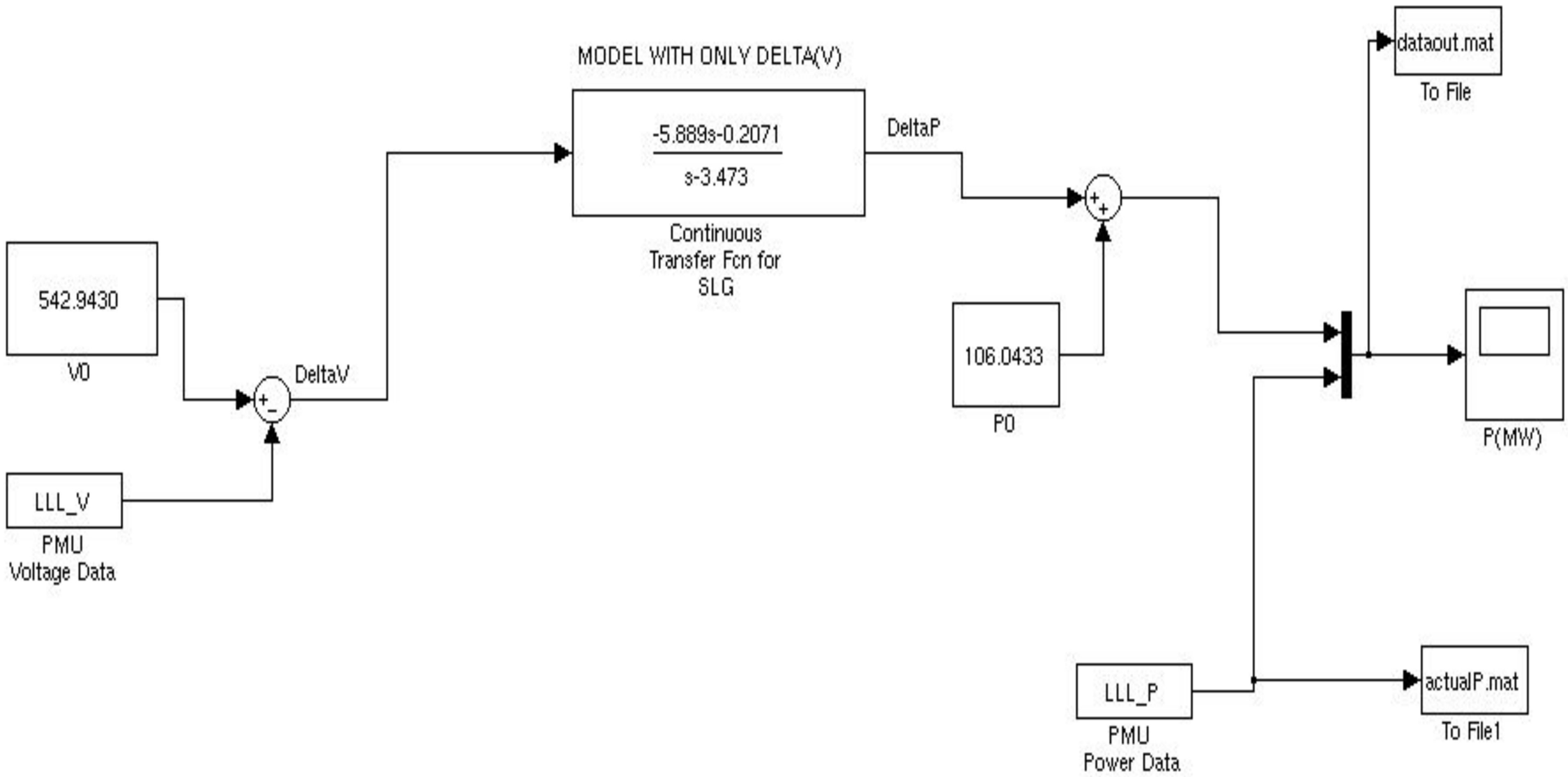



Figure 4: SLG reactive power model tested using SLG data.

# Simulations of $\Delta P$ *and* $\Delta Q$




- Simulations of the continuous model's $\Delta P$ and $\Delta Q$ can be run in Simulink.
- The simulation takes an initial voltage and voltage from PMU data to calculate $\Delta V$.
- The transfer function then outputs a $\Delta P$ which is added to an initial power to give the new power in MW/MVAR.
- Actual PMU power data is then given as input to the display along with the new approximated power.

