permissible = 3047 V. The voltage rating is not exceeded. The kvar loading is calculated from:

$$\text{kvar} = \sum_{h=1}^{h=35} I_h V_h = 2283$$

The rated kvar = 1351, permissible kvar = 1.35 × 1351 = 1823. The rated kvar is exceeded.

(xi) Sizing capacitor bank to escape resonance: The capacitor bank is sized to escape the resonance with any of the load-generated harmonics. If three capacitors of 300 kvar, rated voltage 2.77 kV are used in parallel per phase in wye configuration, the total three-phase kvar is 2026 at the operating voltage, and the resonant frequency will be approximately 515 Hz [Eq. (18.20)]. As this frequency is not generated by the load harmonics and also is not a multiple of third harmonic frequencies, a repeat of harmonic flow calculation with this size of capacitor bank should considerably reduce distortion.

The results of calculation do show that the voltage distortion and TDD are 4 and 18%, respectively. Amplification of harmonic currents occurs noticeably at the fifth and seventh harmonics. Thus:

- The mitigation of the resonance problem by selecting the capacitor size to escape resonance, may not minimize the distortion to acceptable levels.
- Current amplifications occur at frequencies adjacent to the resonant frequencies, though these may not exactly coincide with the resonant frequency of the system.
- The size of the capacitor bank has to be configured based on series parallel combinations of standard unit sizes and this may not always give the desired size. Of necessity, the capacitor banks have to be sized a step larger or a step smaller to adhere to configurations with available capacitor ratings and over- or under-compensation results.
- The resonant frequency swings with the change in system operating conditions and this may bring about a resonant condition, however carefully the capacitors were sized in the initial phase. The resonant frequency is especially sensitive to change in the utility's short-circuit impedance.

The example is carried further in Chap. 20 for the design of passive filters.

Example 19.2: Large Industrial System

This example portrays a relatively large industrial distribution system with plant generation and approximately 18% of the total load consisting of six-pulse converters. The system configuration is shown in Fig. 19-19. The loads are lumped on equivalent transformers—this is not desirable when harmonic sources are dispersed throughout the system. A 225-bus plant distribution system is reduced to an 8-bus system in Fig. 19-19. Some reactive power compensation is provided by the power factor improvement capacitors switched with the medium-voltage motors at buses 6 and 7. The load flow shows that reactive power compensation of 7.2 and 6.3 Mvar at 12.47 kV buses 2 and 3, respectively, is required to maintain an acceptable voltage profile on loss of a plant generator. This compensation is provided in two-step switching. The power factor improvement capacitors at bus 3 are split into two

