Harmonic Modeling of Networks

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Abstract: Harmonic modeling for power systems involves the incorporation of device models into a power system model. The development of accurate system models for harmonic studies involves the selection of the devices to include in the model as well as the selection of device models which achieve a balance between complexity and accuracy for the study in question.

6.1 Introduction

Harmonic propagation studies begin with the development of a system model which is the group of device models to be included in the study. In nearly every study, it is not feasible to include detailed models of every component of the system. Interconnected power systems typically include hundreds of generators and transmission lines, and even more distribution lines and customers. Even stand alone systems have more loads than can be modeled individually.

Every harmonic study must begin with a determination of the frequency range of interest and the selection of the system components which will be modeled. This chapter describes procedures which are used to develop system models for harmonic studies. The chapter is divided into two major sections which describe system development for distribution systems and for transmission systems, respectively.

6.2 Distribution System Modeling

While distribution systems and transmission systems have the same components- lines, transformers, and machines- there are significant practical differences in developing systems models for the two types of systems. Distribution systems, in fact, are divided into two distinct levels- primary distribution and secondary distribution. Secondary distribution is most often below 600 volts, and is typically owned by the electricity consumer. Primary distribution generally ranges from 4kv through 36kv, and is typically utility owned.

There are two reasons to undertake a distribution system harmonic study: first, to study the impact of a large new harmonic source and secondly, to examine a harmonic problem on an existing system.

Three phase or single phase modeling The first decision to make in any distribution system harmonic study is whether a three phase model is required or if a single phase model will be sufficient. The three phase model is required when:
• a combination of wye-wye and/or delta-wye transformers leads to harmonic cancellation
• single phase or unbalanced capacitors are present
• ground or residual currents are important in the study
• significant unbalanced loading is present

As one or more of these cases is present on many distribution systems, it is often recommended to implement a three phase model on any distribution system study. There have, however, been numerous successful studies which have been single phase in nature. The typical instances where a single phase model may be sufficient are:
• a single large three phase harmonic source is the cause of the study
• the remaining system is well balanced
• ground currents are not an issue

The single phase model of the system can be attractive as it is one third the size of the three phase model and the results can be more compact and easier to interpret. Still, it should be employed only when it is clear that it will be sufficient for the study being undertaken.
The extent of the system model. Most distribution systems are tied into the interconnected power network. The exceptions are certain stand-alone systems such as are encountered on oil-drilling platforms. In stand-alone systems, it can be feasible to model the entire power system. In other cases, however, the system is too large to fully model. A decision must be made as to which components to model in detail, and which areas of the system can be modeled with a network equivalent.

A common primary distribution system is shown in Figure 6.1. The system is radial, with energy supplied to the system through a step down transformer from the transmission network. In many cases, it is sufficiently accurate to represent the transmission network by it’s 60 Hz short circuit equivalent resistance and inductance. There should be consideration of the fact that the short circuit strength of the supplying system will change depending on the system configuration. A more detailed model is needed when capacitance is present on the transmission system near the step down transformer, or in any case where harmonic penetration into the transmission network is of interest.

The final modeling aspect to be aware of is that the transmission system can be a major source of harmonics for the distribution system. The only way to determine if this is the case is through measurements on the transformer secondary. In most cases, these measurements can be made on the existing current and voltage transformers. The measurements should be made with an instrument that will provide phase angle information as well as magnitude information. The length of time over which the measurements are needed must be determined on a case by case basis.

For a study of harmonic propagation on the primary system, the components of the system should be modeled as appropriate for the frequency range of the study. Typically, the capacitance of overhead lines and transformers does not need to be included in studies involving the lower order harmonics. The interaction of power factor capacitors and the line and source inductances is the primary driver of the harmonic impedance at the lower order harmonics, so these need to be modeled with care. The increase in line resistance due to the skin effect provides increased damping at the system resonance points and should be incorporated into the model.

The final component of the distribution system model is the load. Load modeling is difficult, as it is not possible or desirable to identify exactly what the load is at any given point in time. The load model is therefore somewhat empirical in nature, and different methods of determining load models are in use.

