Measuring non-linear rectifier load characteristics with a controlled-current power converter

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Keywords

Active filters, converter circuits, DSP, Measurements, single-phase systems, three-phase systems.

Abstract

This paper presents the results of experimental measurements of the response of single and three-phase diode rectifiers excited by injecting a small perturbing current generated by a switching converter. Results show that the rectifiers are sensitive to the perturbing current, that the response is measurable and that there is an algebraic relationship among the rectifier current frequency components.

Introduction

As the proportion of electrical power that is processed by some form of non-linear rectifier increases the effect these converters have on the power supply system also increases. Generally the characteristics and effects of non-linear rectifier loads are not well known although there has recently been some effort to make response measurements [1]. This lack of research effort is primarily because non-linear rectifiers have, in the past operated, in an almost trouble free way. However emphasis on power quality means that power conditioners are being installed to prevent problems [2]. This means that the end user power system is changing from one where the typical load is the induction motor, resistive heating or filament lighting to one where non-linear rectifiers form a large part of the load.

One area of present consideration in end user power systems is the use of power conditioners to prevent any harmful effects from rectifier loads entering the power system and also to prevent harm being delivered to the load by the power system. The present thinking on power system conditioning assumes that devices that return or move the voltages and currents back to their sinusoidal ideals improve power quality. This view of power quality is simplistic with perhaps a better approach being putting an economic value on the quality of the delivered electric power. The main obstacle to this is determining what value power quality has for the customer. Survey methods attempt to quantify costs from customer's own estimates of the cost of power quality events. This however does not quantitatively assess the sensitivity of the customer's load and hence the effectiveness of any installed power conditioner. This load sensitivity is an area of research that has received little attention. However as the number of installed rectifier non-linear loads and power conditioners increase it is important to determine the behavior of the loads to ensure that the power delivery system continues to operate correctly.

Active power conditioners such as the shunt active filter (SAF) typically have a power converter. This is switched to create a current waveform to compensate for the unwanted components of the voltage or current. By adding to the control of the power converter the ability to inject an arbitrary perturbing current, the conditioner can be made into an active measurement device for the combined AC system/load network to which it is connected.

This paper presents experimental results measured using an actual SAF system as a perturbing source to perform measurements of the small-signal behavior and sensitivity of a single-phase and a three-phase rectifier.

The characteristics of non-linear rectifier loads connected to AC systems

A diode rectifier's essential function is to act as a modulator converting the fundamental 50Hz AC side voltage to 0Hz DC side voltage. As part of this function other current and voltage harmonics occur. When a non-harmonic frequency is applied to the rectifier the response is at a number of frequencies algebraically related to the original applied frequency [3].

Figure 1 shows the electrical circuit equivalent of the experimental system. The AC system is defined by its impedance, Z_{Sys}, because it has a current to voltage transfer. The load has a voltage to current transfer and is therefore represented as an admittance, Y_{Load}. Measurements are made of the small-signal response by injecting the perturbing current, I_{Inj} into the point of coupling of the rectifier and the AC system. The change in the load current, ΔI_L is recorded. The effect of the AC system on the measurement can be seen by considering Figure 2. At frequencies where the AC system has no voltage source the injected current divides between the AC system and the load. It is typically assumed for shunt active power conditioner systems that the amount of the active filter current flowing into the load is zero. However it is in fact the relative sensitivity of the load with respect to the AC system that determines the amount of the injected current that flows into the load. The measurements made with the experimental system give this relative sensitivity.

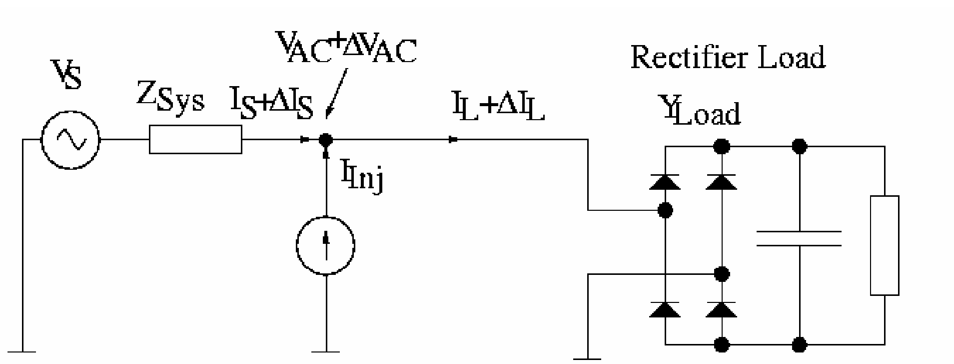

Figure 1 Circuit diagram of experimental system.