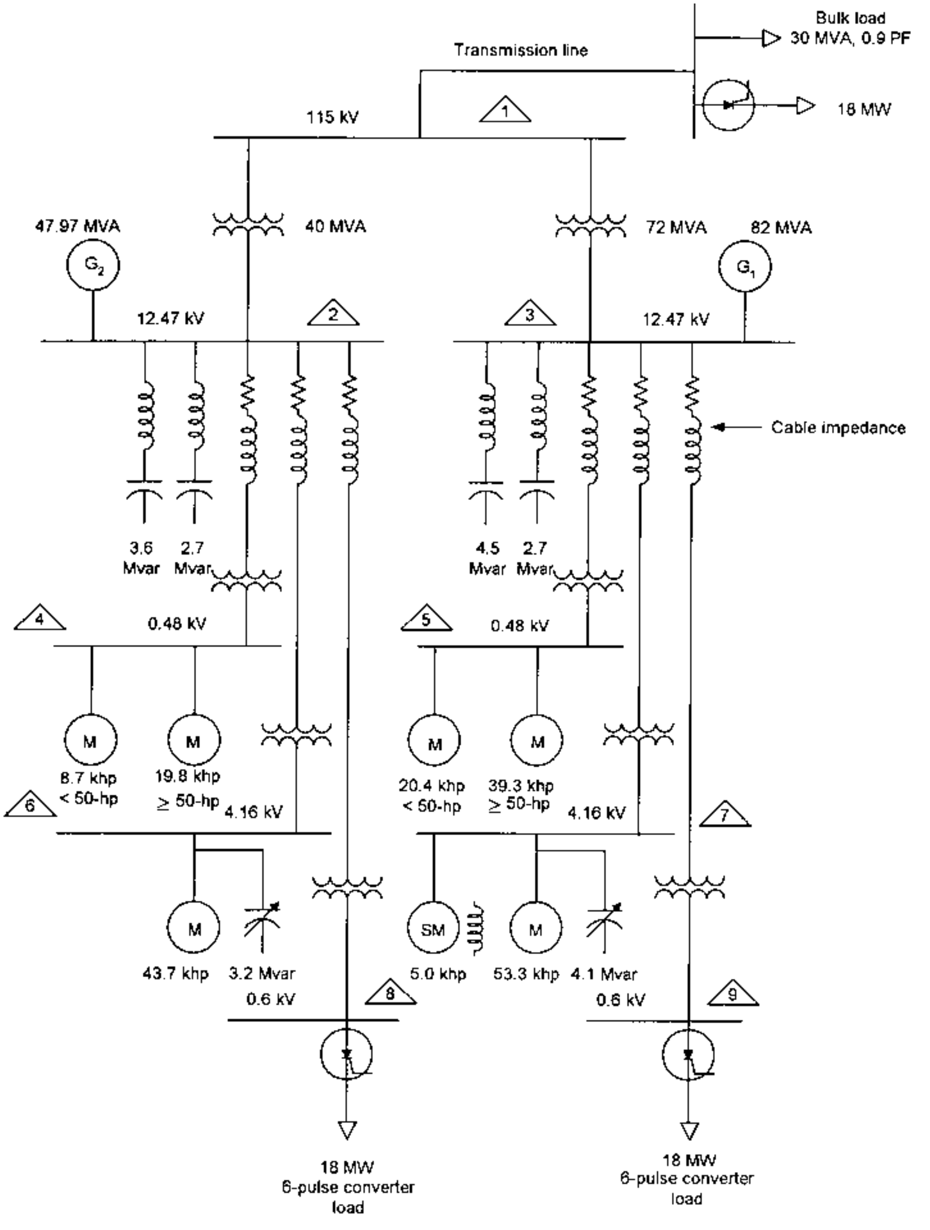

Figure 19-19 Single-line diagram of a large industrial plant, loads aggregated for harmonic study (Example 19.2).

sections of 4.5 and 2.7 Mvar, respectively. The capacitors at bus 2 are divided into two banks of 3.6 and 2.7 Mvar, respectively. The series reactors can be designed to turn the capacitor banks into shunt filters, but here the purpose is to limit inrush currents, especially on back-to-back switching, and also to reduce the switching duty on the circuit breakers (not shown in Fig.19-9).

Some medium-voltage motor load can be out of service and their power factor improvement capacitors will also be switched out of service. The loads may be operated with one or two generators out of service, with some load shedding. The medium-voltage capacitors on buses 2 and 3 have load-dependent switching and one or both banks may be out of service. This switching strategy is very common in industrial plants, to avoid generation of excessive capacitive reactive power and also to prevent overvoltages at no load.

The following three operating conditions are studied for harmonic simulation:

1. All plant loads are operational with both generators running at their rated output, and all capacitors shown in Fig. 19-19 are operational. Full converter loads are applied.
2. No. 2 generator is out of service. The motor loads are reduced to approximately 50%, and 2.7 Mvar capacitor banks at buses 2 and 3 are out of service, but the converter load is not reduced.
3. The effect of 30 MVA of bulk load and 18 MW of converter load connected through a 115-kV 75-mile transmission line (modeled with distributed line constants), which was ignored in cases 1 and 2 is added. These loads and transmission line model is superimposed on operating conditions 1.

The results of harmonic simulation are summarized in Tables 19-7 and 19-8. Table 19-7 shows harmonic current injection into the supply system at 115 kV and generators nos 1 and 2. Table 19-8 shows the parallel and series resonant frequencies. The impedance modulus versus frequency plot of the 115-kV bus and 12.47-kV buses 2 and 3 for all three cases of study are shown in Figs 19-20–19-22. The R/X plots of the utility's supply system and impedance modulus verses frequency plots are shown in Fig. 19-23.

It is seen that the resonant frequencies vary over wide limits and so does the harmonic current flow. In operating condition 2 with partial loads and some capacitors out of service, additional resonant frequencies occur, which did not exist under operating condition 1. Under condition 3 the harmonic current injection at higher frequencies in the utility system increases appreciably. Condition 2 gives higher

