Distribution System Harmonic Filter Planning

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***Abstract-* A planning methodology for distribution system harmonic filtering is proposed. The method is intended for use on radial distribution systems with no large harmonic sources. It is proposed that 60 hertz var planning be done first to allocate the var resources. Following this process, the harmonic filter planning can be readily accomplished. Characteristics of the distribution systems and the harmonic sources are exploited to provide a practical filter planning technique which is effective and efficient.**

Keywords: Harmonic filtering, electric power distribution systems.

1. Introduction

The harmonic voltage levels on electric power distribution systems are generally increasing due to the changing nature of the system load. On a number of these systems, harmonic levels will soon require reduction through the application of tuned filters. This paper proposes an approach to planning filter installations on radial distribution systems with primary capacitor banks.

Harmonic performance and filter design are well understood in cases where the harmonic levels are due to a single large harmonic source- a motor drive or electrochemical installation, for example[1,2]. In particular, the planning of harmonic filters for industrial plants has been widely studied and is generally well understood when the supplying utility source has a low distortion level. Primary radial distribution systems (generally 12kv-23kv), however, have a number of characteristics which make harmonic filter planning and design quite different than is the case for industrial plants. These include :

- differing X/R ratios and larger electrical distances
- the need for capacitor switching
- the number of capacitors involved on the system and the presence of multiple untuned capacitor banks
- a wider variation in load with limited information on load characteristics
- the use of capacitors to control voltage and to minimize loss in addition to power factor correction
- the fact that harmonic excitation is generally due to a large number of dispersed harmonic sources

There have been a number of proposed methods for optimally placing capacitor banks based strictly on the 60 hertz considerations of power loss and voltage. A recent trend is to simultaneously consider optimization of capacitance resources considering both 60 hertz and harmonic frequency effects simultaneously.

The reduction of harmonic levels strictly through capacitor placement has been studied by Ortmeyer and Zehar [3] and by Baghzouz [4]. This procedure can effectively reduce harmonic levels, at the expense of the 60 hertz performance. Chu, Wang, and Chiang [5] have investigated the optimization of capacitors and tuned filters based on costs, harmonic constraints, and fundamental frequency considerations. While this approach has some attraction, it is very complex and leaves the planner with little insight into the system performance. It is proposed here that a two step procedure be followed: first, the var resources are placed to optimize 60 hertz performance, then harmonic performance of the system is considered as a separate problem. In accomplishing the harmonic performance portion of this study, some of the var sources that were originally scheduled to be purely capacitive are changed to become tuned filters. The reader is cautioned not to interpret this as adding a tuning reactor to an existing capacitor bank- a practice that will often result in operating problems. A method for determining the filter current requirements is presented in the fourth section of this paper.

Methods of developing filtering strategies for distribution systems are needed, but have not previously been developed. This method must account for the unknown magnitude and location of the harmonic sources as well as the changes in the system operating configuration which will be encountered. There is an immediate need for this methodology as a number of recent studies have reported harmonic voltages at or near levels where filtering is desirable [6-10].

This paper proposes efficient methods of modeling the unknown parameters which will be encountered on the primary distribution system. It investigates the nature of the harmonic voltage problem under distributed source conditions. The correlation of this modeling with previous measurement programs is described. Finally, the paper proposes a systematic approach to filter placement planning and design on systems with excessive harmonic voltage levels.

2. Distributed Harmonic Sources

Harmonic voltage levels on the distribution system are increasing due to the increasing levels of nonlinear loads on the power system. While some of these loads are large point sources of harmonics located primarily in industrial areas, residential and commercial loads are also generating increasing levels of harmonics from traditional electronic loads as well as the newer, higher power loads such as high efficiency lamps and heat pumps. The distribution engineer is increasingly likely to find systems with high harmonic voltage levels which result from numerous small, widely dispersed nonlinear loads. In this context, small harmonic sources are nonlinear devices whose individual contribution to the harmonic voltage distortion would be a small fraction of the total distortion present on the system.

High harmonic voltage levels, regardless of the source, will lead to operating problems on the electric power distribution system. These problems, which include equipment heating, overvoltage, and load disruption, have been discussed in IEEE 519-1992[1] as well as a recent committee report[11].