As indicated in Figure 6.1, most if not all system loads generate harmonic currents to some degree. Every system will have some background harmonic level even when no large harmonic sources are present. A generic load model therefore includes both a harmonic source and a harmonic impedance. An example load model is shown in Figure 6.2. The series impedance is often taken to include the effect of the distribution transformer. Several different methods have been used to select the shunt impedance values for a given load[1,2]. One method is to model motor load separately from the other load. The passive load MVA is converted to an equivalent parallel R-L impedance. The motor load is modeled as a single lumped induction motor with appropriate leakage reactances and stator and rotor resistances.
Another issue in model development is load aggregation, as it is not necessary or feasible to model each load individually. Load aggregation was studied in [3], where it was shown that feeder loads can be aggregated into fairly large groups without excessive loss of accuracy. For the feeders involved in that study, the load was grouped into approximately 10 equivalents per feeder.

Many harmonic studies involve a small number of large harmonic sources. In these studies, the background harmonic level is often ignored in the study, and considered separately as a source of error. The background harmonic level, however, is important for several reasons, including in the design of harmonic filters. At present, the only way of determining background levels on a given system is through measurement. An efficient measurement and modeling procedure is described in [4]. A procedure which combines measurement and modeling is generally required in performing harmonic studies on primary distribution systems.

Secondary distribution systems. Studies of secondary distribution systems involve studies of a single plant or commercial installation. Many of the modeling characteristics of primary distribution systems also hold for secondary systems. The one line diagram for a typical industrial system is shown in Figure 6.3. The plant model is likely to include several different voltage levels and likely will have fewer capacitors, but more of the capacitors will be installed with tuning coils for filtering purposes. Line and transformer capacitances are typically negligible, as is also the case for short cable runs. In many cases, measurements are easier to perform on secondary systems, and load data may be more readily available.

Figures 6.2. Generic per phase load model

Data preparation. At present, most studies are performed with one of the several commercial harmonics analysis software packages which are available. The device data entry and model synthesis using these packages is convenient once the data has been gathered. Typical data which is needed for studies is summarized in Table 6.1.
Table 6.1. Summary of typical data needed for a distribution harmonic study.

<table>
<thead>
<tr>
<th>Device</th>
<th>Data needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>transformer</td>
<td>Actual turns ratio, connection diagram, short circuit impedance</td>
</tr>
<tr>
<td>overhead lines, cables</td>
<td>phase and neutral conductor size, layout, length, or short circuit impedances; capacitance (when needed)</td>
</tr>
<tr>
<td>capacitor</td>
<td>voltage rating, var rating,</td>
</tr>
<tr>
<td>tuned filter</td>
<td>tuned frequency, volt, var rating, configuration</td>
</tr>
<tr>
<td>generator/large motor</td>
<td>subtransient impedance, configuration</td>
</tr>
<tr>
<td>load, linear</td>
<td>watts, power factor, composition, balance</td>
</tr>
<tr>
<td>load, nonlinear</td>
<td>expected level of harmonic current injection, magnitude and phase angle</td>
</tr>
</tbody>
</table>

6.3 Transmission System Modeling

Transmission system modeling is somewhat different than distribution system modeling for a number of reasons. The level of capacitance of lines and, in some cases, transformers, is such that these capacitances must be included in the models. Transmission systems have higher X/R ratios than distribution systems, so that harmonics can propagate for much longer distances- and distant components can have a significant impact on harmonic propagation. The third aspect of transmission system modeling is that the interconnected system of generators and transmission lines will typically take on a much wider range of operating configurations than is observed in most distribution systems.

A representative transmission system is shown in Figure 6.4. For convenience, only a single source and critical bus are shown, although there may be more than one of either of these. A transmission system harmonic study begins with the identification of a local system which must be modeled in detail- i.e., each component modeled individually with an accuracy appropriate for the study. Due to size and time constraints, distant portions of the system must be represented as lumped equivalents. There is a third, intermediate area where system representation is needed for accuracy. The key to transmission system model development lies in accurately and efficiently selecting the boundaries of the intermediate system and selecting appropriate lumped models for the remote system representations. This can be a difficult task, and there exist several different methods for making these selections.
Figure 6.4. Representative transmission system for a harmonic propagation study.

Model size selection. The sizing of the system to be modeled in detail- the local system - has been approached in three basic ways.

1. Engineering experience. The engineer conducting the study decides what parts of the system are to be modeled based on previous experience [5,6]. This experience is based on previous studies—preferably harmonic studies—and identification of key components such as capacitor banks, large generators, etc. This method can work well, but also can fail when the study is outside the range of the experience of the engineer doing the study.

2. Distance methods. Distance from the source bus is often used as a modeling criteria—geographic distance, series line impedance, and number of buses distant from the source have each been used [7]. In order to get sufficient accuracy when strictly applied, these methods can result in modeling unimportant system segments which are a similar distance (from the source bus) as important system components.