Table 19-7 Example 19.2: Harmonic Current Flow, Operating Conditions 1, 2, and 3

Harmonic order	Current in generator 1			Current in generator 2			Current in utility's system		
	1	2	3	1	2	3	1	2	3
5	187	257.00	167.00	209	Generator	196.00	3.22	69.02	23.3
7	353	7.06	340	84.2	out of	82.90	44.9	18.31	44.60
11	1.52	17.10	1.83	102	service	109.00	3.80	2.13	4.32
13	6.76	3.25	5.10	21.40		18.50	0.22	0.500	3.67
17	2.88	2.71	4.31	2.74		3.34	0.48	0.33	1.55
19	0.68	19.00	0.27	1.03		0.74	1.28	2.23	1.88
23	0.06	0.93	0.09	0.12		0.15	0.003	0.18	1.64
25	0.19	0.37	0.16	0.11		0.09	0.03	0.08	1.63

Table 19-8 Example 19.2: Resonant Frequencies and Impedance Modulus, Operating Conditions 1, 2, and 3

	1			2			3		
Bus ID	Parallel resonance	Series resonance	Impedance modulus	Parallel resonance	Series resonance	Impedance modulus	Parallel resonance	Series resonance	Impedance modulus
Utility	403	424	239.6	373 496	385 530	318.6	400	425	213.6
Bus 2	586	1436	17.68	367 905	647	41.5	589	1436	28.26
Bus 3	400 893	635 1343	33.76	493 1153	860 1699	26.24	401 892	635 1342	12.89

distortion at the PCC, though the distortion in generator 1 is reduced. The continuous negative sequence capability of generators ($I_2 = 10\%$) is exceeded in operating conditions 1 and 3.

The analysis is typical of large industrial plants where power factor improvement capacitors are provided in conjunction with nonlinear plant loads. The variations in loads and operating conditions result in large swings in the resonant frequencies. The example also illustrates the effect of power capacitors and nonlinear loads which are located 75 miles away from the plant distribution. The need for mitigation of harmonics is obvious, and the example is continued further in Chap. 20 for the design of passive harmonic filters.

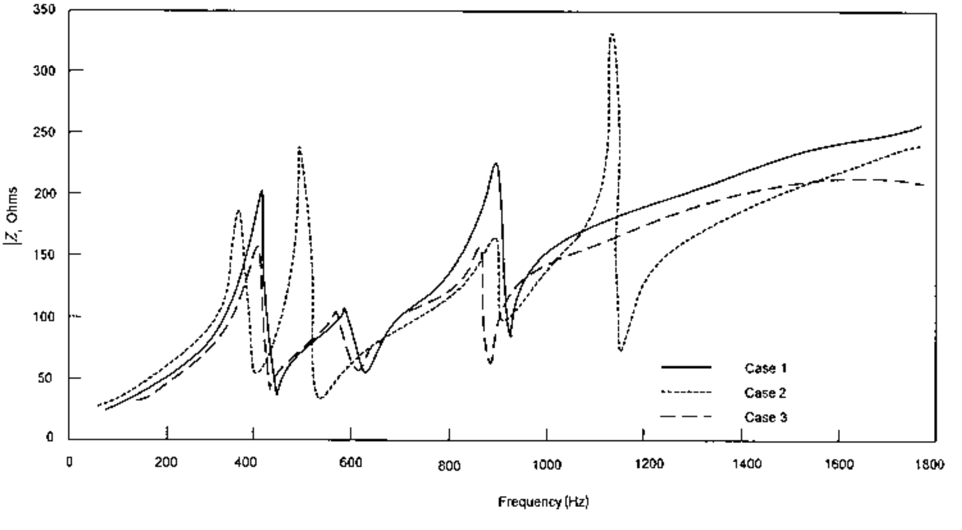

Figure 19-20 Impedance modulus versus frequency plot for three conditions of operation, 115 kV utility's bus (Example 19.2).

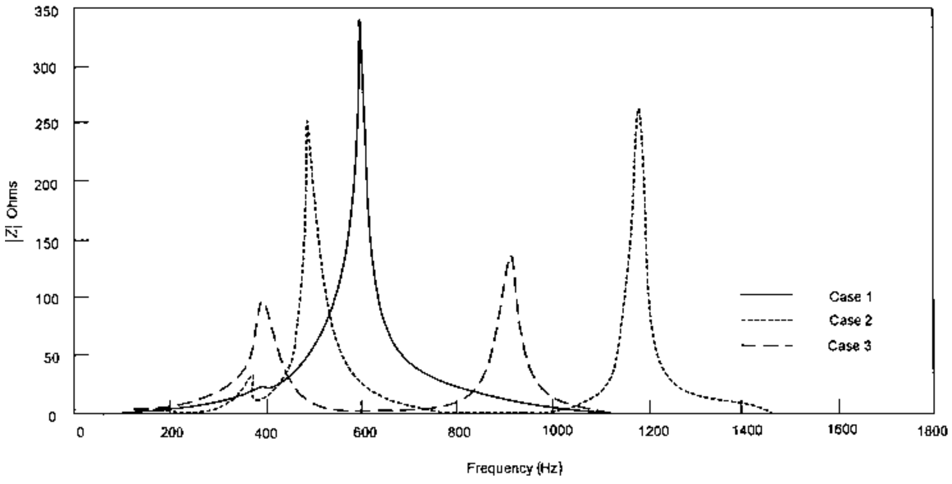

Figure 19-21 Impedance modulus versus frequency plot for three conditions of operation, 12.47-kV bus 2 (Example 19.2).