A previous study of distribution system harmonic performance [6] has investigated the nature of small, widely distributed harmonic sources. In [12], it was shown that these loads will generate smaller currents at the higher harmonics, and the phase angles of these currents are widely distributed, resulting in a high degree of cancellation. At the lower frequencies, particularly the third, fifth and seventh harmonics, the cancellation will not be complete, and there is a resulting harmonic excitation at these frequencies. Reference 13 shows that these numerous small loads can be readily aggregated for the purpose of distribution system harmonic propagation studies.

More recently, measurements of harmonic levels on distribution systems from across the United States have been performed. Emanuel, Orr, Cyganski and Gulachenski [7] reported on measurements on 5 distribution feeders. They show that the significant harmonic voltage levels are occurring on these systems at the third, fifth, and seventh harmonics. In Reference [10], the same authors report measurements at 6 customers' sites: 4 residential/commercial and 2 light industrial. The industrial customers are reported to have low penetrations of large power electronic equipment. Again, the dominance of the lower order harmonics is confirmed. Etezadi-Amoli and Florence [8] report on a measurement program involving a wide variety of transmission and distribution locations, and observed significant harmonic levels primarily at the lower order harmonics. Govindarajan, Cox, and Berry [9] surveyed 76 sites on the Southwest Electric Power Company system. These sites included general distribution system locations as well as large industrial customer sites. Their results again show a dominance of the lower order harmonics for the majority of cases including many of the large industrial sites.

On four wire multi-grounded distribution systems, the third harmonic is primarily zero sequence, and it can often be dealt with as a zero sequence quantity to avoid installing tuned filters at this frequency. Also, the balance of the load kva between phases affects the harmonic performance of a feeder, and the feeder balance should be verified prior to undertaking a harmonic filtering study. In particular, unbalanced loading of the feeder can result in high harmonic currents in the neutral and/or ground paths[13].

At the fifth and seventh harmonic frequencies, the nonlinear loads can be modeled as current sources distributed throughout the system. When the magnitude of the harmonic sources are determined by measurement of the harmonic voltage level for a load group, it is reasonable to assume that the relative magnitudes are proportional to the load level and that the phase angles for a load group at a given harmonic are in phase. This estimation procedure was developed in Reference 13. For a group of loads, this method will estimate the harmonic excitation after cancellation due to phase angle differences. It therefore estimates the effective level of harmonic excitation rather than the algebraic sum of the individual harmonic sources. This measurement based technique for estimating the effective harmonic excitation from a group of loads is necessary for distribution systems with a large number of diverse harmonic sources, as it is not possible or desirable to model each source individually. This method provides harmonic excitation models which are efficient and effective for filter planning studies.

Radial distribution systems with primary capacitor banks will generally exhibit a single resonance or a clustered group of resonances which are in the vicinity of the fifth and seventh harmonic frequencies, and which involve the entire group of capacitors. This resonance is much broader than the higher frequency resonances which involve only one or two capacitor banks. At frequencies near this lower resonance, the harmonic voltages typically will be lowest at the substation bus, and will increase along the length of the feeders. The highest voltages are generally found near the feeder ends- or rather, at one of the last capacitor banks on the feeders. It is these two features which can be exploited to develop a filtering plan which will be effective and sufficient for most distribution systems.

In the planning approach developed in this paper, it is assumed that the locations and sizes of the reactive compensation to be installed on the system have been optimized based on 60 hertz considerations. The choice of capacitor bank versus filter at a given location is then determined based on harmonic considerations. This method therefore does not effect the fundamental frequency optimization of reactive sources. The reader is cautioned that reactors cannot generally be added to existing capacitor banks to create filters. In cases where this planning method calls for a filter in the location of an existing capacitor bank, the capacitor bank would generally be removed and replaced by a new filter. The important point to note is that this can be done without affecting the fundamental frequency performance of the system.

3. Planning Approach

In order to properly plan the filter installation, measurements of the harmonic voltage levels are required. Prior to this, however, preliminary modeling is advisable for two reasons. First, to identify which feeders will exhibit the largest voltage rise along their length, so that measurements can be concentrated on these feeders. Secondly, frequency scans involving single point current sources can be used to get an assessment of the character of the system, and note sensitivities to capacitor switching. The analytical portions of the planning study can be conducted on any of a number of harmonic analysis software packages which are currently available. In this study, the harmonics analysis software used was based on the current injection method, which is suitable for the accuracy requirements of this type of study when the harmonic voltage levels are within the IEEE 519-1992 levels.