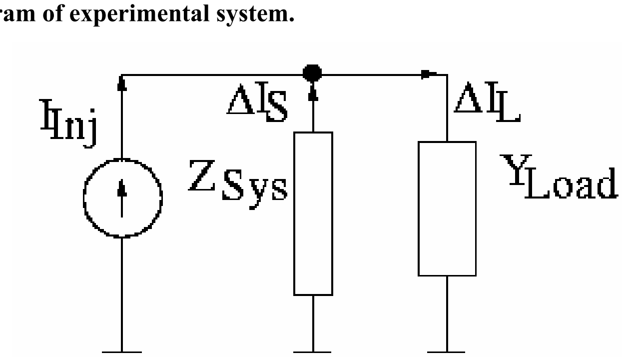

Figure 2 Equivalent small-signal circuit at frequencies without a voltage source.

Experimental system functional overview

The experimental system is designed and built to perform three functions. These are to shunt active filter, to generate and inject perturbing currents for frequency response measurements and to collect and store measurements of the currents and voltages. Figure 3 shows the total measurement and acquisition system. The current into the load and the voltage at the load terminals is measured by analogue to digital converters (ADCs). These ADCs are connected to the field programmable gate array (FPGA) part of the central controller by serial communication links (SCL). The FPGA provides all the interfacing, handshaking and logic functions for the controller. An ADC also measures the load DC bus voltage for completeness. The three-phase converter current is measured along with its DC bus voltage. Switching signals from the FPGA complete the current loop. The DSP provides the processing power for the system and executes the control software. The PC host is used to house and power the controller. Software running on the PC provides supervisory control of the entire system and a user interface. The user interface allows the system to be started, stopped and reset from fault states. It also displays system information and data to the user. In order to facilitate the measurement and collection of experimental data the PC software includes a system that can change the operating condition, record the resulting data, store it to the PC hard drive and then move on to the next operating condition. This allows frequency and phase sweeps to be made automatically.

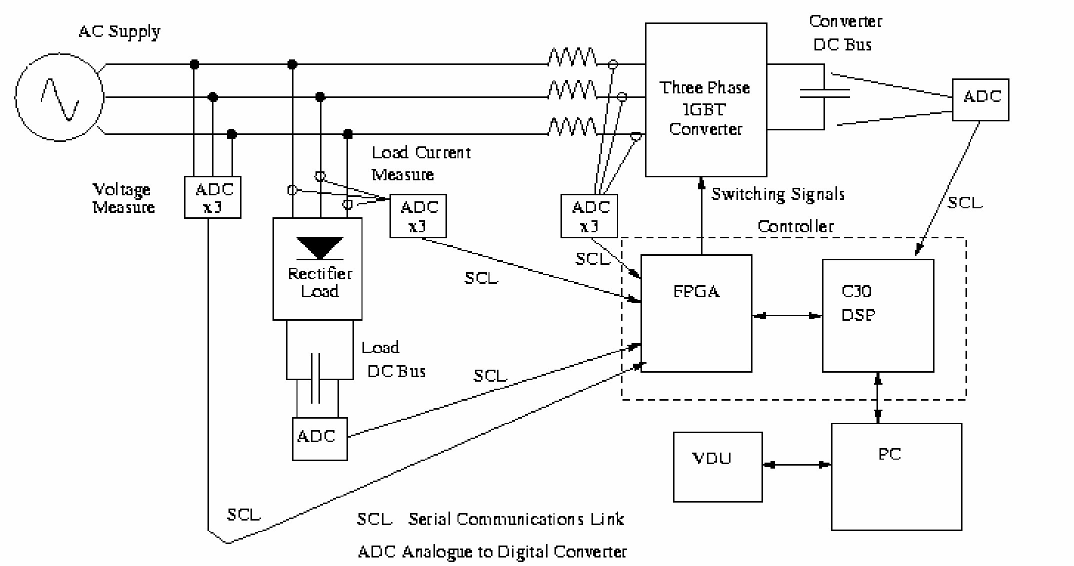

Figure 3 Experimental system showing power circuit, measurement and control functions.

The IGBT converter is operated as a hysterisis current-controlled voltage-source converter. This means that the current is controlled with a high bandwidth and the control is robust to system parameter change, disturbances and noise [4].

