Load Modeling in Harmonics Analysis with OpenDSS

27 May 2013

Original Load Model

The LOAD object model from the time it was made open source in 2008 until March 2013 was a Norton equivalent as shown in Figure 1. The current source in the model was set to the value of the fundamental current, I_{fund}, times the multiplier for the SPECTRUM object associated with the LOAD for the frequency being solved. The load equivalent admittance, $G + jB$, was represented in the model as shown with only B adjusted for frequency. Thus, loads which were highly resistive could provide significant damping.

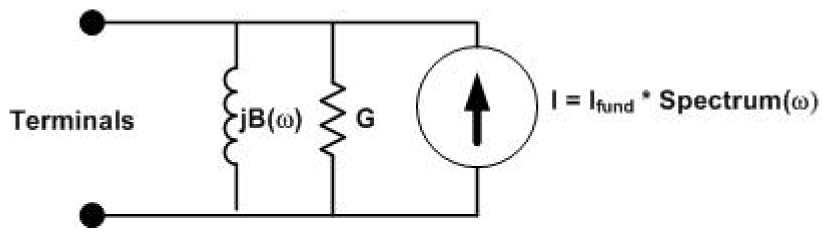

Figure 1. Original Norton Equivalent Model Of a LOAD Element in Harmonics Mode

This model was sufficient for most cases where LOAD objects were retained for harmonics analysis. Most harmonics problems on distribution systems are the result of *resonance* with power factor correction capacitor banks. A distribution planner wanting to get an idea of whether or not a capacitor configuration would cause a problem could simple solve a power flow and then execute a "Solve Mode=Harmonics" command. This would automatically convert all LOAD objects to the model in Figure 1 and solve for all frequencies present is all SPECTRUM objects.

For frequencies where the system is not near resonance, most of the current exited the model through the terminals into the power system. The short circuit impedance of the typical power system looking into it from a load is usually less than 5% of the load's equivalent impedance. Therefore, very little current is siphoned off into the shunt admittance branch of the model.

At frequencies where the system was near resonance, the driving-point impedance looking into the system can be very high. Therefore, a significant portion of the harmonic current is bled off into the model, which also provides significant damping of the resonance as will be discussed later.

Revised Load Model

In March 2013, users in the discussion forum complained that the terminal currents did not match the expected harmonic current. A special beta version was made in which the shunt admittance path was completely removed. This, incidentally, was the original approach when OpenDSS was first developed in 1997. When users complained that the model greatly exaggerated the voltages that would appear near resonant conditions, the equivalent shunt admittances were added. Users were content with this approach until March 2013 when the shunt admittances were temporarily removed. So it not surprising that users once again objected to there being no representation of the load damping.

In response, options were added to the program and to the LOAD object specifically to give the user control over the load model in Harmonics mode. As of Version 7.6.3.13, the LOAD model for harmonics mode is as shown in Figure 2.

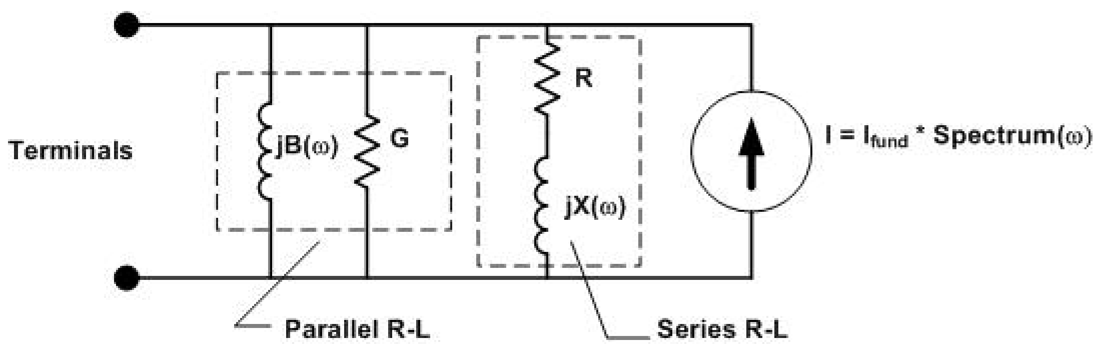

Figure 2. Revised LOAD Model in Harmonics Mode

Users can specify what percentage of the load is to be modeled as a serried R-L and the remainder will be considered to be a parallel R-L model. A Property has been added to the LOAD object:

Property	Description
%SeriesRL	Percent of load that is series R-L for Harmonic studies. Default is 50. Remainder is assumed to be parallel R and L. This has a significant impact on the amount of damping observed in Harmonics solutions.