The use of accurate voltage measurements is essential to a good design. In particular, the substation bus voltage harmonics need to be recorded over a period of time sufficiently long to capture the peak harmonic voltage conditions. The two most important operating points are:

(1) The operating conditions which produce the highest harmonic voltages.

(2) The peak load conditions with all capacitors on line.

It is essential that capacitor bank status be known for these two conditions. In systems where the peak harmonic levels occur at peak load, it would also be useful to consider a representative light load condition, although this would be of lesser importance. After initial measurements have determined these quantities at the substation bus, further measurements are needed for these two conditions. The most important measurements are the harmonic voltage levels at or near the outer capacitor banks on the feeders. Frequency scans can be used to identify important locations, but these should be verified through measurement. Also, the harmonic current levels (magnitude and angle) of the feeders at the substation bus can be useful. Again, the capacitor bank status must be known for the measurement conditions.

These measurements are used to develop the harmonic source models for the system, as described in Reference 13. As would be expected, better measurement data will lead to a more accurate model. For each section of the system, the harmonic source magnitudes are assumed to be in phase and in proportion to the load power levels [13]. The transmission system can often be modeled by a voltage source behind an equivalent impedance when there are no capacitor banks near the distribution substation. The magnitudes of the various sources are adjusted to provide the voltage levels of the measurements, which can be done easily through superposition. Both light load and full load models are needed, particularly in cases where the peak harmonic voltages occur under off-peak conditions. Finally, the absence of the higher harmonics on the system should be verified.

Tuned filters are most effective at locations where the harmonic voltage is the highest. Therefore, filter placement should be investigated at the location(s) of highest harmonic voltage, which are at or near the feeder ends for these low order harmonics. Fifth harmonic filter placement should be undertaken first. The placement of a fifth harmonic filter can be expected to reduce fifth harmonic voltages throughout the system, with greater reduction achieved at locations closer to the filter. Fifth harmonic levels on adjacent feeders will show varying degrees of effect depending on the system specifics. As the ratio of line impedance to source impedance goes up, the harmonic coupling between feeders is reduced.

Fifth harmonic filter location should be investigated at one or more of the capacitor locations where the highest fifth harmonic levels are experienced. In most cases, a single filter installation should be considered initially. An examination of resulting voltages will indicate whether additional filtering is needed. Once a filter is in place near the end of a feeder, the maximum voltage on that particular feeder will then move toward the electrical center of that feeder, so that this point must be examined for compliance with design goals.

The effect of fifth harmonic filters on the seventh harmonic voltage varies depending on the system. In very general terms, replacing a capacitor bank with a tuned fifth harmonic filter replaces capacitance with inductance at the seventh harmonic frequency. This will tend to shift the resonance points above the fifth harmonic to a higher frequency, and the resulting voltages at the seventh harmonic will depend on the location and strength of these resonances.

On systems where a fifth harmonic filter also reduces the seventh harmonic voltage near the filter location, a choice exists as to the frequency of additional filters. Any further filtering investigations should include a comparison of both fifth and seventh harmonic filters, as the best choice is not necessarily at one or the other frequency.

On systems where a fifth harmonic filter increases seventh harmonic voltages, however, the frequencies must be treated separately- i. e., a fifth harmonic filter is required to reduce fifth harmonic voltages, while a seventh harmonic filter is required to reduce seventh harmonic voltages. While additional filters at one frequency may raise voltage at the other, this is generally a second order effect, and the filter placements can be done independently. Due to capacitor switching effects, the need for a seventh harmonic filter should be evaluated on this type of system, even when the seventh harmonic levels are modest at full load.

4. Estimation of Filter Current

The filter placement studies outlined in the previous section will provide an estimate of the harmonic currents which can be expected to flow in the filters. When the system model is based on accurate measurements of the maximum voltage at the filter location, these results give a good estimate of the filter current to be expected under the present system conditions. The calculations should be conducted at both the peak harmonic voltage condition and the peak load condition, the latter with all capacitors on line. Also, the effects of variation in the tuned frequency due to equipment tolerances should be evaluated. With this knowledge of the range of fundamental voltage and harmonic current to be expected, the detailed design of the filter can be undertaken.

An alternative method of estimating the harmonic current which will flow in a proposed filter at the tuned frequency is available when the harmonic voltage levels have been measured at the filter site. The distribution system model is then excited by a single current source at that location, with magnitude sufficient to generate the measured voltage. This current then will be the predicted peak current which would flow in the filter at the tuned frequency. Some additional allowance, of course, should be made for future increases in harmonic source levels or system capacitance.