# $\Delta P$ and $\Delta Q$ for SLG Data

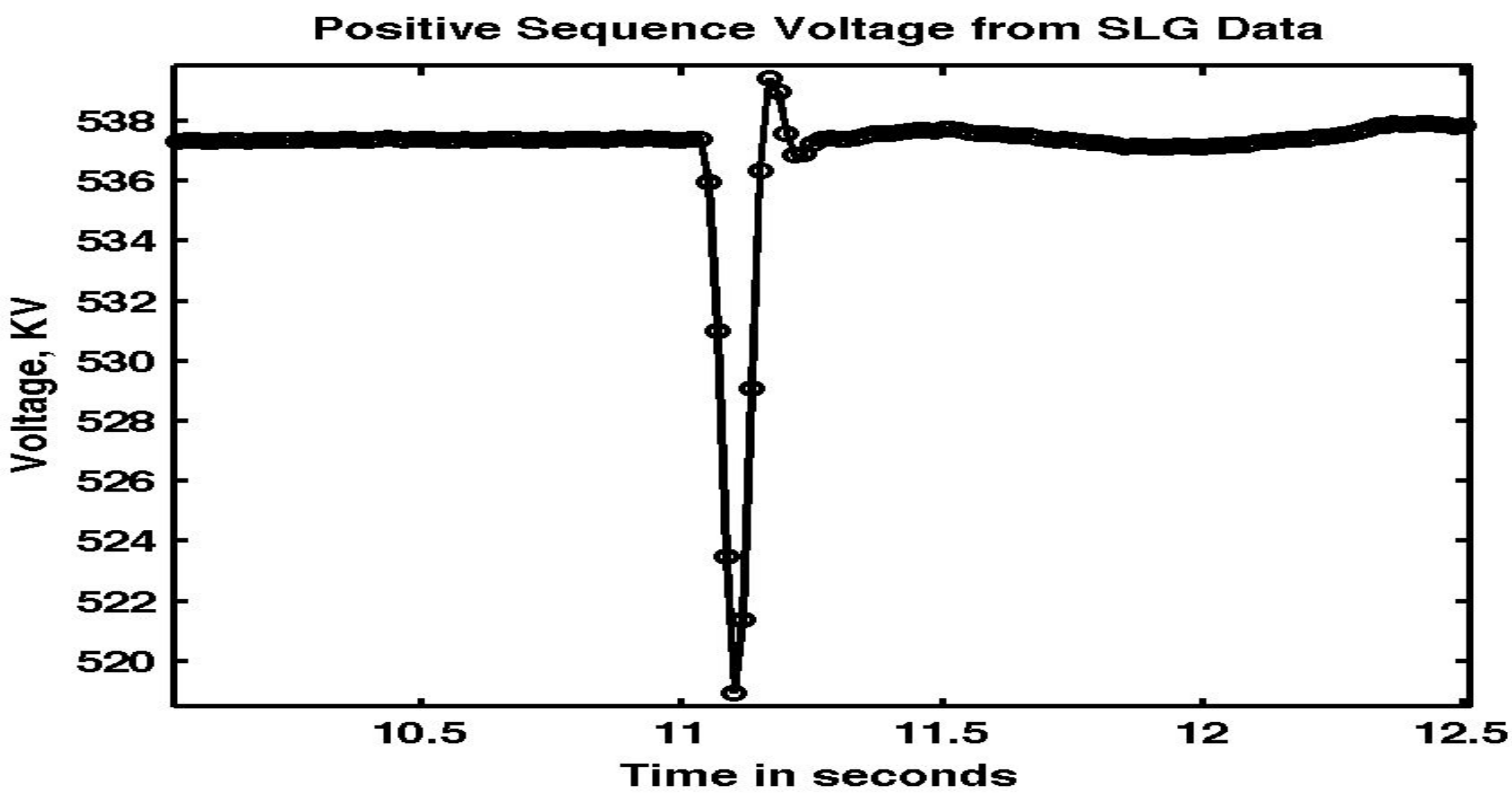



Figure 5: SLG observed positive sequence voltage data .