In addition, a global option, **NeglectLoadY**, has been added that will enable users who so desire to completely neglect the load damping. It is defined as follows:

Option	Description
NeglectLoadY	{YES/TRUE | NO/FALSE} Default is NO. For Harmonic solution, neglect the Load shunt admittance branch that can siphon off some of the Load injection current. If YES, the current injected from the LOAD at harmonic frequencies will be nearly ideal.

To use this, you would use the **Set** command, for example:

```
Set NeglectLoadY=Yes
Solve    ! --- (power flow)
Solve Mode=Harmonics
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Transformer X/R: XRConst Property

Generally, the resistance in a power system has a minor effect on the flow of harmonic currents when the system is not in resonance. However, the damping of harmonic resonance by resistance of loads, lines, and transformers can have quite a significant impact on the level of harmonic voltage distortion predicted by the models.

Substation transformers and larger transformers supplying industrial consumers have a relatively high X/R ratio of 10 or greater at fundamental power frequency. Distribution service transformers such as those that serve residential loads can have a much lower X/R. It would not be surprising to find that a 25 kVA transformer would have an X/R ratio only slightly greater than 1.0. In either case, there is a question about what to assume for the variation of R for harmonic frequencies.

If no modification to the winding R is made, the equivalent X/R will increase in proportion to the harmonic. This can lead to a prediction of very little damping at harmonic frequencies. For example, if a substation transformer has an X/R ratio of 10 at fundamental, the model will have an X/R of 50 at the 5^{th} harmonic, which generally results in an unrealistically high-Q circuit model with exaggerated predictions of voltage distortion. The apparent resistance of transformers increases with frequency at a rate that is dependent on its design. The chief component of the increase comes from the stray eddy current losses and can be quite significant in transformers that have conductors with large cross-sectional areas. Also, designs with conductors in parallel can have circulating currents withing the windings that yield an effective increase in R.

Until version 7.6.3 build 13, the OpenDSS transformer model did not have any provisions for modifying R as a function of frequency. The XRCONST Boolean property was added to the TRANSFORMER object. It is defined as follows:

Property	**Description**
XRConst	={Yes|No} Default is NO. Signifies whether or not the X/R is assumed contant for harmonic studies.

If XRConst=YES the winding R is increased proportional to frequency just like X. This is a typical assumption of harmonics analysts when no other data are available. This approximates what happens in some large power transformers. It will not be a good fit for some transformers, but at least it adds some damping to the model to nullify the exaggerated high voltages and impedances that would otherwise be predicted.

This parameter is not generally as critical for small utility distribution transformers in the frequency range up to the 13^{th} harmonic. The windings are constructed with wire having a small cross section and the stray eddy losses do not generally increase as rapidly as for large power transformers. The normal low X/R of these transformers tends to contribute somewhat to the damping of resonance anyway, yielding results that are only moderately conservative.

Note that the default is NO. Thus, scripts from prior studies will yield the same result.

Future versions of OpenDSS are slated to have user-defined frequency correction curves. The curves will be applicable to the REACTOR model as well. Until that feature is implemented, if it is necessary to adjust R for frequency, users can script the resistance and solve for each frequency separately rather than using the built-in Harmonics solution mode or use the REACTOR model to achieve an approximate frequency-dependent resistance variation.

Figure 3 shows a one-line diagram of the OpenDSS REACTOR model. The model is nominally a series, multiphase R-L with user-defined properties of R and X. In addition to scalar values, R and X may also be defined as matrices. A feature of the model that, perhaps, is seldom used is the parallel resistance, *Rp*, that is around the entire branch. Its default value is infinite (open) so that it doesn't enter into the calculations. However, it can be employed to model frequency dependence of R-L elements, including transformers. This would require a separate REACTOR to be added in series with the transformer and defined with an appropriate value so that the total through impedance of the transformer is correct.

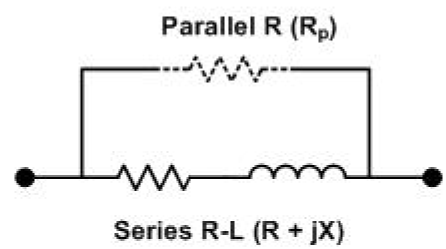

Figure 3. One-Line Diagram of REACTOR Object

Comparison of Models

Figure 4 illustrates the different results that can be obtained by the various assumptions about theload damping model.

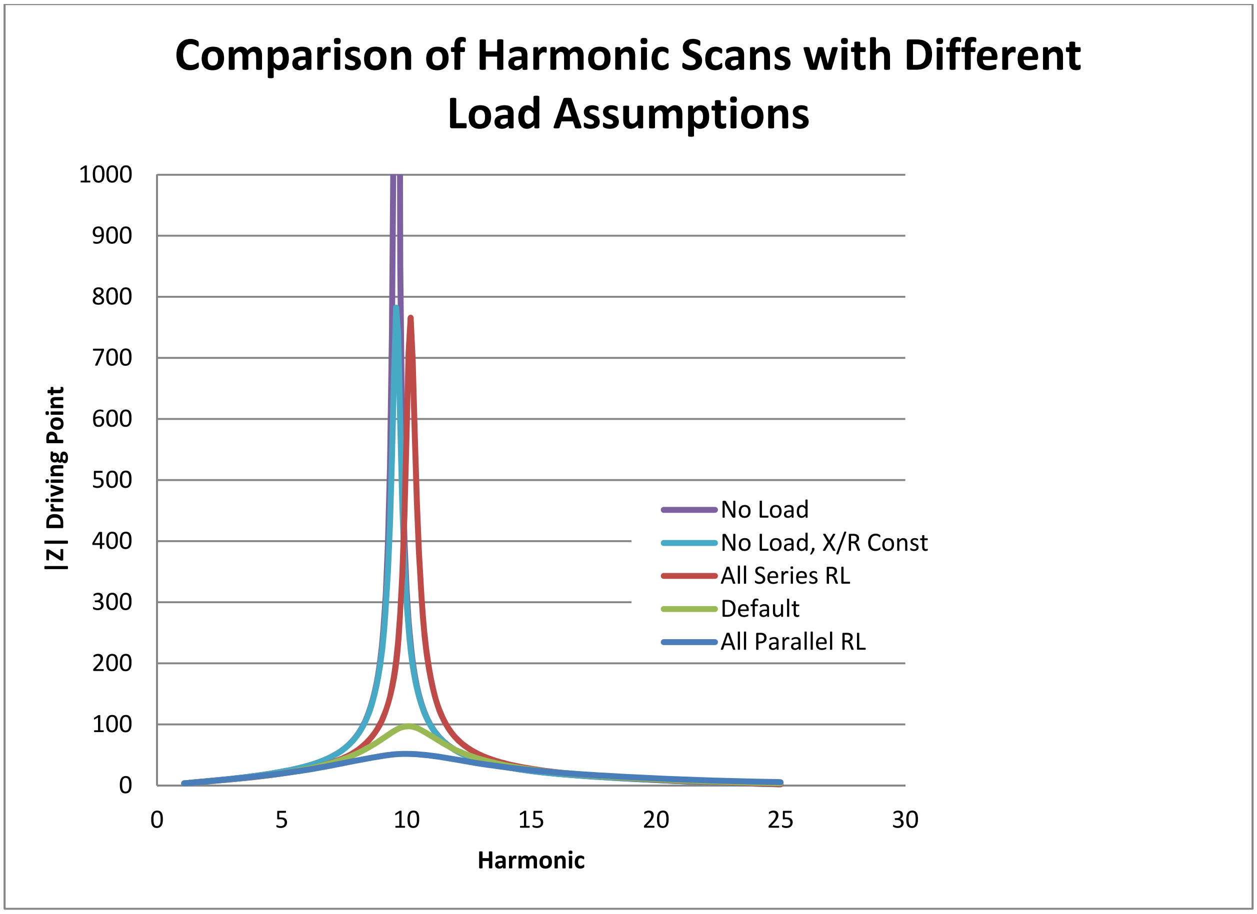

Figure 4. Comparison of Using Different Load Models