In order to minimise the system's data acquisition overhead and therefore maximise the available processing time for the DSP, the data measurement system is implemented so it requires no software intervention from the DSP. The system is included in the FPGA design which provides all necessary interfacing from the ADCs, Phase locked loop (PLL) and IGBT converter to the DSP. This interface is made by programming an FPGA with the design using circuit capture and design entry tools. The FPGA design has a bus interface that connects to the DSP expansion bus. This interface produces an internal data, chip select and control bus that connect the subsytems. The ADC subsystem receives serial data from the external ADC boards and stores the data in parallel latched registers. Writeable memory mapped command and control registers allow the DSP to give current demands and other control commands. This allows functions such as starting, stopping and the change of system parameters. The phase lock loop subsystem locks the entire control system to the positive sequence fundamental of the AC system voltage and produces a regular sampling clock at 128 times the fundamental frequency. This is used as the sampling clock for the DSP software and generates the start pulse for the ADC system and also the DSP interrupt. The current control sub-system uses three dedicated ADC sampling at 200kHz to measure the converter current. By comparing these feedback currents to the current demands from the DSP, the inverter switch signals are generated.

The DSP software and the control system operate at a sample rate of 128 times per AC cycle. This means that each cycle has a constant number of samples which ensures that the signals can be processed with a Fast Fourier Transform without having to use any windowing typically used with unsynchronised sampling [5]. Eight AC cycles are collected realising a data length of 1024 samples at 128 samples per AC cycle therefore giving frequency resolution of 6.25Hz in the resulting FFT.

Experimental Measurements

The system is used to make measurements of a number of different rectifier configurations. Both three-phase and single-phase rectifiers are used as loads. Results of the single-phase measurements are presented first.

Single-phase diode rectifier measurements

The experimental system is set up with the single-phase diode rectifier load connected line to line between to of the three-phases. This avoids having to use a neutral connection. The converter system is made to generate a single-phase single frequency constant amplitude current injection. Figure 4 shows the effect of injecting the sinusoidal perturbing current I_{Inj} of 0.365A (peak) at frequency of 18.75Hz on the current flowing into the single-phase diode rectifier load. As can be seen from the highlighting dotted lines, the diode rectifier current has an oscillatory variation away from its base case, or unperturbed, waveform.

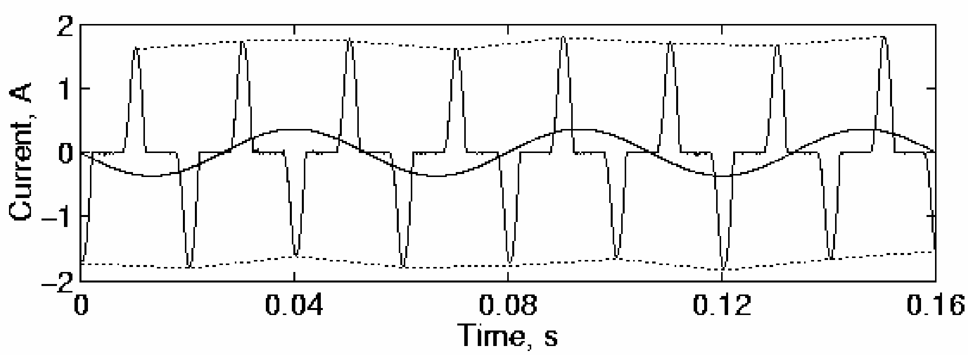

Figure 4 Perturbed rectifier load current, $I_L + \Delta I_L$, waveform for perturbing current I_{inj} of 0.365A (peak) at frequency of 18.75Hz.

The spectrum of this perturbed load current waveform, $I_L+\Delta I_L$, is shown in the upper part of Figure 5. Removing the base case, I_L, spectrum leaves the spectrum of the only the small-signal response, ΔI_L as is shown in Figure 5 (Lower). Notice that the spectrum of ΔI_L has components at frequencies 18.75Hz, 100-18.75=81.25Hz, 100+18.75=118.75Hz and that this pattern continues. This shows the frequency coupling behaviour of the single-phase rectifier and that it has a small-signal response characterized by a one frequency perturbation to a many frequency response [3].