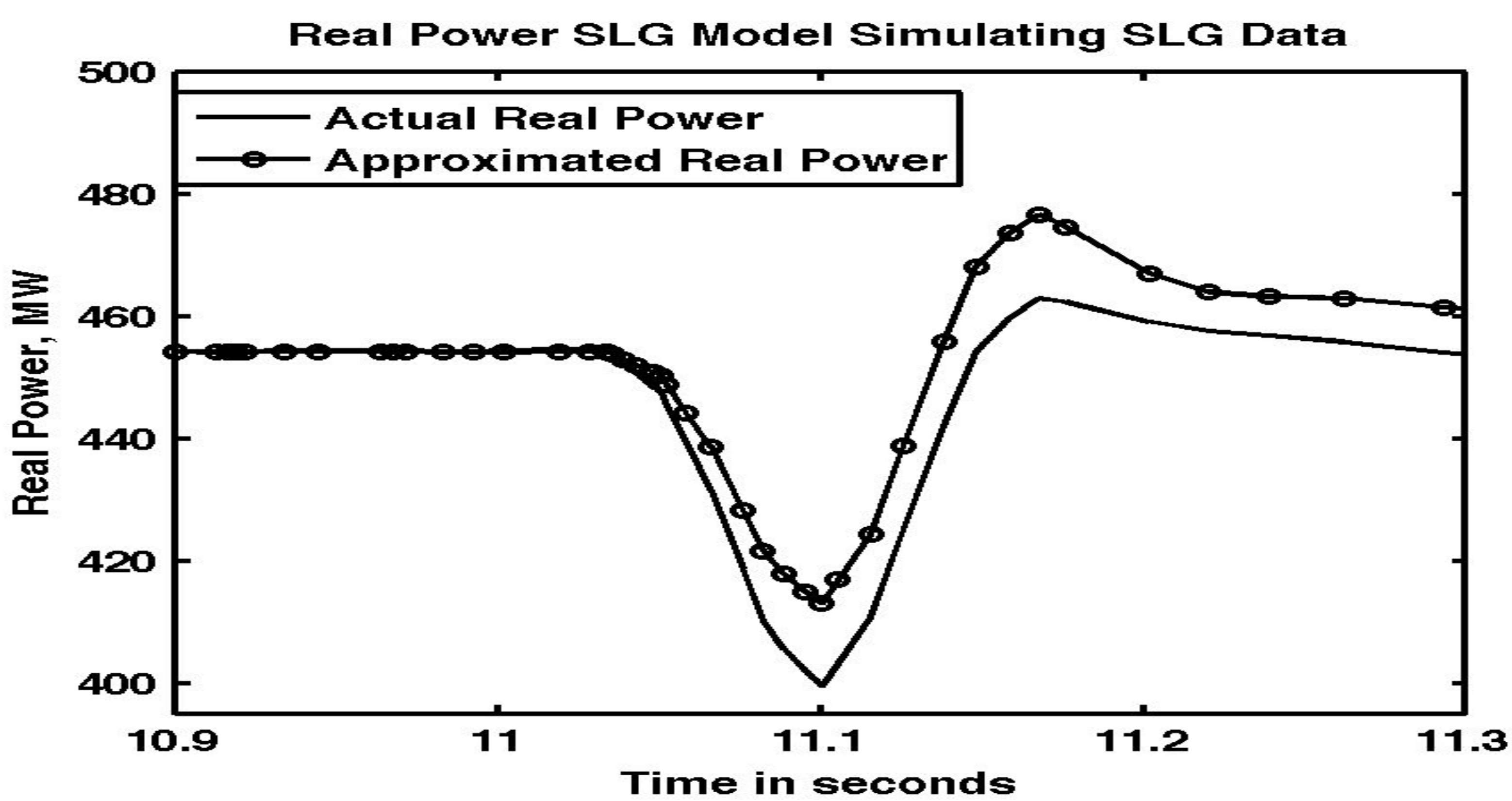



Figure 6: SLG $\Delta P$ model simulating SLG data in the continuous domain S.

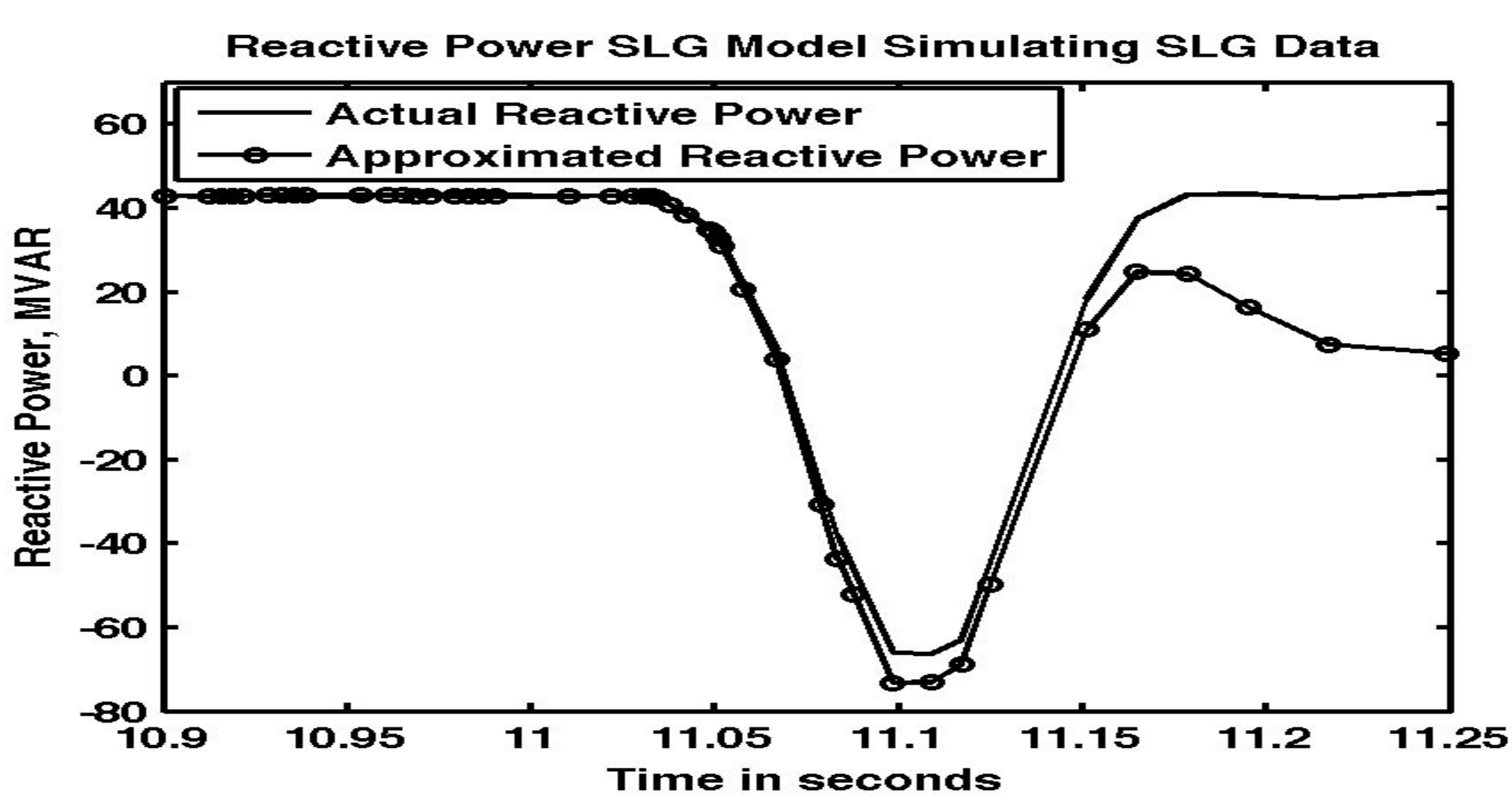



Figure 7: SLG $\Delta Q$ model simulating SLG data in the continuous domain S.

