ACTIVE FILTER DESIGN AND SPECIFICATION
FOR CONTROL OF HARMONICS IN INDUSTRIAL AND COMMERCIAL FACILITIES

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Abstract

Active filters have become a viable alternative for controlling harmonic levels in industrial and commercial facilities. However, there are many different filter configurations that can be employed and there is no standard method for rating the active filters. This paper describes the active filter operation characteristics and develops standard ratings that can be used for filtering different types of nonlinear loads. Limitations of the active filters are also described.

1.0 Introduction

Applications of active filters have been described in a number of previous publications [1-5]. The increasing use of power electronics-based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions. Also, passive filters often need to be significantly overrated to account for possible harmonic absorption from the power system.

Passive filter ratings must be coordinated with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions. Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. This means that the rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another.

The active filter concept uses power electronics to produce harmonic components which cancel the harmonic components from the nonlinear loads. These active filters are relatively new and a number of different topologies are being proposed [6-10]. Within each topology, there are issues of required component ratings and methods of rating the overall filter for the loads to be compensated. Development of a detailed model for the active filter using the Electro-Magnetic Transients Program (EMTP) facilitates the evaluation of these design and application considerations without extensive field tests. This paper describes the results of an extensive investigation to evaluate specific design and application concerns.

2.0 Active Filter Configuration

The active filter uses power electronic switching to generate harmonic currents that cancel the harmonic currents from a nonlinear load. The active filter configuration investigated in this paper is based on a pulse-width modulated (PWM) voltage source inverter that interfaces to the system through a system interface filter as shown in Figure 1. In this configuration, the filter is connected in parallel with the load being compensated. Therefore, the configuration is often referred to as an active parallel filter. Figure 1 illustrates the concept of the harmonic current cancellation so that the current being supplied from the source is sinusoidal.
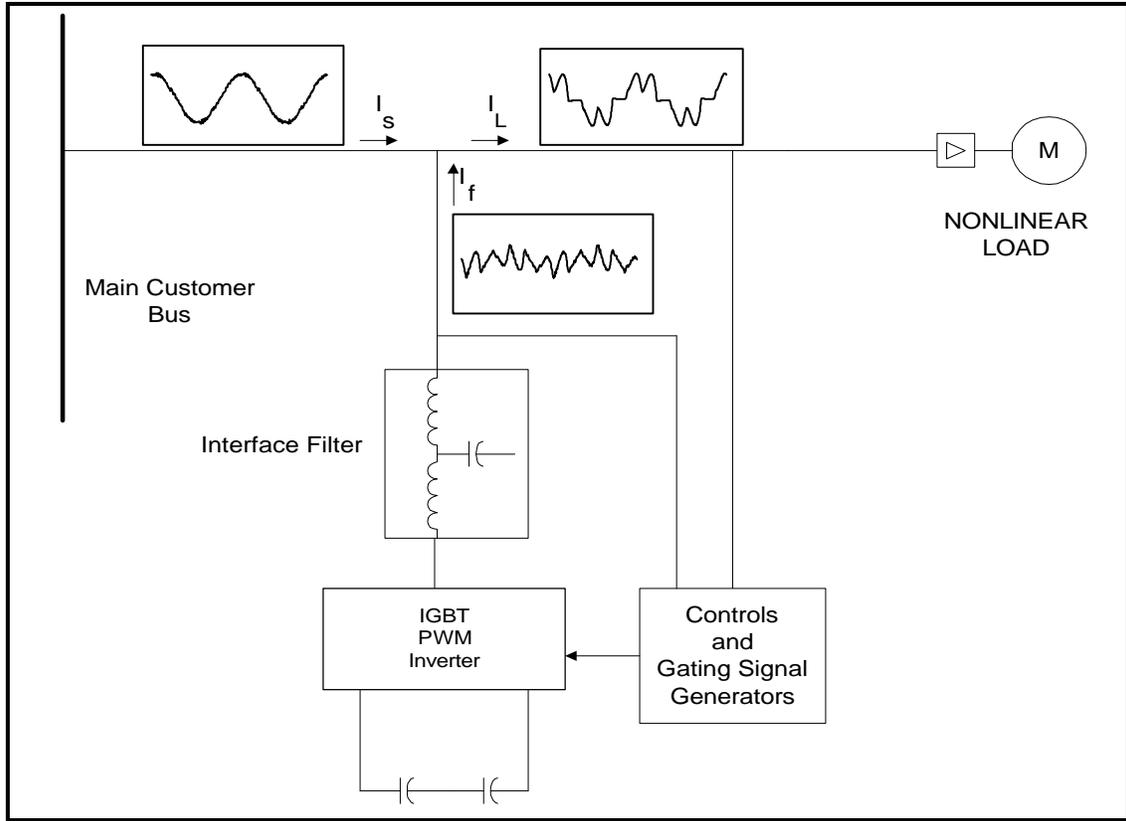
Figure 1. Diagram illustrating components of the shunt connected active filter with waveforms showing cancellation of harmonics from an ASD load.