Example 19.3

Calculate TIF, IT, and kVT at the sending end of line L1 (Fig. 19-19), operating condition 3 of Example 19.2.

IT and kVT is calculated from Eq. (18.22) and TIF factors are given in Table 18-7. The harmonic currents or voltages in the line are known from harmonic analysis study. Table 19-9 shows the calculations. From this table:

$$\left[\sum_{h=1}^{h=49} I_h^2\right]^{1/2} = 0.159\,\text{kA}$$

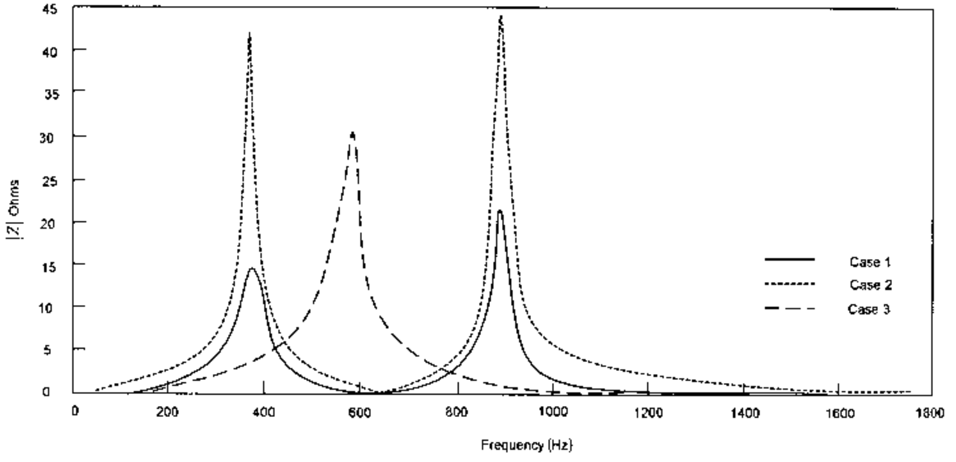

Figure 19-22 Impedance modulus versus frequency plot for three conditions of operation, 12.47-kV bus 3 (Example 19.2).

