Appendix H

Transducer Modeling and Simulations

This appendix is an expansion of Chapter 6, §6.5.

Laboratory tests and field examination of transducer performance have been reinforced through the use of computer models. The general approach involves:

- Use of SPICE computer software [6-21,6-22] to examine interface and circuit performance.
- Use of MATLAB computer software [6-23] to examine the generic signal processing

Models were developed for the (analog) PRM megawatt transducer of Figure 6-14, plus digital megawatt transducers of both algebraic and phasor types (Figures 6-15 and 6-16). The MATLAB codes permit direct changes to signal processing parameters, such as filter type and settings, and they support a broad menu of test waveforms.

Figure H-1 shows internal waveforms for a PRM transducer simulation.

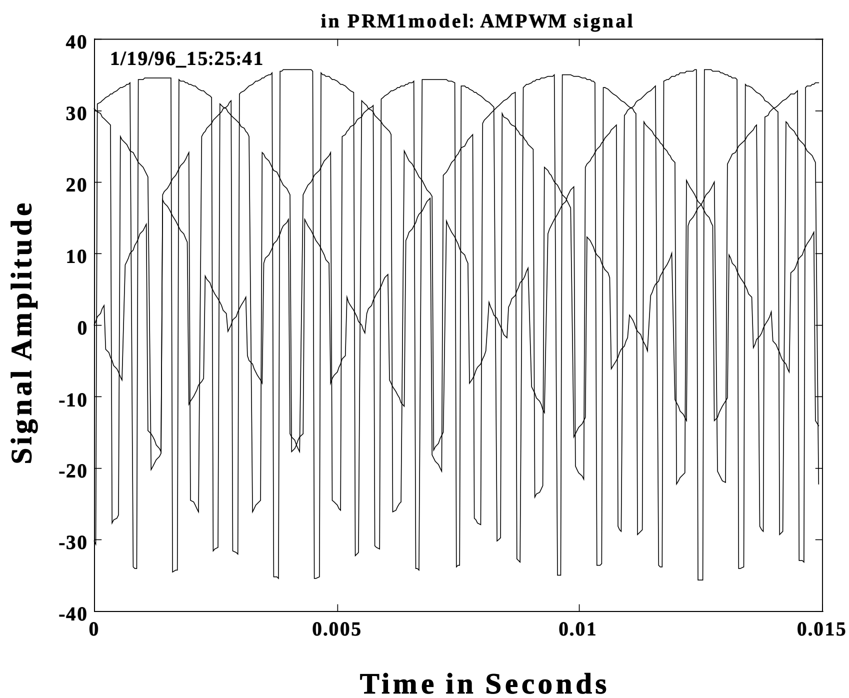

Fig. H-1. Internal waveforms for PRM transducer model.

The Figure H-2 autospectrum is typical of many PRM transducer simulations that were performed under unbalanced conditions. The considerable range of spectra resembles the observed data in Figure 6-28.

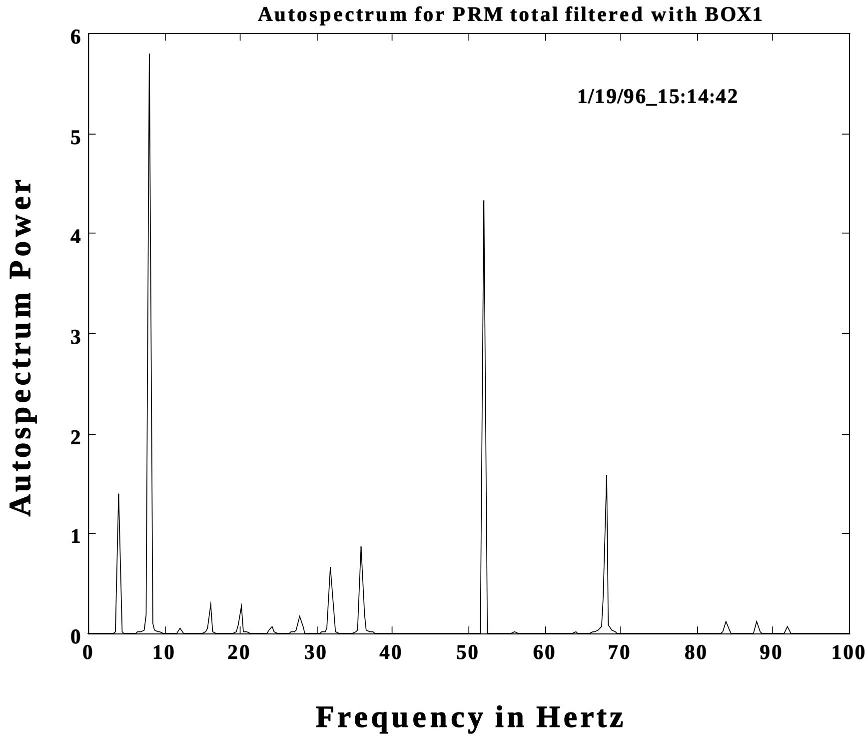

Fig. H-2. Typical output autospectrum for PRM transducer model.