The voltage source inverter used in the active filter makes the harmonic control possible. This inverter uses dc capacitors as the supply and can switch at a high frequency to generate a signal which will cancel the harmonics from the nonlinear load. One leg of the inverter is shown in Figure 2 to illustrate the configuration.
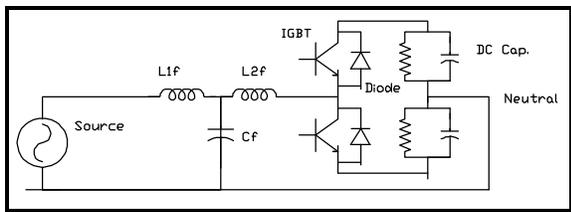

Figure 2. One line diagram for one leg of the active filter.

The active filter does not need to provide any real power to cancel harmonic currents from the load. The harmonic currents to be canceled show up as reactive power. Reduction in the harmonic voltage distortion occurs because the harmonic currents flowing through the source impedance are reduced.

Therefore, the dc capacitors and the filter components must be rated based on the reactive power associated with the harmonics to be canceled and on the actual current waveform (rms and peak current magnitude) that must be generated to achieve the cancellation.

The current waveform for canceling harmonics is achieved with the voltage source inverter and an interfacing filter. The filter consists of a relatively large isolation inductance to convert the voltage signal created by the inverter to a current signal for canceling harmonics. The rest of the filter provides smoothing and isolation for high frequency components. The desired current waveform is obtained by accurately controlling the switching of the insulated gate bipolar transistors (IGBTs) in the inverter. Control of the current waveshape is limited by the switching frequency of the inverter and by the available driving voltage across the interfacing inductance.

The driving voltage across the interfacing inductance determines the maximum di/dt that can be achieved

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by the filter. This is important because relatively high values of di/dt may be needed to cancel higher order harmonic components. Therefore, there is a tradeoff involved in sizing the interface inductor. A larger inductor is better for isolation from the power system and protection from transient disturbances. However, the larger inductor limits the ability of the active filter to cancel higher order harmonics.

3.0 EMTP Model of the Active Filter

The Electro-Magnetic Transients Program (EMTP) is an ideal tool for studying the effectiveness of the active filter and evaluating control system requirements. The model permits evaluation of the possible configurations without expensive field tests and prototype development. Important elements of the model are described briefly here.

3.1 IGBT Voltage Source Inverter

The voltage source inverter is the heart of the active filter. This three-phase, full-wave inversion bridge is built using three identical IGBT inverter legs. A dc link neutral is established by equally dividing dc capacitance between the positive and negative poles. This design combined with separate controls of the individual legs allows the filter to compensate for unbalanced loads or even single phase loads.