5. Capacitor Switching

The capacitors on the distribution system will be switched on and off depending on time of day, fundamental voltage level, or similar criteria. This means that a wide variety of switching configurations is possible on any given system, and all cases need to fall within the harmonic limits.

In systems where the replacement of a capacitor bank with a filter has reduced both the fifth and seventh harmonic voltages, the switching out of capacitors will tend to reduce harmonic voltage levels in most cases. Conversely, the switching in of capacitors will increase levels, which is why the initial full load studies should be done with all capacitors in place.

With both fifth and seventh harmonic filters in place, the switching out of capacitors will typically reduce the voltage levels at both harmonics for most of the system. On the other hand, in systems which experience a rise in seventh harmonic voltage with the addition of a fifth harmonic filter (and no seventh harmonic filter has been installed), further increases in the seventh harmonic voltage are likely to occur with the switching out of a capacitor bank. There is the possibility on this type of system, therefore, of reducing a dominant fifth harmonic voltage level at the expense of creating a new dominant harmonic at the seventh. The addition of seventh harmonic filtering will eliminate this risk.

Regarding switching of the filters, the most straight-forward solution is to leave the filters on line, and use other capacitor banks to provide voltage and power factor regulation. On systems with a number of filters, it is possible to include them in the switching strategy, but this should be studied closely. If this is being considered, a good general strategy is to remove a seventh harmonic filter before a fifth harmonic filter. **6.**

6. Example Case

The 13.2 kv Rock Cut distribution system described in References [3] and [12] is shown in Figure 1. The system parameters are given in the references. The system includes three feeders, and there are 13 capacitor banks installed on these feeders. Nodes 6 through 9 generally exhibit the highest harmonic voltages on this system. The frequency response of node 8 voltage to 1 amp of current injected at node 8 is shown in Figure 2, for peak load conditions with all capacitor banks on line. This system has several low frequency resonances, but overall, the frequency response at this node exhibits an increasing characteristic up to approximately 300 hertz, then flattens off before falling.

Figure 1. One Line Diagram for Rock Cut distribution system.

Using commercially available harmonics analysis software, harmonic voltage levels for this system are calculated at full load conditions with fifth and seventh harmonic current levels at 2.8% of the fundamental current at each load site. The resulting voltage levels are shown in Table I. Also shown in Table I is the predicted effect of converting a 300 kvar capacitor bank to a similar sized filter at the three feeder end locations on the system. The tuned frequencies of the fifth harmonic filters analyzed in this study are 4.9 per unit. The seventh harmonic filters are similarly detuned. All filters considered are 300 kvar. Table I shows that the most effective filter location is at node 8. The fifth harmonic filter at this location reduces all voltages to levels below 300 volts, which is 4% of the nominal fundamental voltage level. The seventh harmonic voltage in the vicinity of the filter is reduced, with seventh harmonic voltages on the other feeders rising.

The voltage levels with this filter in place will remain high enough to warrant the consideration of a second filter. Both fifth and seventh harmonic filters are considered. Table II contains the result of the predicted effect of adding a second filter at various locations. Note that the node 7 voltage shows the highest voltage level in Case A. The best options for a second filter appear to be either a fifth harmonic filter at node 6, or a seventh harmonic filter at node 6.

Table I. Fifth and seventh harmonic voltage levels for various fifth harmonic filter locations.

	300 kvar 5th harmonic filter location			
	unfil-tered	node 18	node 13	node 8
Node	5th harmonic voltage			
1	108v	60v	67v	83v
13	119	68	37	93
18	184	44	152	174
6	210	160	166	110
8	311	251	257	20
	7th harmonic voltage			
1	91v	81v	84v	144v
13	106	96	84	170
18	161	126	166	240
6	173	179	174	226
8	355	380	365	178

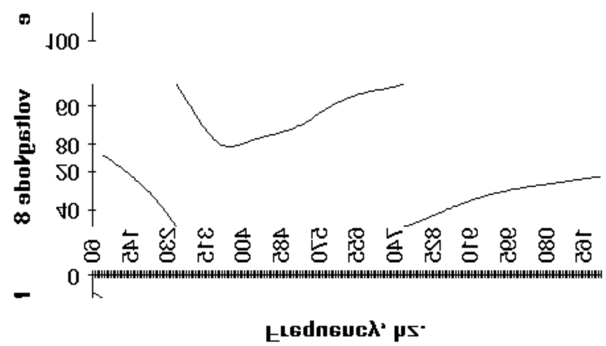

Figure 2. Frequency response at node 8 with 1 amp of current injected at node 8. All capacitors on line, no filters, full load.