# $\Delta P$ and $\Delta Q$ for LL Data

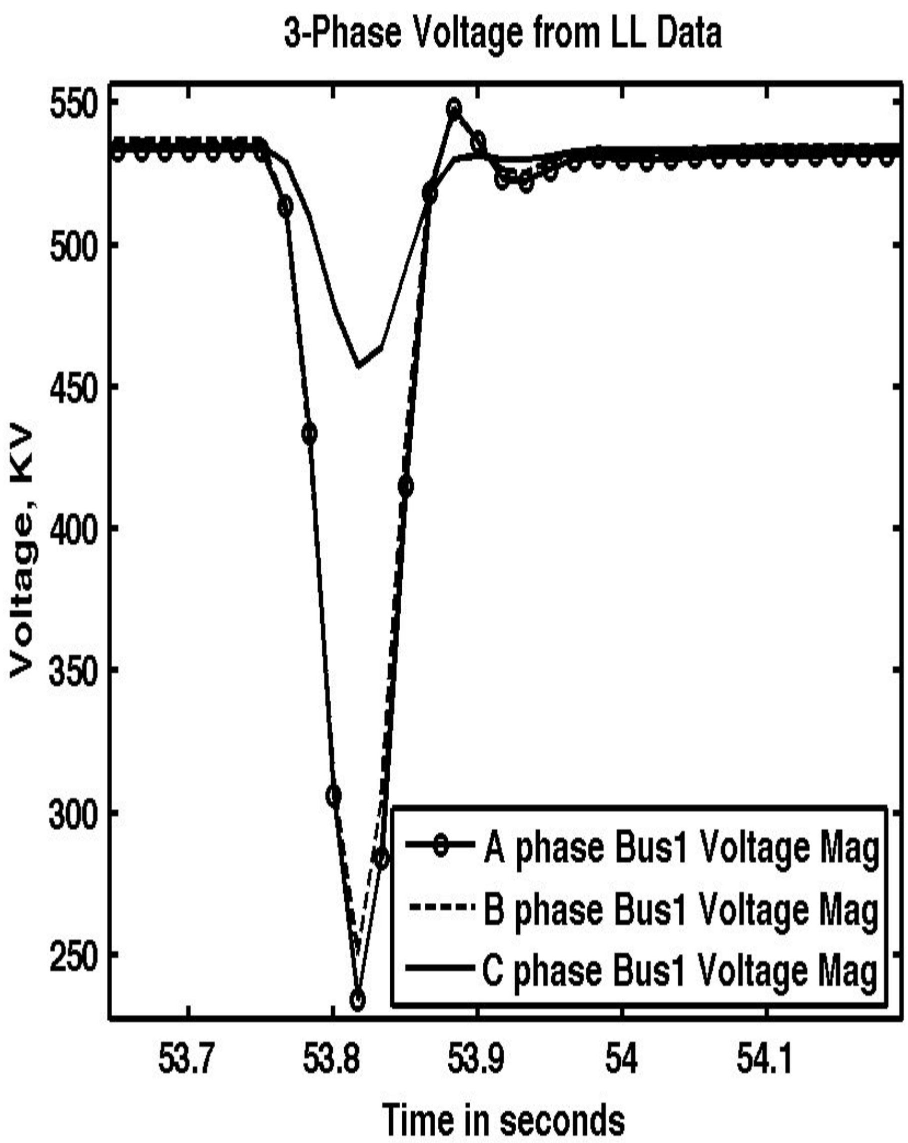



Figure 5: LL observed 3-Phase voltage data.