3.2 Sampling and Control Reference

In this parallel active filter configuration, control is accomplished by monitoring the current to the nonlinear load and then generating gating signals for the inverter to create a current waveform that will cancel the harmonics in the load current. Sampling of the load current must be at a high enough rate to accurately characterize all the harmonics to be canceled - 256 samples per cycle is used in this case. Then the sampled load current is further processed to obtain a harmonic power compensation reference.

There are many different control methods that can be used to generate the compensating current that cancels the harmonics in the load current. They are distinguished by how the current reference signal for the harmonic compensation is derived from the measured quantities. This paper focuses on one particular method, known as the *FFT* method.

This method compensates for individual harmonic components in the load current by performing a

rolling FFT on the sampled load current waveform and then reproducing a current waveform that has the same harmonic components with the opposite phase angle. This calculation is performed each cycle and the desired compensation is implemented in the successive cycle. This one cycle of delay could be a problem for nonlinear loads with rapidly varying characteristics.

3.3 PWM Firing Pulse Generation

As in most PWM applications, the interval between two consecutive switching actions varies constantly within a power frequency cycle. A rigid definition of the switching frequency is not applicable. Thus, the concept of an average frequency is commonly used. In principle, increasing the inverter operating frequency helps to get a better compensating current waveform. However, the actual performance of the active filter becomes limited by the isolating inductance once a high enough switching frequency is achieved. Control of the average frequency is realized by introducing a hysteresis characteristic into the PWM firing pulse generation logic as shown in Figure 3.
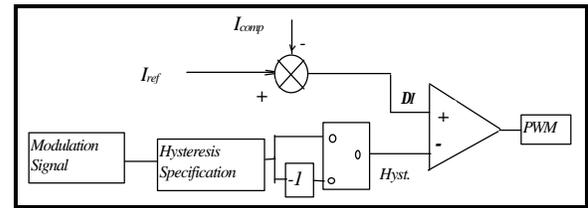

Figure 3. PWM firing single generation with hysteresis characteristic.

In Figure 4, I_{ref} is the desired compensation current reference signal. I_{comp} is the actual inverter leg output current. An unmatched quantity ΔI is the current shaping error which is sent to the positive terminal of the comparing unit. The negative terminal of the comparing unit is connected to the output of a hysteresis characteristic generator.

When I_{ref} is greater than I_{comp}, the resultant ΔI is positive. If the magnitude of the ΔI exceeds the upper boundary of a specified hysteresis band, the comparing unit output goes high, firing the upper bridge device of the leg and making the leg current increase. When I_{comp} becomes greater than I_{ref}, ΔI becomes negative. If the magnitude of the ΔI exceeds the lower boundary of the hysteresis band, the comparing unit goes low, firing the lower bridge device of the leg and making the leg current

decrease. By increasing or decreasing the allowable current shaping error, which is determined by the bandwidth of the hysteresis characteristic, the average switching frequency can be controlled. This firing algorithm is sometimes called a delta-modulation. In the simplest delta modulation control, an equal bandwidth over the whole power frequency cycle is used for the hysteresis. In this case, the modulation frequency is a constant. A nonlinear modulation can be used to help reduce the variations in the switching interval associated with a constant bandwidth.

3.4 System Interface Module

The system interface module provides the isolation and filtering between the output of the voltage source inverter and the power system where the active filter is connected. The isolation consists of two inductors, L_{1f} and L_{2f} (refer back to Figure 2) and a high frequency attenuation filter formed by a small capacitor with these inductors.

The isolation inductance allows the output of the active filter to look like a current source to the power system. The inductance makes it possible to charge the dc capacitor to a voltage greater than the ac phase-to-phase peak voltage. The isolation inductance also functions like a commutation impedance. It limits the magnitude of a current spike during commutation and prevents the switching device from seeing an excessive rate of current change.