Physical considerations, reinforced by examination of signal conditions in the field, argue that a fully represented test case for examining transducer performance should include:

- Unbalanced phases.
- Significant excursions in system frequency.
- One or more additive signals at frequencies characteristic of network resonances (e.g., 35–55 Hz). These should include both voltage and current.
- Modulation of the first harmonic (60 Hz) at frequencies that are characteristic of fast controllers (e.g., 20–25 Hz).
- Modulation of the second harmonic (120 Hz) at frequencies that are characteristic of both mechanical vibrations (e.g., blades) and modulation for all harmonics at a controlled power electronics device (e.g., 20–25 Hz).
- Numerous harmonics above the second. Their modulation is not required except in very special cases.

Figures H-3 and H-4 show voltage spectra for HarmSigs1B, one of several sets of test signals that have been constructed along the above guidelines. General characteristics of HarmSigs1B are these:

a) Harmonic number 1 (the fundamental) has a frequency of 60 Hz, and a per-unit (pu) weight of 1.0 relative to all other harmonics.

b) Voltages and currents for the first harmonic are amplitude modulated at three frequencies: 1.05 Hz, 1.46 Hz, and 18.2 Hz.

c) There is a total of 7 harmonics, with relative weights defined by the MATLAB statement:

```
Harmwt = [100 4.0 6.1 1.2 2.5 1.8 4.2]/100
     (1)
```

d) There are 3 modulating terms for each of the first 4 harmonics. Their relative weights for voltage and current are:

```
Vmmag = [2.2 1.9 1.2; 0.0 3.9 0.0; 1.85 0.0 0.0]/100
     (2)
```

```
IMmag = [1.8 1.8 1.6; 0.0 2.7 0.0; 0.00 4.8 0.0]/100
(3)
```

e) A 52 Hz sinusoidal signal is added to voltage and current.

f) A record length of maxBcyc = 560 cycles (9.33 seconds), with refspc = 128 samples per cycle.

Matlab statement (1) defines an array of 7 elements, each of which is divided by 100. Statements (2) and (3) are a bit more complicated, in that each of the semi-colons defines the end of an array row.

Figure H-3 shows an autospectrum voltage components in the general vicinity of the 60 Hz fundamental, and Figure H-4 shows the entire autospectrum. Both were calculated with fast Fourier transform (FFT) logic applied to a record of 2^{16}=65,536 sample points. Ideally both spectra should consist of discrete lines. The fact that the peaks have finite widths instead is characteristic of numerical processing, plus the fact that the signal record does not contain an exact number of cycles for every component.

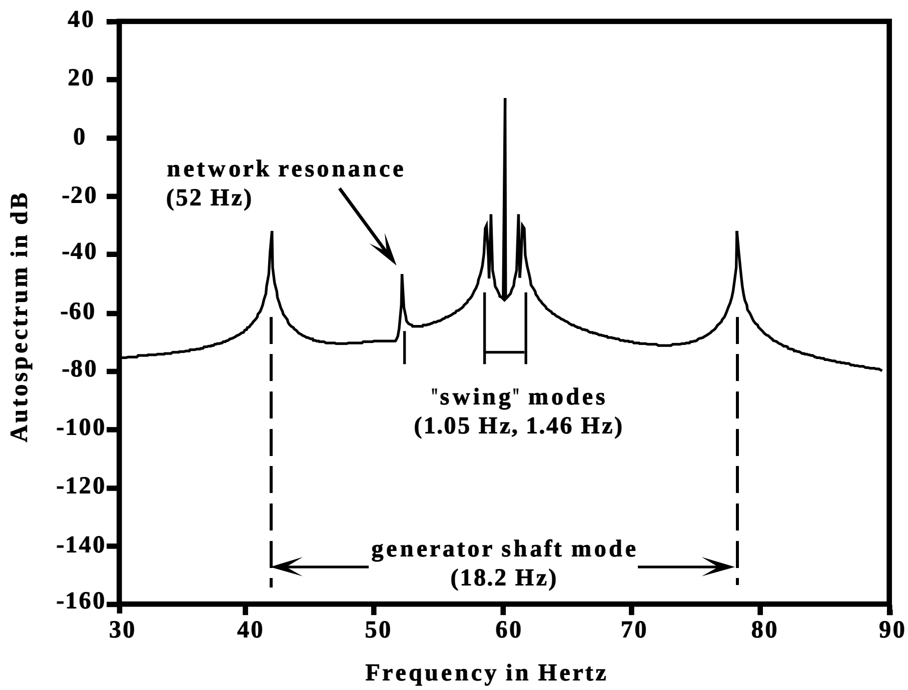

Fig. H-3. Spectrum detail for voltage VA of test input HarmSigs1B.