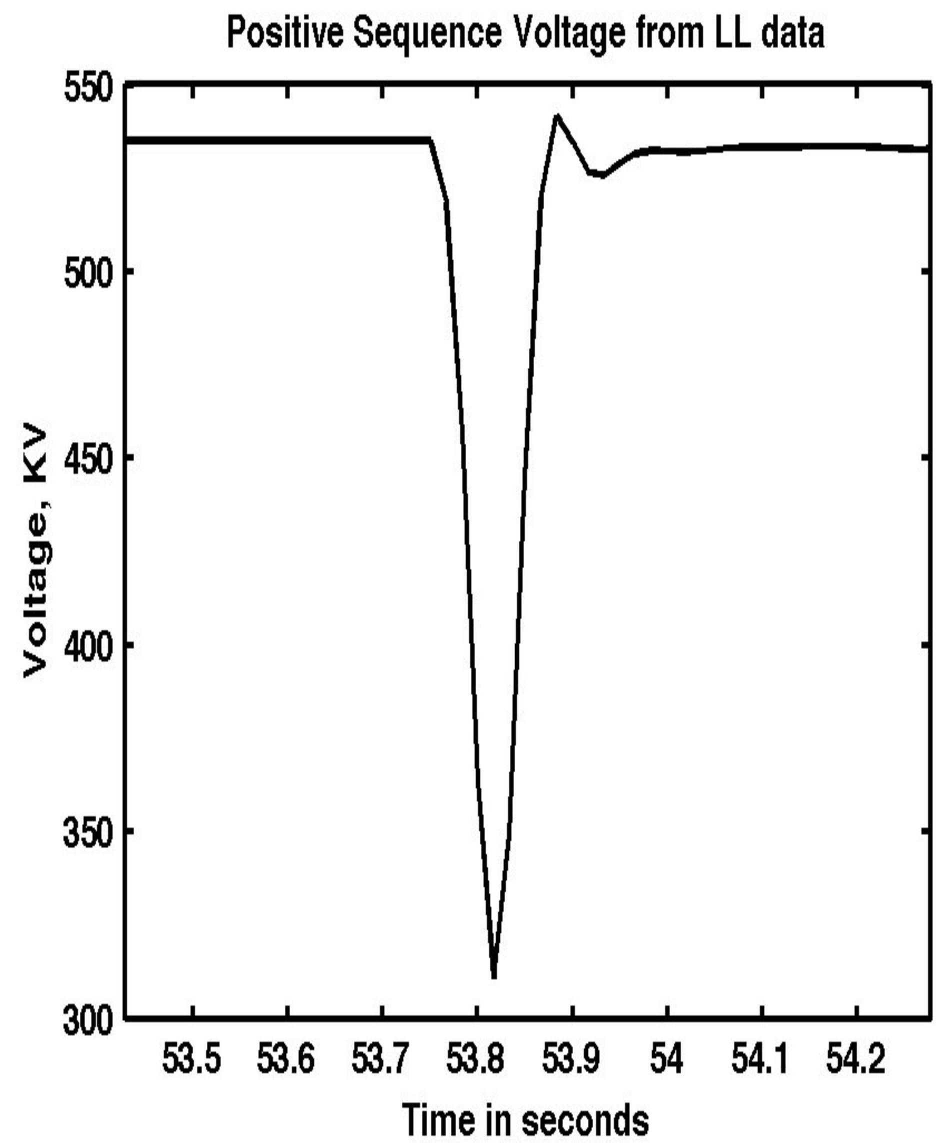



Figure 6: LL observed positive sequence voltage data .

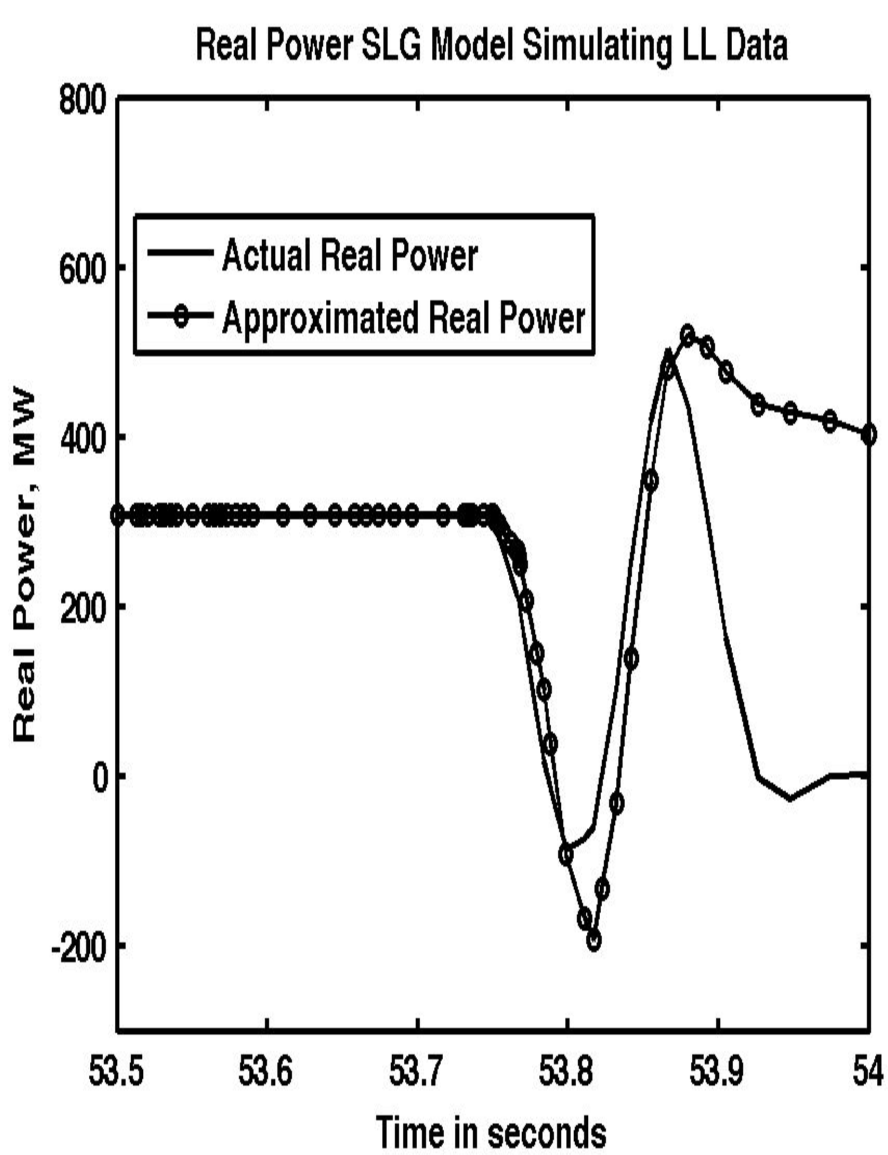



Figure 7: SLG $\Delta P$ model simulating LL data in the continuous domain S.