The PWM switching of the filter inverter generates high frequency components. To prevent these components from being injected into the source, a capacitor is included with the isolation inductance to form a second order passive filter. The capacitor must also be isolated from the power system by an inductor (L_{2f}) to prevent overloading due to transients and high frequency harmonic components from the power system.

Sizing of the inductor and capacitor values must take into account control of the inverter switching frequencies, power system switching transients, and the characteristics of the nonlinear load to be compensated. One of the main objectives of the application study was to evaluate the possible impacts of system switching events on these filter components.

4.0 Example System for Active Filter Performance Evaluation

A simple example system was modeled to evaluate the active filter performance for different types of loads and to evaluate the impact of system switching events on the design requirements for the active filter. A typical distribution circuit as shown in Figure 4 was selected for this evaluation. Important parameters are as follows:

Source strength at transmission supply point = 200 MVA
138/13.8 kV Transformer: 10 MVA, 7% impedance
Substation capacitor bank size = 3.0 Mvar (switched)
Equivalent load for parallel feeders = 3.0 MW
Modeled feeder circuit: 3.0 miles to example customer
Feeder capacitor bank on 13.8 kV side at example customer: different sizes evaluated
Customer low voltage capacitor bank: varied
Customer service transformer: 1500 kVA, 6% impedance
Customer load = 1.0 MW
Active Filter size = 400 Vrms, 30 Arms
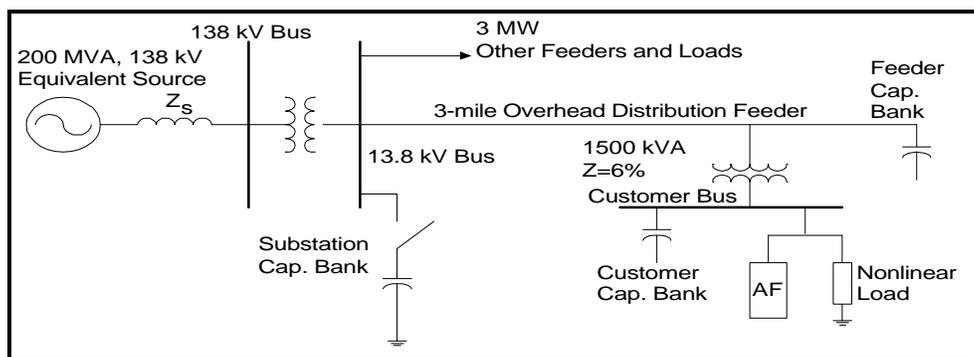Nonlinear load: different loads evaluated

Figure 4. Example distribution circuit for active filter application evaluations.

5.0 Determining Active Filter Ratings for Nonlinear Load Types

One of the confusing aspects of applying active filters is trying to figure out the active filter rating that is required to compensate for the harmonics from a particular load. A parallel-connected active filter should be rated in terms of the rms current it can provide. Then the task is to figure out the rms current required to compensate for the harmonics from different types of loads. Simulations were performed for a number of typical nonlinear loads to develop some guidelines for active filter ratings.

One advantage of the parallel-connected active filter, as compared to passive filters, is that it is self-limiting in terms of the harmonic cancellation provided. there is no concern for overloading the filter due to harmonics from the utility supply system or under-rating the filter for the loads involved. The worst case scenario if the filter is under-rated is that it just won't completely compensate for all the nonlinear load current harmonics. In fact, it may not be necessary to compensate for all the harmonics from a nonlinear load. With the active filter, the size can be selected to achieve any desired level of cancellation. One good way to use this concept would be to provide only enough compensation so that the load/filter compensation was within some specified guidelines for harmonic generation (e.g. IEEE 519-1992).

5.1 Effect of Load Waveform on Filtering Effectiveness

The effectiveness of the active filter in compensating for harmonic components of the load current depends on the specific load current waveform involved. Two different waveforms may have the same rms harmonic content but the active filter may do a better job of compensating for one of the waveforms because of the waveshapes involved.