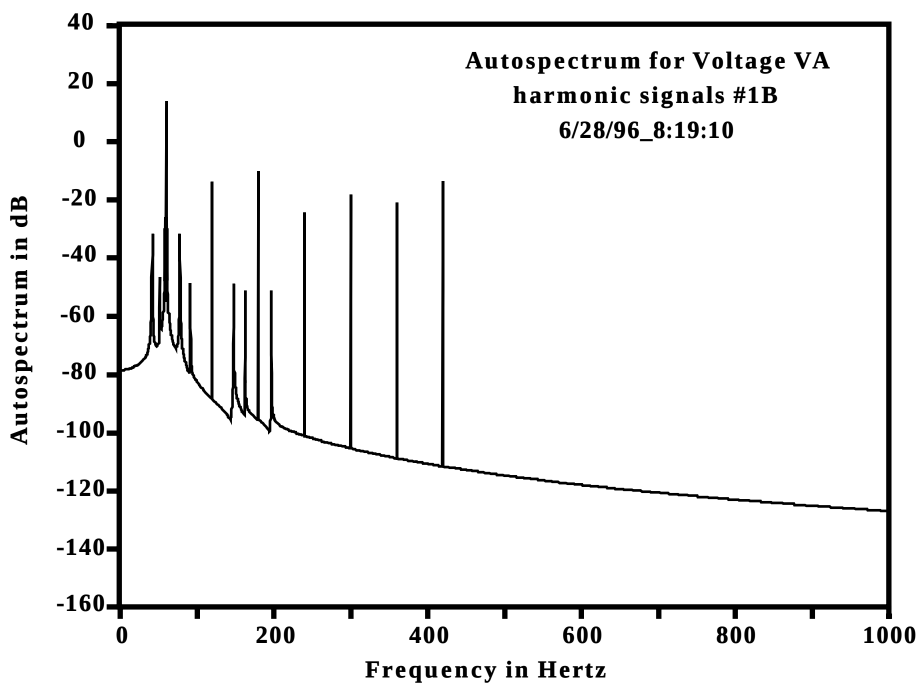

Fig. H-4. Full spectrum for voltage VA in HarmSigs1B.

It is a basic and well known fact that, under ideal balanced conditions, the total instantaneous power flowing on a three phase transmission line is constant, with second harmonic terms canceling (Appendix D).

Transducers that exploit this can be very practical, but they require close attention to filtering if they are to be very selective with respect to the physical phenomena that they track. Figures H-5 and H-6 illustrate this for the single-phase test signals of HarmSigs1B, for which the instantaneous power is

$$\begin{aligned} P_{inst}(t) &= v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) \\ &\hat{=}\, v(t) \bullet i(t) \end{aligned} \qquad (4)$$

The full spectrum for $P_{inst}(t)$ is much more complex than those of v(t) shown in Figure H-4, but the detailed spectrum for $P_{inst}(t)$ is fairly similar to fundamental modulation spectrum in Figure H-3. (Spectra for i(t) are similar to those of v(t).) The major differences are these:

- The strong peak at 0 Hz represents total power.
- The significant peak at 8 Hz is an image of the 52 Hz additive signal.
- The small feature at 28 Hz is one of the many signal artifacts produced by multiplying the voltage and current signals together, thereby convolving their spectra [6-16–18].

The original modulation band can be recovered through low pass filtering, provided that the 8 Hz peak is somehow recognized as an additive rather than a modulating term. It’s unlikely that this can be done without directly examining v(t) and i(t), however.