The predicted frequency response with fifth harmonic filters at nodes 6 and 8 is shown in Figure 3, again with node 8 voltage plotted in response to 1 amp injected at node 8. The addition of the fifth harmonic filters has caused the frequency response at node 8 to become increasing to frequencies above 600 hertz. As this peak will tend to move upward on the frequency scale as capacitors are switched out, generally lower voltages can be expected with capacitor switching in
type shows the relationship of one node voltage to one source current, and the system contains many sources and many nodes. With this limitation understood, however, the frequency response(s) for a system contain useful information.

Table II. Predicted Rock Cut system harmonic voltages with two filters installed.

	Case		
	A	B	C
Node	5th harmonic voltage		
1	40v	59v	87v
13	47	67	97
18	39	151	177
6	77	28	124
7	122	81	162
8	16	9	22
	7th harmonic voltage		
1	143v	137v	96v
13	170	163	116
18	200	256	232
6	250	161	20
7	291	214	100
8	202	143	52
Case A: 5th filter at node 8 5th filter at node 18			
Case B: 5th filter at node 8 5th filter at node 6			
Case C: 5th filter at node 8 7th filter at node 6			

Table III. The effect of capacitor bank switching on the node voltages at full load.

	Capacitor removed at node			
	13	18	7	17,18
Node	5th harmonic voltage			
1	57v	55v	58v	51v
13	62	63	66	59
18	149	136	150	124
6	28	27	27	27
7	80	80	70	79
8	9	9	9	9
	7th harmonic voltage			
1	128v	135v	133v	128v
13	140	162	159	154
18	255	234	261	207
6	157	169	143	169
7	214	230	159	236
8	142	153	132	156

Table III shows the effects of the capacitor switching studies conducted for this system with 5th harmonic filters placed at nodes 6 and 8. In comparison with Case B of Table II, note that the seventh harmonic voltage is predicted to rise in certain conditions, but the rise is modest. The guidelines stated in the previous section are not absolute, and the effects of switching should be studied for each system. It is not, however, necessary to test every possible switching combination, but only to establish the trend of the switching effects and from that to determine the peaks of the critical node voltages.

7. The Effect of Load Level

It is very difficult to predict what effect changing load levels will have on the fifth and seventh harmonic voltages. This effect is dependent on no less than three separate parameters: (1) the level of effective harmonic current injection by the nonlinear portion of the load; (2) the level of damping provided by the linear portion of the load; and (3) the system impedance, which changes with the capacitor bank switching.

Measurements have shown that some distribution systems will exhibit peak harmonic voltage levels during full load conditions, while other systems will exhibit peak harmonic levels during light loads. Therefore, the planning of filter placement on any particular distribution system must include measurements which show the relationship between harmonic levels and load levels. For a fixed system configuration and fixed harmonic current injection levels, it can be expected that the harmonic voltage levels will increase as linear load goes down. Also, obviously, the harmonic voltage levels will go down as the effective level of harmonic current due to the disturbing nonlinear loads goes down. These two effects will therefore cause changes which offset to some extent or other. What is not known, however, is how the ratio of nonlinear load to total load varies on a given system with the load level or time of day. It can be expected that distributed nonlinear loads will correlate more closely with total load level than is the case with some industrial systems, where a production system may consist largely of nonlinear load and be in operation 24 hours a day while the linear load varies with time of day.

For the Rock Cut distribution system described in the previous section, the effect of load level is illustrated with three frequency scans with 1 amp of current injected at node 18 and voltage measured at node 18. Figure 4 shows the frequency scans with fifth harmonic filters in place at nodes 6 and 8. In this case, the seventh harmonic voltage per amp of excitation approximately doubles when the linear load is cut in half, and roughly triples when the linear load is one quarter of its original value. The fifth harmonic levels are relatively constant, due to the filter presence. If the harmonic currents generated by the nonlinear loads on this node are proportional to the total load current, the seventh harmonic voltage due to this current will decline slightly as the load level drops when all the capacitors are in place. While this effect is location dependent, similar responses are seen over much of this particular system.