An ac voltage regulator is used for illustration. Two cases are compared in Figure 5. The only difference between the two cases is the load of the ac regulator. In the waveforms on the left side of the figure, the load is a pure resistance. The waveforms on the right side are for the case where the load is a series combination of resistance and reactance. The performance is much better for the smoother load current waveform (RL load). It is worthwhile to note that the majority of applications for the active filter will involve waveforms like those on the right hand side of Figure 6 (e.g. adjustable speed drives with diode bridge rectifiers or single phase electronic loads), rather than the left side.
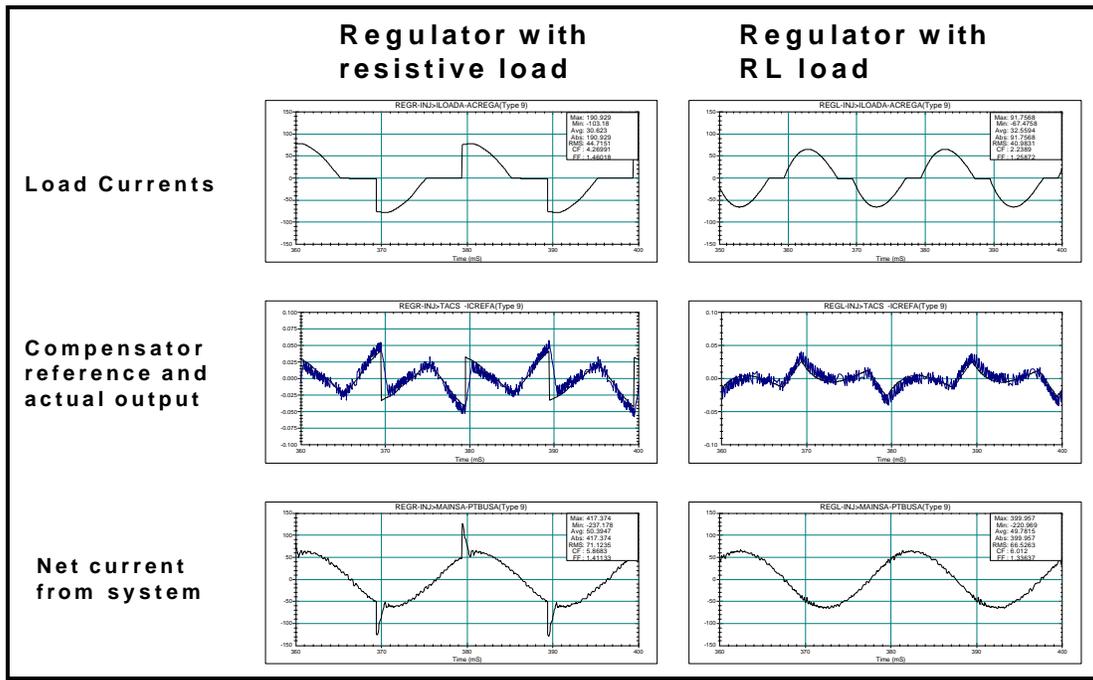

Figure 5. Comparison of active filter performance for an ac voltage regulator with resistive load and with RL load.

In general, the current waveform of an ac regulator with resistive load is an example of the waveshape that poses the severest challenge for an active filter. The problem is the high di/dt that is required of the filter to compensate for the high di/dt at turn on of the regulator. The problem is most severe when the regulator is turned on with a firing angle close to 90 degrees because this is when the available driving voltage stored on the dc capacitor is at a minimum. The output di/dt capability can be raised either by increasing the dc voltage setting or by reducing the size of the interfacing inductance. The limiting factor for increasing the dc voltage is the voltage withstand capability of the IGBT devices. The limiting factors for reducing the interfacing inductance include the IGBT di/dt withstand capability, control requirements, the interface passive filter requirement, and overall system stability. If the interfacing inductance becomes too small, the dc voltage cannot be kept constant for normal operation.