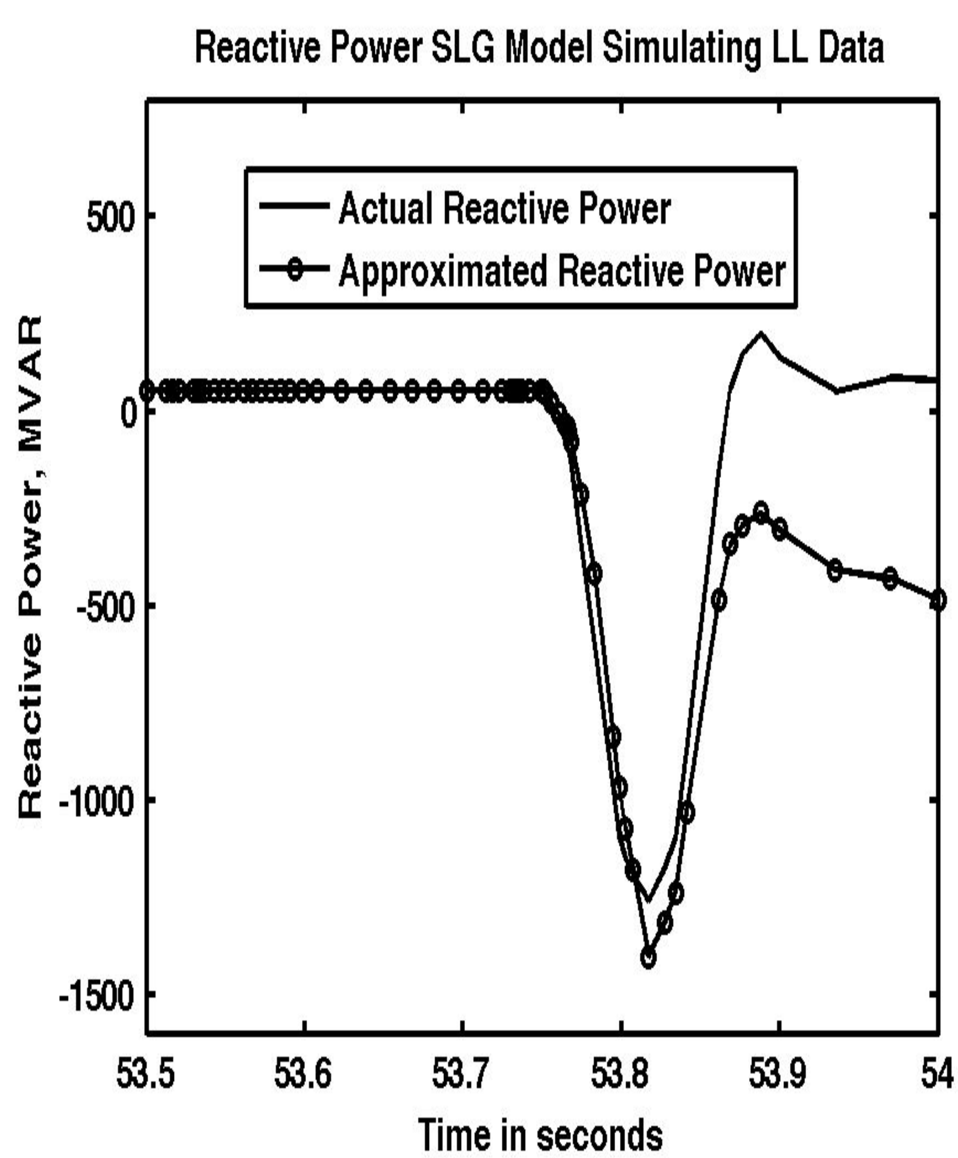



Figure 8: SLG $\Delta Q$ model simulating LL data in the continuous domain S.