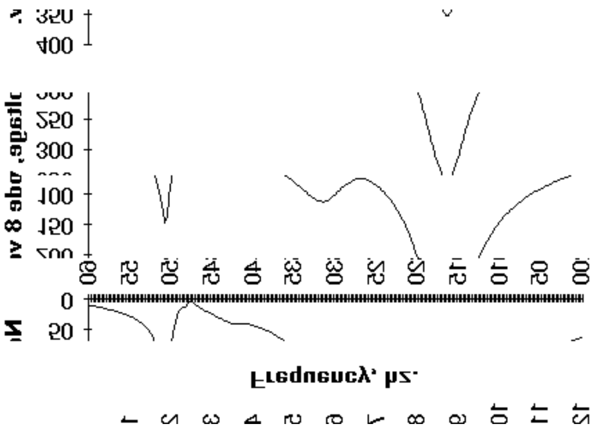

Figure 3. Frequency response to node 8 current with fifth harmonic filters at nodes 6 and 8.

The effect of capacitor switching at light loads is also of interest. Table IV shows the effect of switching out capacitor banks at light loads on the Rock Cut system. In this case, both the linear load and the fifth and seventh harmonic current injection levels have been reduced to 25% of their full load values. Table IV shows that overall, the removal of capacitors on this system lowers the voltages. The node 18 7th harmonic voltage does rise slightly, however, before beginning to fall off. The load and multiple normal combination of light capacitors switched out will produce reduced harmonic voltage levels here.

Table IV. The effect of capacitor bank switching at light loads with filters in place.

	Capacitors removed at node(s)			
	all in	6	6,7	6,7,18
Node	5th harmonic voltage			
1	23v	23v	22v	19v
13	26	25	25	22
18	59	59	59	49
6	10	10	9	8
8	3	3	3	3
	7th harmonic voltage			
1	106v	109v	108v	95v
13	126	129	128	114
18	212	227	232	185
6	112	98	86	87
8	94	86	76	82

8. Future Growth

The distribution system is, of course, a dynamic system which will exhibit changing load patterns over time. Therefore, distribution systems which have harmonic level concerns should be monitored periodically for changing conditions. With no system changes, monitoring the substation bus for increases in harmonic voltage levels should be sufficient (where the voltage rise along the feeder has been predicted and is factored into the analysis). When system changes are being made, however, a closer look at the system performance is warranted. In particular, the addition of a capacitor bank onto the system should be studied, and a decision made as to whether a filter should be installed, or a simple capacitor bank is acceptable. It is noted that the addition of capacitance can create a requirement for seventh harmonic filtering where none existed before.

9. Conclusions

A planning approach to distribution system harmonic filtering is proposed. The proposed method is suitable for radial distribution systems which have no large point source of harmonics. This method consists of the following steps:

Perform preliminary system analysis
Develop and conduct a measurement program
Determine harmonic source models
Determine filter location and tuning based on system characteristics
Conduct switching studies, determine filter performance requirements

The planning approach exploits the characteristics of this type of system, particularly the limitation of the harmonic excitation to the low orders and the nature of the system response at these frequencies. The method relies on system measurements to develop an effective harmonic model, and proposes efficient development techniques using this model.

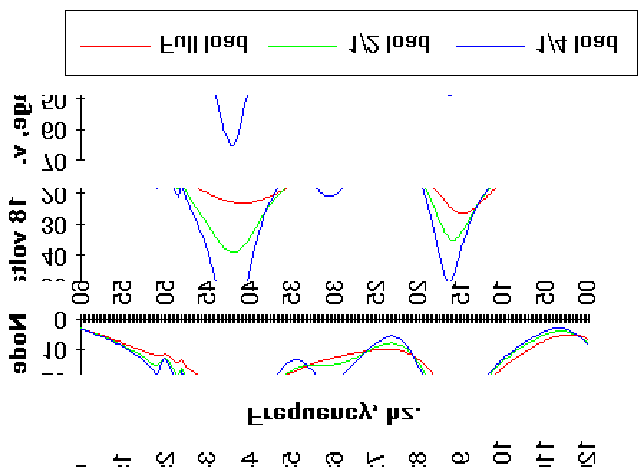

Figure 4. Frequency response at node 18 for three load levels. Fifth harmonic filters are located at nodes 6 and 8.

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Biographies

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