5.2 Steady-State Rating Requirements and Active Filter Effectiveness

The best way to provide a rating for an active filter is in terms of the rms current that it must provide to compensate for harmonics from nonlinear loads. Table 1 provides a convenient summary of different nonlinear load types with example waveforms and typical levels of harmonic current distortion associated with each load. Using these typical waveforms, it is possible to calculate a theoretical value for the required harmonic compensation from the active filter. The summary includes the THD for each nonlinear load waveform and the required active filter rating in rms amps per kVA of load rating. These ratings assume that the active filter rating should be based on the total rms harmonic current content of the load. A simulation waveform illustrating the active filter effectiveness for each of these waveforms is also provided.
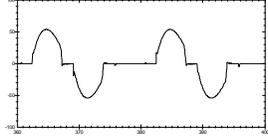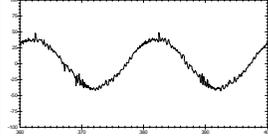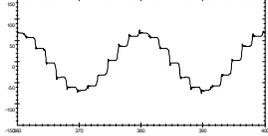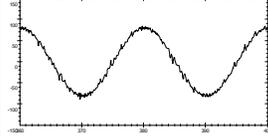
The ratings in Table 1 assume ideal active filter characteristics. That is, they assume that the active filter can compensate for every amp of harmonic current created by the nonlinear load. It is clear from the simulation result waveforms also included in the table that the harmonic cancellation is not perfect. The distortion in the supply current is also provided in the table to illustrate the effectiveness of the active filter.

It is important to note that these simulations were for steady state conditions (load was not changing). Therefore, the effect of the response time associated with the FFT control was not a factor.

A number of important observations can be made based on the results summarized in Table 1:

- The overall filtering effectiveness depends significantly on the types of loads being compensated. There is no simple relationship between the load current THD and the filter effectiveness.

- The active filter is most effective when the load current waveform does not have abrupt changes. As a result, it is very effective for most voltage source inverter-type loads, even when the distortion is high.

- The active filter effectiveness was not as good for 12 pulse loads. This is caused by the fact that the higher frequency components are more dominant in these loads.

- The rating requirement for the passive filter capacitor is also dependent on the load current characteristics. Load current waveforms with more high frequency content (e.g. ac regulator with resistive load or 12 pulse converters) result in higher duties on the filter capacitor.

Table 1. Required active filter ratings for different types of nonlinear loads.