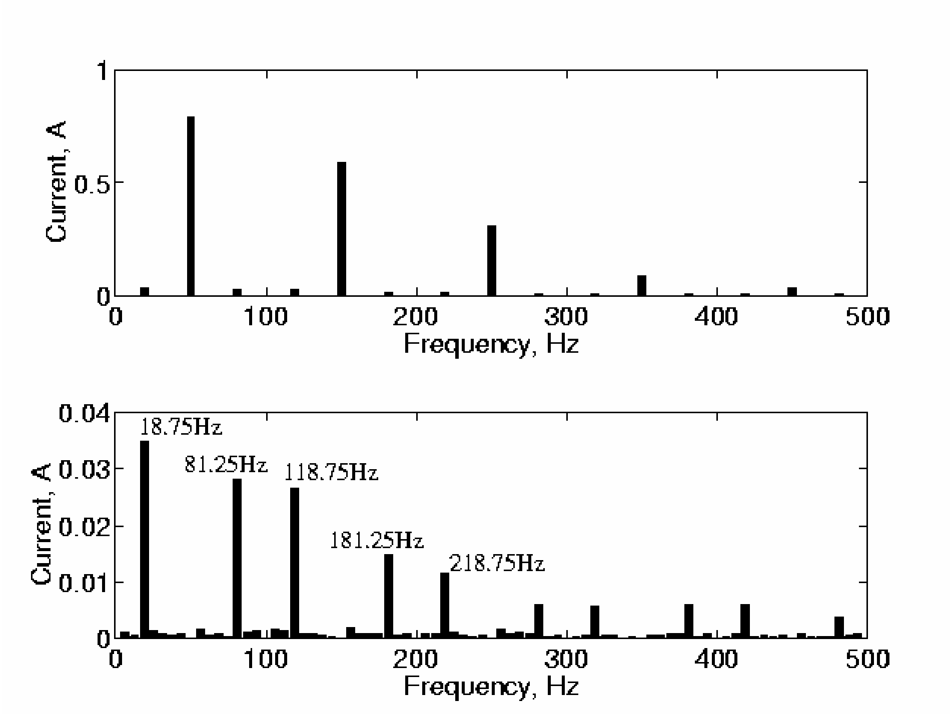

Figure 5 Perturbed rectifier load current spectra $I_L + \Delta I_L$, for perturbing current I_{inj} of 0.365A (peak) at frequency of 18.75Hz. Upper spectrum includes base case. Lower spectrum has base case removed.

Single-phase diode rectifier frequency coupling measurements

The frequency coupling pattern of the single-phase rectifier is shown in Figure 6. This shows frequency components that arise in the output load current for a given input frequency and is measured by taking FFTs of the change in the load current for increasing injected perturbing current frequencies. The constant base case harmonic currents, which form the horizontal lines, are retained. The figure shows the way in which a perturbing current at a given frequency gives rise to a number of frequencies in the output. Consider an applied 25Hz signal. By tracing down the imaginary vertical line from 25Hz the frequencies that arise can be found. Ignoring the characteristic harmonics of the single-phase rectifier these are 25Hz, 100-25=75Hz, 100+25=125Hz, 175Hz, 225Hz ....

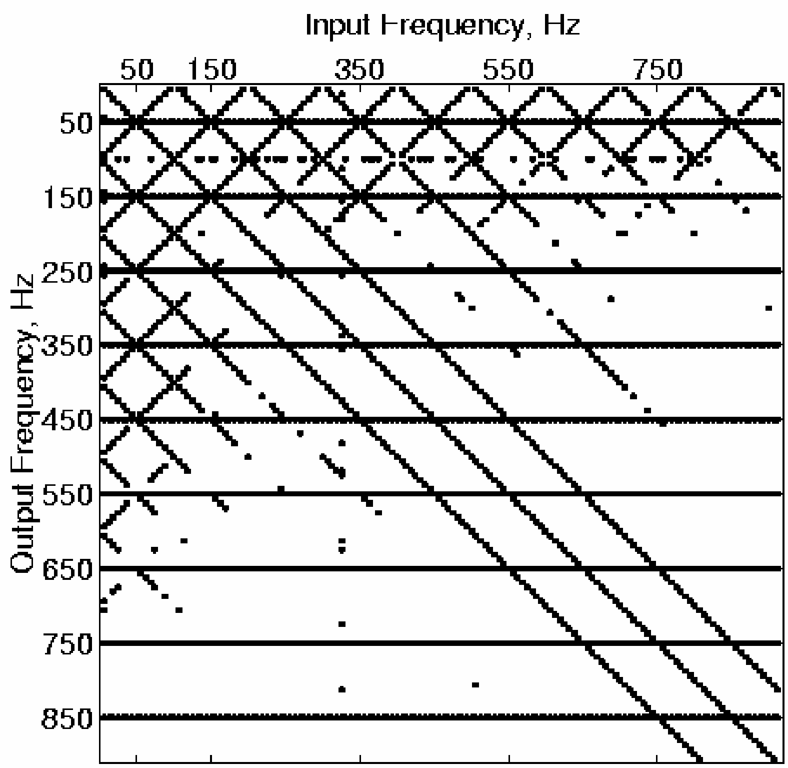

Figure 6 Experimentally measured frequency coupling of single-phase rectifier. Dark areas show where a given frequency in the input (the injected current $I_{Inj)}$ gives rise to a given frequency in the output (the change in the rectifier load current).