# $\Delta P$ and $\Delta Q$ for LLL Data

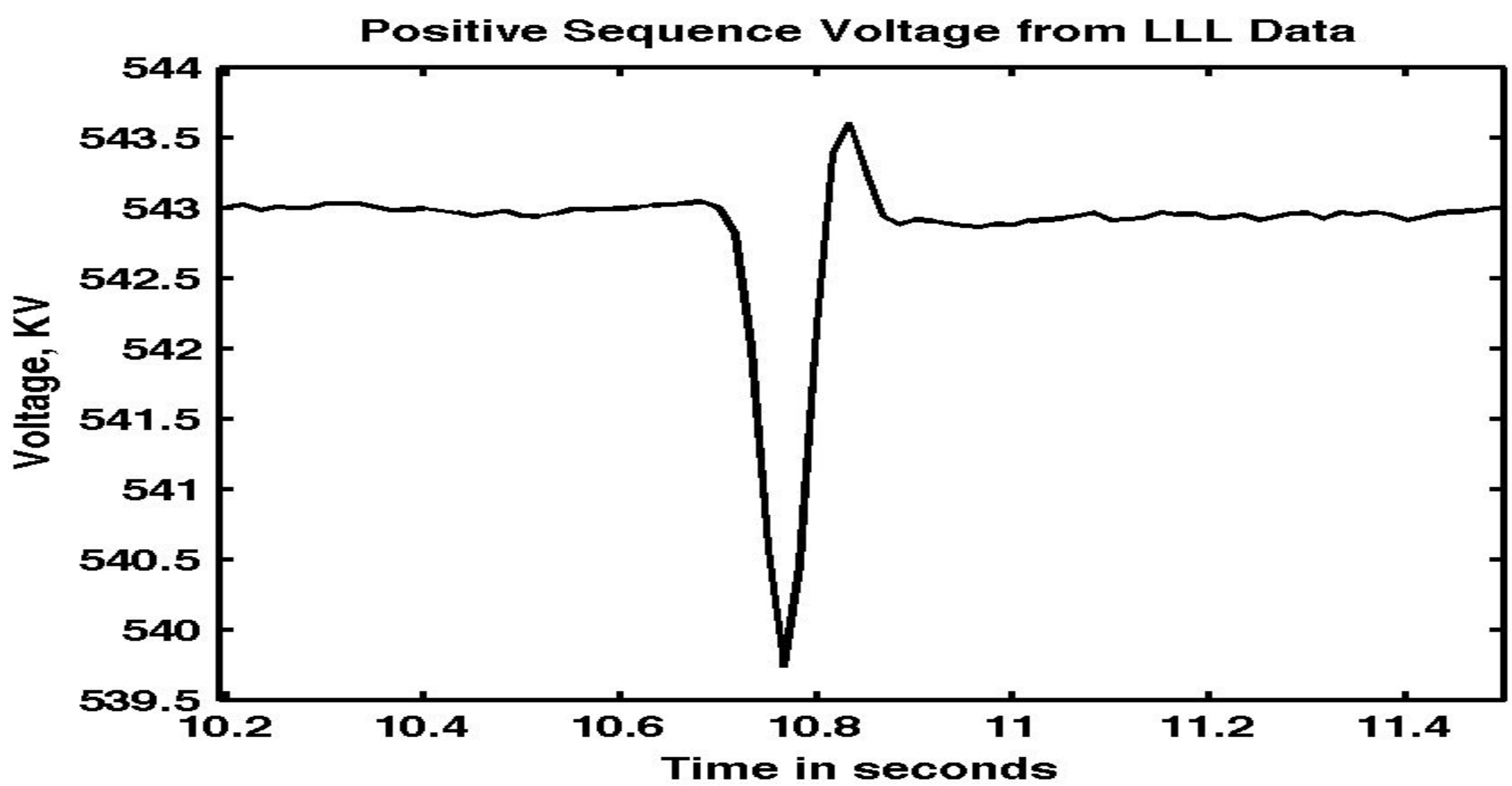



Figure 9: LLL observed positive sequence voltage data .