3. Sensitivity methods. More rigorous approaches to system model development involve the use of one or more network sensitivity tools [8-10]. Two examples of sensitivity methods are as follows.

Remote system equivalencing. There are 2 basic equivalencing methods. The first and simplest is the use of the fundamental frequency short circuit impedance (here, short circuit impedance is taken to mean \( R + j \omega L \), where \( R \) and \( L \) are constant as frequency changes) [6]. This approach has the advantage of simplicity. Some studies have used open circuits or short circuits in place of the short circuit impedance and have used the sensitivity of the results to these two models to judge the feasibility of using a lumped model at that bus.

The second approach involves the use of a frequency response curve which represents the changes in impedance of the remote system with respect to frequency variations [11]. This method is more flexible than the previous method, and has the capability of yielding accurate results with a smaller system model. It is particularly useful in time domain studies where system size can be more severely limited. It is, however, difficult to perform switching studies involving components in the equivalenced network. In these cases, it is preferable to build a larger system model which includes component models of all equipment which will be involved in a switching study. A second weakness of most frequency response methods is the inability to model coupling between remote networks— the systems 1-5 of Figure 6.4.

Sensitivity Analysis Method: The adjoint network analysis can be used to efficiently determine the sensitivity of the system response to component parameter variations [10]. The transmission network \( \mathcal{N} \) and its adjoint network \( \mathcal{\tilde{N}} \) can be used to determine the sensitivity of the system response to parameter variations. The transfer impedance \( T \) is defined as the harmonic voltage at the bus of primary interest divided by the injected harmonic current. The network \( \mathcal{N} \) is excited by a unit current source at the harmonic source bus to get network branch currents \( I_1, I_2, \ldots, I_n \). The adjoint network \( \mathcal{\tilde{N}} \), which has the same topology as the original network, is excited by a unit current source from the output to get adjoint network branch currents \( \tilde{I}_1, \tilde{I}_2, \ldots, \tilde{I}_n \). The sensitivity of a transfer impedance \( T \) with respect to any parameter \( x \) (\( R, L, \) or \( C \)), at frequency \( \omega \), denoted by \( S^T_x \), is defined as

\[
S^T_x = \frac{\partial T}{\partial x} \left( \frac{x}{T} \right)
\]

These sensitivities can be calculated using

\[
\frac{\partial T}{\partial x} = I(x) \cdot \tilde{I}(x)
\]

where \( I(x) \) and \( \tilde{I}(x) \) are the \( x \) element branch currents from the analysis of \( \mathcal{N} \) and \( \mathcal{\tilde{N}} \) respectively.
The calculation of the transfer impedance sensitivity is efficient. Its effectiveness is limited to small parameter variations as it involves partial differentiation.

**Bilinear Theorem:** The large variations which can occur in an external system impedance cannot be reliably predicted by using small signal analysis. Large changes in the transfer impedance of a network to changes in an element \( Z \) (in this case the remote system equivalent impedance) can be assessed by pulling that element \( Z \) out of the network, effectively forming a three port network [9]. For the transfer impedance \( \frac{V_2}{I_1} \) the following general equation is obtained:

\[
T = \frac{V_2}{I_1} = \frac{Z_{xin} \cdot T(0) + Z \cdot T(\infty)}{Z + Z_{xin}}
\]

where \( T(0) \) is the transfer impedance when branch impedance \( Z = 0 \) while \( T(\infty) \) corresponds to the transfer impedance when \( Z = \infty \). \( Z_{xin} \) is the input impedance looking into the network from the nodes of \( Z \). In order to assess the modeling accuracy at a tie bus at some harmonic frequency, \( T(0) \), \( T(\infty) \) and \( Z_{xin} \) are determined through three respective network solutions. The bilinear formula can then be used to determine the transfer impedance \( T \) for any value of \( Z \). A typical result of the bilinear analysis is shown in Figure 6.5, which shows the impedance regions where large errors will occur in a given transfer impedance. If the actual system impedance will not enter these regions, a simple equivalent can be used. In the case shown in Figure 6.5, the positive error will never exceed 5% as this sensitivity does not occur in the positive resistance region.

**Summary**

This chapter describes methods which can be used to develop system models for harmonic studies. The chapter covers modeling techniques for both distribution and transmission level harmonic studies. The development of an effective system model depends on the accurate determination of which system elements to model in detail. The second aspect of system modeling is to use the appropriate device model which will provide accurate results without undue complexity.

**References**