The diagonal lines show that the component frequencies in the load current have a first order relation to the applied perturbing frequency. That is the output has frequencies that are related only to some arbitrary frequency plus or minus the input frequency and not to twice or some other multiple of the input frequency. This has important implications for modeling and analysis of rectifier devices [6] and is discussed further in the discussion section. The disappearance of the diagonal lines as the input perturbing frequency increases is caused by the magnitude of the resulting component falling below the arbitrary plotting cutoff magnitude chosen to suppress the noise inherent in the measurements.

Single-phase diode rectifier describing function measurements

In order to give develop a single-input, single-output representation of the behaviour of the single-phase rectifier, measurements were made of the transfer from the injected current to the change in the load current that occurs only at the same frequency. This is the equivalent to a describing function of the transfer. Figure 7 shows the result of the measurement with the dashed line showing the measured results. Interesting features to note are the rapid changes in phase at 50Hz and 150Hz and the corresponding low values of the transfers at these frequencies. The rapid magnitude change without a corresponding resonance type phase change that can be seen at 100Hz is the result of the dependence of the single-phase rectifier's response on the phase of the injected current at characteristic harmonic frequencies. The accuracy and validity of the measurements is born out by the match in both magnitude and phase to the results from analytic models [7].

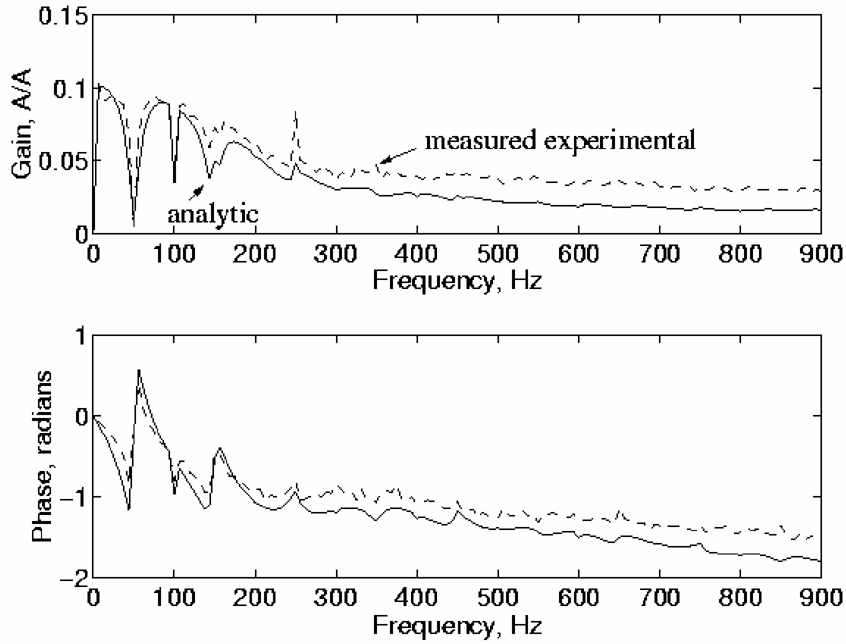

Figure 7 Describing function of injected current perturbation to single-phase diode rectifier load current perturbation (Dashed -measured experimental, solid analytic)

Three-Phase Measurements

Although common the single-phase rectifier is not the only rectifier used to convert AC power to DC power. A large amount of rectification is performed with three-phase diode rectifiers. In order to make three-phase measurements experimental system converter of Figure 3 is made to generate a positive or a negative sequence current injection.

The measurements of the three-phase diode rectifier are made by injecting a current, I_{Inj} at a certain sequence, frequency, amplitude and phase, recording the rectifier load current and then repeating the measurements for another different frequency and phase. The sequence coupling behavior of the three-phase rectifier can be seen Figure 8 which presents the results of repeated measurements. The diagonal lines show the frequencies at which the rectifier small signal response is of significant magnitude for both negative sequence perturbing current injections (shown as negative frequencies on the x axis) and positive sequence perturbing current injections (shown as positive frequencies). The base case spectrum, which forms horizontal lines, is not removed.