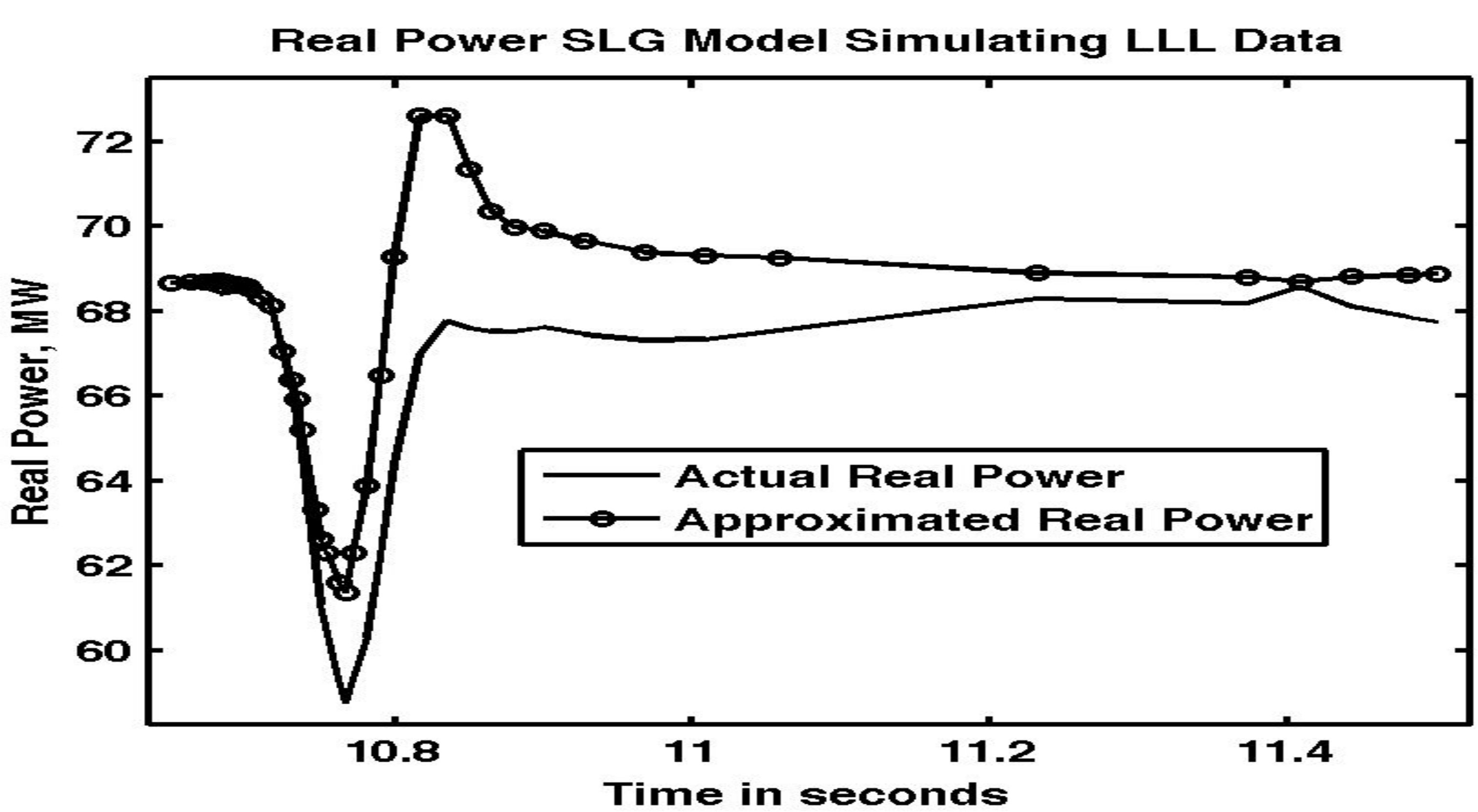



Figure 10: SLG $\Delta P$ model simulating LLL data in the continuous domain S.

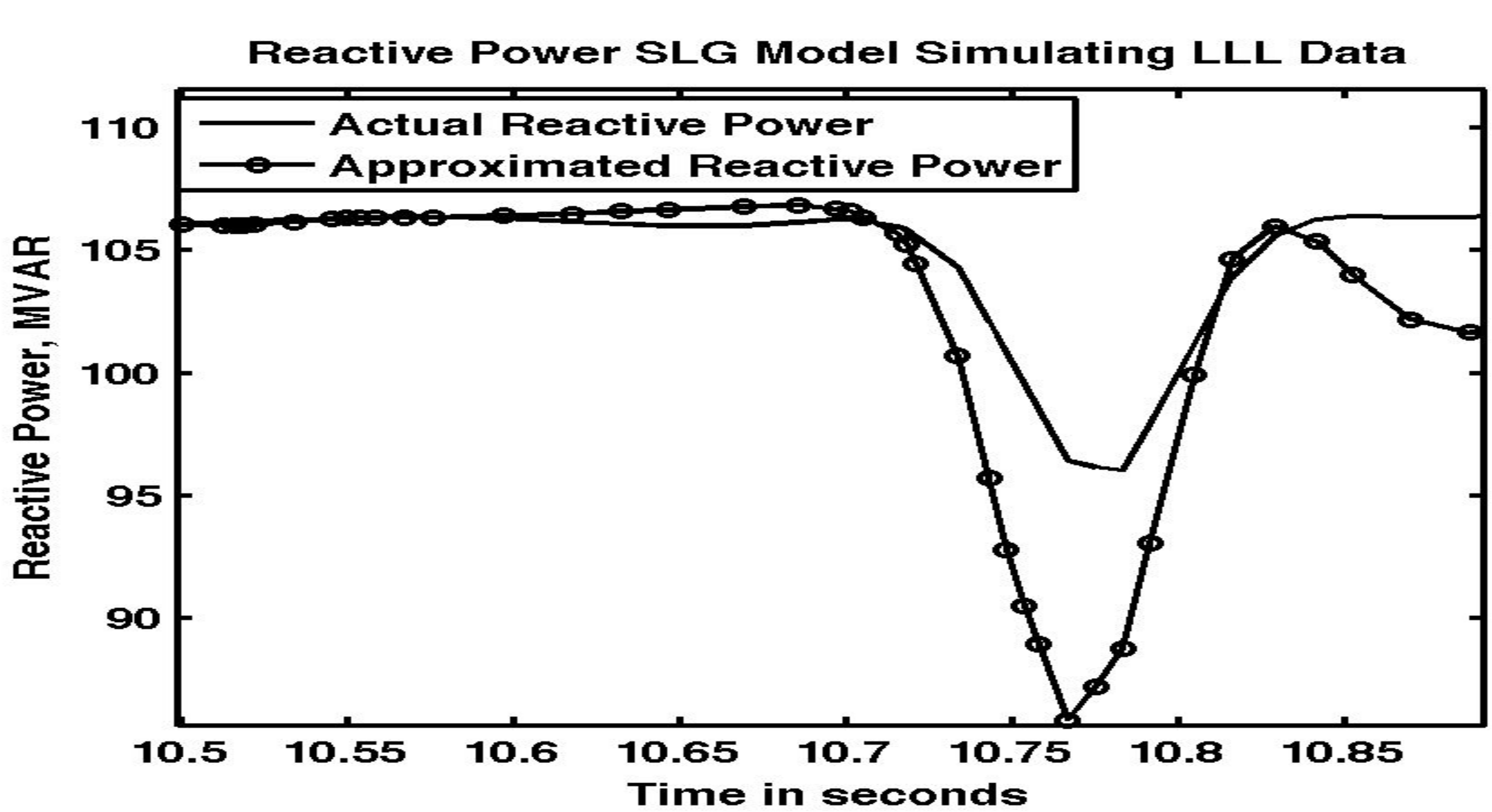



Figure 11: SLG $\Delta Q$ model simulating LLL data in the continuous domain S.

# Conclusion

- Based on PMU data, we can create a transfer function based load model which matches the data well. Although the model captures the overall system dynamics, work is still needed in order to capture the system dynamics more accurately. Specifically, we would like the fault peaks to be captured more accurately.

# Future Work

- Scaling the data to reduce errors.
- Adding a frequency variable transfer function to the model.
- Initial investigation of data shows that errors follow an AR(1) model. This means we can create an error transfer function to include in the model.