Type of Load	Nonlinear Load Current Waveform	Supply Current with Active Filter	Nonlinear Load Current THD (%)	Supply Current THD (%)	Active Filter Rating (rms Amps/kVA of Load)	
					120/208 volt applications	480 volt applications
Single Phase Power Supply			84%	8.2%	1.79	0.77
Semiconverter			87%	9.6%	1.82	0.79
ac Voltage Regulator, RL Load			23%	4.3%	0.62	0.27
ac Voltage Regulator, Resistive Load			51%	16.7%	1.26	0.54
6 Pulse Drive, Current Source Inverter			31%	10.3%	0.82	0.36
6 Pulse Drive, Voltage Source Inverter no series inductance			109%	13.2%	2.05	0.88
6 Pulse Drive, Voltage Source Inverter 3% ac input choke			45%	5.0%	1.14	0.49
12 Pulse Converter, Current Source Inverter			13%	5.6%	0.36	0.15
12 Pulse Converter, Voltage Source Inverter			13%	6.3%	0.36	0.15
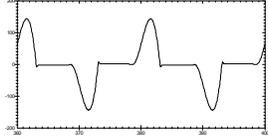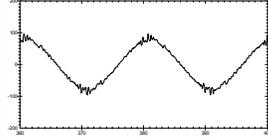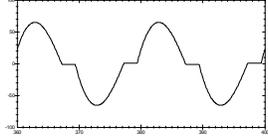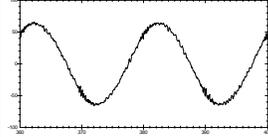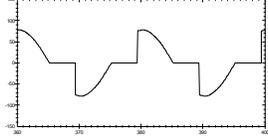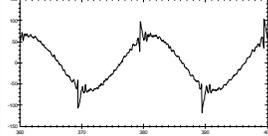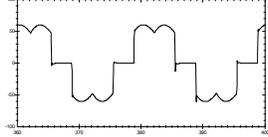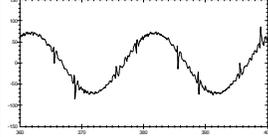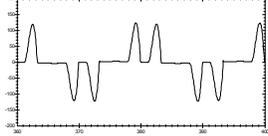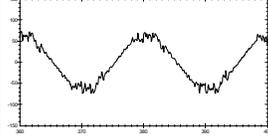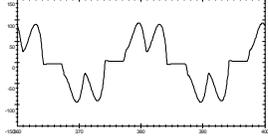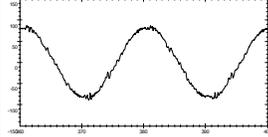
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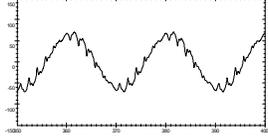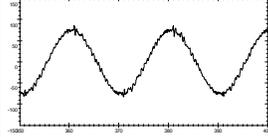
6.0 Effect of Power System Transients on the Active Filter

The active filter is not designed to control transient currents flowing to the load. It is a steady state controller. However, it is important to understand the impacts of transient conditions on the components of the active filter. The inverter controls include hard limits to prevent excessive compensating current generation during either steady state or transient conditions. The main concern during transients is for the passive filter components in the interface module between the inverter and the power system (see Figure 1).

The interface module includes inductors and capacitors. Surge suppressors can limit high frequency voltage spikes that may be associated with load switching events within a facility or coupled transients during lightning strokes. The concern evaluated in this study involves transient voltages caused by capacitor switching on the utility supply system. Capacitor switching on the primary distribution system has the potential of causing an oscillation frequency that could be magnified by the inductor/capacitor series combination in the interface module.