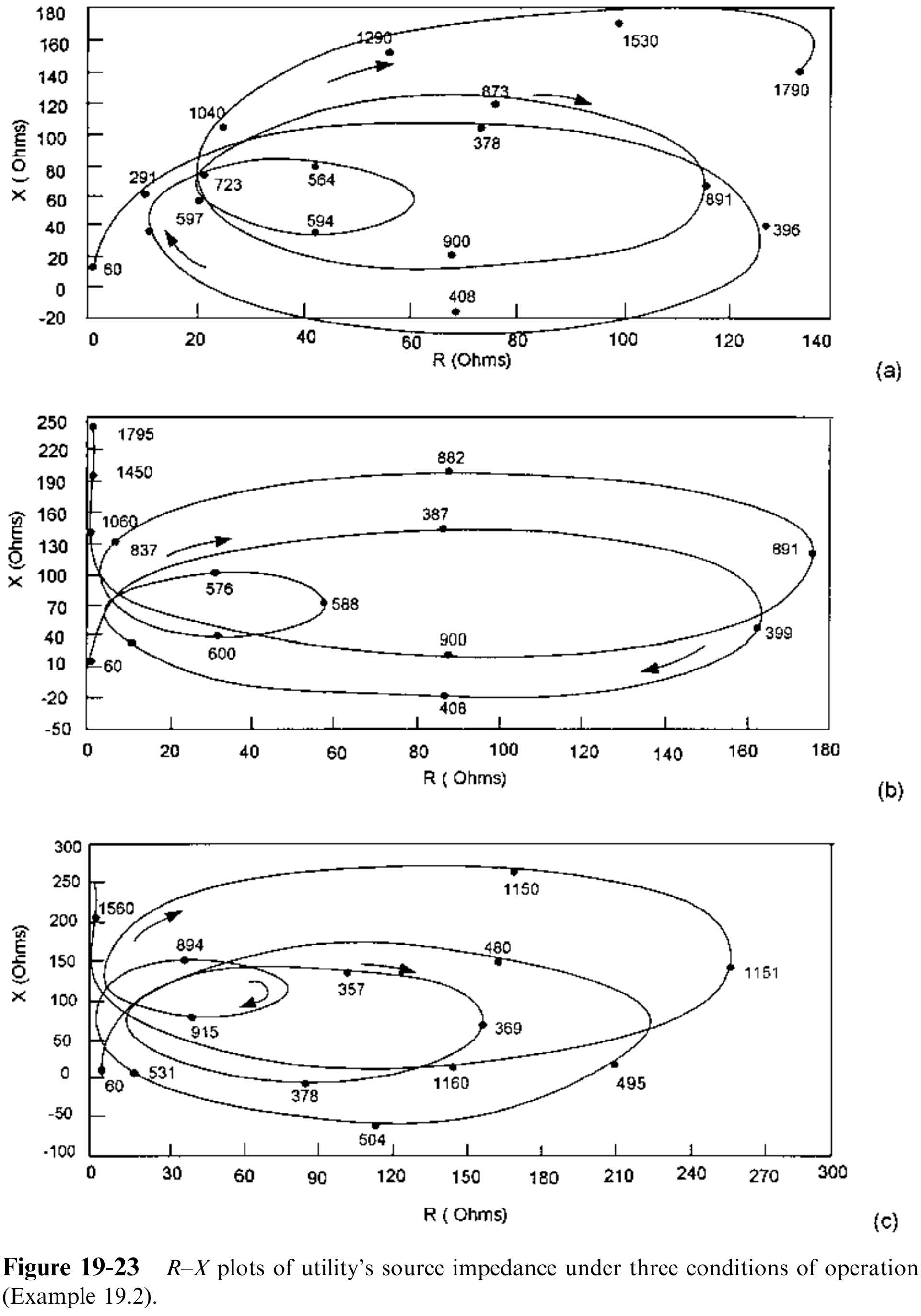

Figure 19-23 *R–X* plots of utility's source impedance under three conditions of operation (Example 19.2).

Table 19-9 Example 19.3: Calculation of IT Product, Sending End, Distributed Parameter Line L1 (Fig. 19-22)

Harmonic	Frequency	TIF weighting (W_f)	Harmonic current in kA (I_f)	$W_f I_f$	$(W_f I_f)^2$
1	60	0.5	0.158	0.079	0.006
5	300	225	0.0127	2.857	8.165
7	420	650	0.00269	1.749	3.057
11	660	2260	0.0110	24.860	618.020
13	780	3360	0.00438	14.717	216.584
17	1020	5100	0.00431	21.980	483.164
19	1140	5630	0.00381	21.450	460.115
23	1380	6370	0.00257	16.371	268.006
25	1500	6680	0.00324	21.643	468.428
27	1740	7320	0.00292	21.374	456.865
31	1860	7820	0.00247	19.315	373.085
35	2100	8830	0.00175	15.453	238.780
37	2220	9330	0.00157	14.648	214.567
41	2460	10,360	0.00146	15.126	228.784
43	2580	10,600	0.00150	15.900	252.810
47	2820	10,210	0.00150	15.315	234.549
49	2940	9820	0.00135	13.256	175.748

The TIF weighting factors are high in the frequency range 1620–3000 and, for accuracy, harmonic currents and voltages should be calculated up to about the 49th harmonic. From Table 19-9:

$$\left[\sum_{h=1}^{h=49} W_f^2 I_f^2\right]^{1/2} = \sqrt{4700.73} = 68.56$$

Therefore IT = 68.56/0.159 = 360.85; kVT can be similarly calculated using harmonic voltages in kV. TIF factors for industrial distribution systems are, normally, not a concern.

Example 19.4: Transmission System

Harmonic load flow in a transmission system network is illustrated in this example. The system configuration is shown in Fig. 19-24. There are eight transmission lines and the line constants are shown in Table 19-10. These are modeled with distributed parameters or π networks. Also, the six-pulse and 12-pulse converters are modeled as ideal converters.

The frequency scan with *only harmonic injections* and without bulk linear loads shows numerous resonant frequencies with varying impedance modulus, e.g., Fig. 19-25 shows these at the 230-kV bus 1. The resonance at higher frequencies is more predominant. The harmonic current flows in lines as shown in Table 19-11.

Figure 19-26 is a frequency scan with bulk loads applied. The resonant frequencies and a number of smaller resonance points are eliminated. The impedance