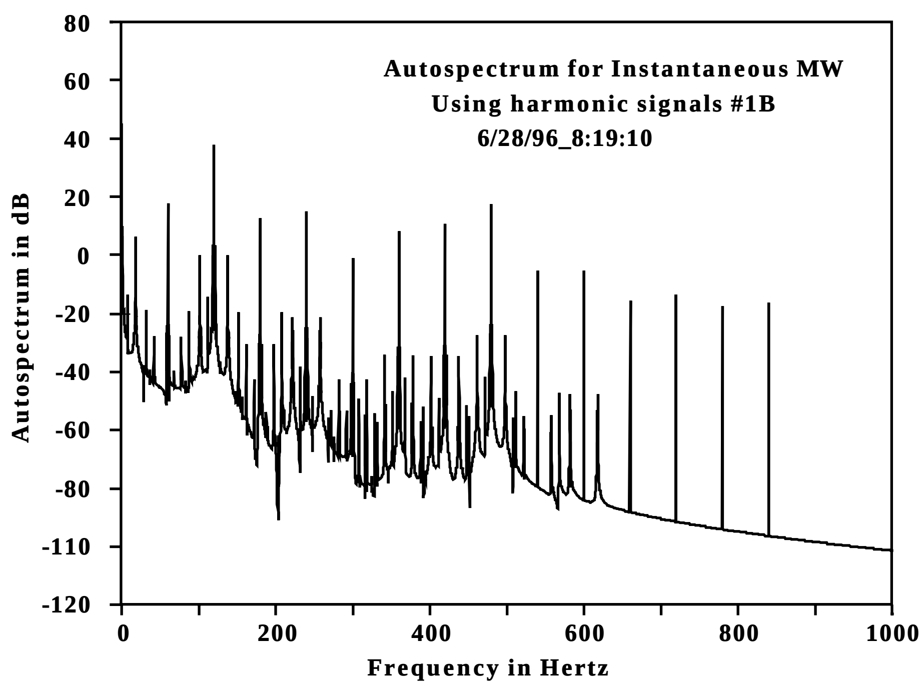

Fig. H-5. Spectrum for raw instantaneous power signal.

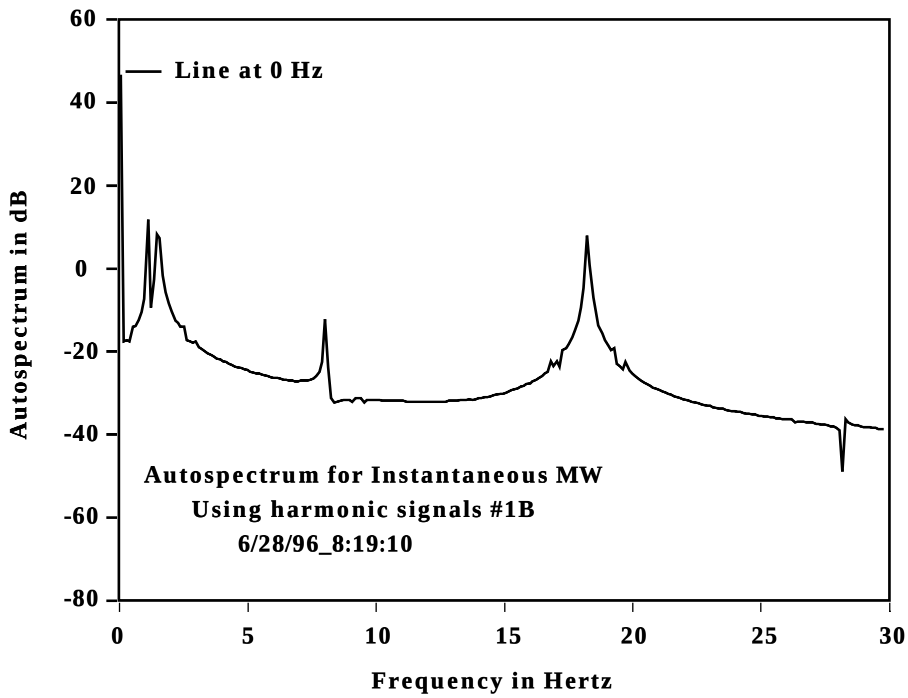

Fig. H-6. Spectrum for raw instantaneous power signal (detail).

There is a more formidable problem with the total power calculation. Every peak that is common to the autospectra for voltage and current contributes a component at 0 Hz, and thereby to the total power calculation. Separating out the fundamental power associated with the 60 Hz carrier calls for prefiltering that must be performed prior to multiplying the instantaneous voltages and currents together.

In an algebraic transducer the prefilter would, ideally, pass no signals that are more than 30 Hz away from the 60 Hz carrier. This can be achieved directly, with bandpass filters [6-18], but it's probably better to re-center the information band at 0 Hz and then use lowpass filtering. The frequency shift is readily accomplished through multiplication by a 60 Hz sinusoid. Separate multiplication by the corresponding cosine leads to the projection of Figure 6-13, and thereby to a phasor transducer.