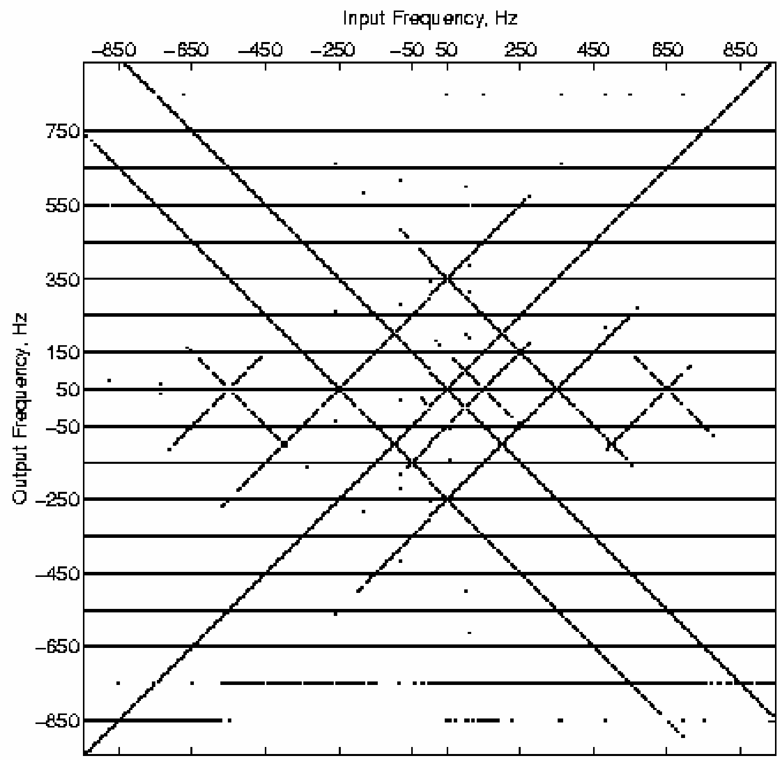

Figure 8 Plot of measured frequency coupling results for three-phase diode rectifier with DC bus capacitor.

The way the three-phase rectifier couples sequences can be seen by considering an input of -50Hz (negative sequence fundamental). By tracing the vertical line down from the -50Hz label it can be seen that positive sequence 450Hz, positive sequence 250Hz, positive sequence 150Hz, negative sequence fundamental, negative sequence 150Hz and negative sequence 350Hz all occur. (The horizontal lines are the base case harmonic spectra of the three-phase rectifier. The un-characteristic harmonic currents are due to imbalance in both the supply voltage and system impedance.) Of considerable interest is the positive sequence third harmonic. Since this triple-n harmonic is not zero sequence so can propagate through a three wire three-phase system.

Discussion and Conclusion

The results of the measurements made using the DSP controlled power converter show that rectifier type non-linear loads have a measurable and well patterned response when excited by an injected perturbing current. This means that the rectifiers are sensitive to variation in the terminal voltage caused by the injected current. This counters the constant current source assumption made with respect to diode rectifier loads when they are considered connected to power conditioners such as shunt active filters. The implications of these measurements for power conditioner connection are that since the diode rectifier non-linear loads are indeed sensitive to changes in their terminal voltage the behavior of the load needs to be considered in power conditioner control system design. As the system used to make the measurements is of the type used to implement a shunt active filter this suggests that the load measurements could be made by the shunt active filter itself. This opens the door for power conditioners to self adapt or self tune depending on their load conditions.

Perhaps of equal interest is the fact that the measurements show that non-linear rectifier loads have a non-zero small-signal response and so contribute to the response of the total AC power system to any disturbance. The measurements made are injected current to load current change. However by measuring the AC system impedance the behavior of the load can be found as a voltage to current transfer which then gives an effective admittance for the diode rectifier loads. This can be used to solve for the interaction of the rectifier with the AC system and any power conditioner.

The frequency and sequence coupling behavior of the single-phase and three-phase rectifier respectively indicates that the behavior of both these devices is first order. That is to say that the frequencies or sequences that arise in both cases are dependent on the first multiple of the applied frequency only. These first multiple terms are typically called first order. As the size of first order effects is directly proportional to the magnitude of the applied perturbing signal the rectifier can be modeled using a constant transfer. The authors have completed such an analysis which has proved to be an extremely accurate match for the measured response of diode rectifiers [7].

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