Simulations were performed to evaluate the effect of switching the 3.6 Mvar capacitor at the substation in Figure 4. Substation capacitor switching usually causes the most severe transients and has the most potential to cause magnified transient voltages. The characteristics of the transient seen at the active filter were varied by changing the size of the feeder capacitor bank located close to the customer facility and by evaluating the effect of a low voltage capacitor connected at the customer bus. The waveforms in Figure 6 illustrate the magnification within the customer facility for a case with both a feeder capacitor and a customer capacitor in service. Note that the transient voltage across the interface filter capacitor is approximately the same as the transient voltage at the customer bus due to the relatively low frequency of this transient (no additional magnification across the inductor L_{1f}). It is important to evaluate conditions such as this as part of the active filter design process. If the isolation inductor size was increased, the concern for transient magnification on the interface capacitor would be even more severe. Also, a damping resistor is added in the interface circuit to help prevent magnification problems.
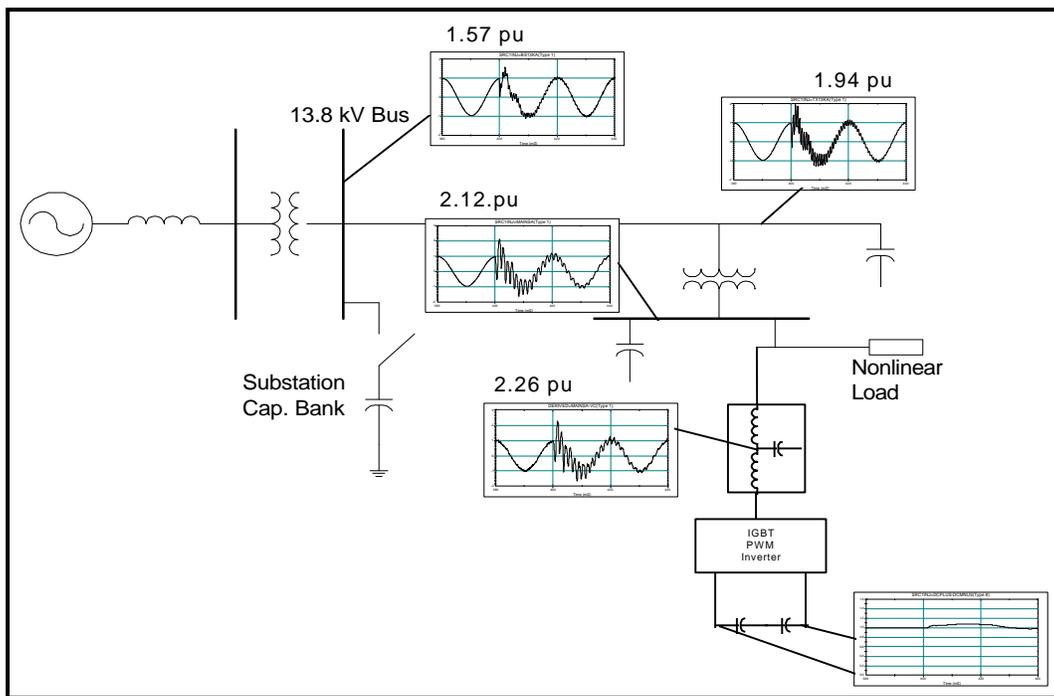

Figure 6. Transient voltage waveforms caused by substation capacitor energizing.

It is also interesting to evaluate the effect of this transient on the active filter currents. Since the transient voltage exceeds the voltage on the dc capacitors for this case, all control is lost during the transient (no driving voltage for the IGBTs). Instead, there will be a significant transient current that flows through the converter to charge up the dc capacitors. The waveforms in Figure 6 shows that the additional charge on the dc capacitors is not significant but the current waveform in Figure 7 below illustrates that the transient current during the capacitor switching can be quite high. This current does not flow through the IGBTs since they are not being gated. Instead it all flows through the anti-parallel diodes, resulting in possible overloading and failure of the diodes.
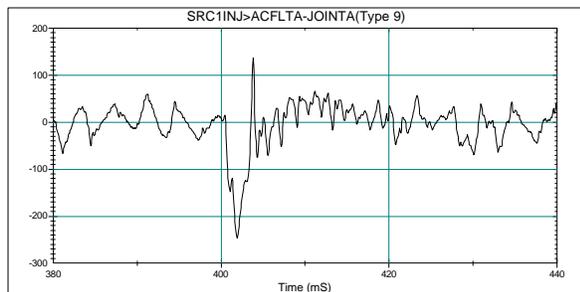

Figure 7. Active filter current output during capacitor switching transient.

These transients must be considered in selecting the capacitors to be used for the interface filter. All of the capacitor switching transients can cause high currents in the anti-parallel diodes.

7.0 Conclusions

Active filters could have wide application for controlling harmonic currents from nonlinear loads. The best performance is obtained for loads such as PWM type ASDs and switch mode power supplies, where the current waveform does not have abrupt changes that are hard for the active filter to follow. Guidelines for rating the active filters are presented.

Capacitor switching transients should not be a major problem for the active filter inverter and controls. However, the interface filter capacitor could experience high transient voltages that may exceed the capabilities of the capacitor and surge suppressors. The capacitor switching transients could also cause overload of the anti-parallel diodes in the inverter bridge. Other devices in customer facilities can also have problems with these

transients and many utilities are making efforts to control substation capacitor switching transients.

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