OPERATING THE CALIFORNIA INSTRUMENTS MX-45-3Pi IN DYNAMIC SOURCE/LOAD MODE WITH BI-DIRECTIONAL POWER FLOW

Introduction

When using a programmable AC source to supply power to electric motors or other reactive loads, it is not uncommon to have situations where power flow reverses. In some cases, this can be a short lived or transient event, such as when an electric motor is shut down. In other cases, it can be a continuous type operation with power flow into the unit under test for part of the 50/60 Hz cycle, while the UUT supplies power back to the AC source for another part of the cycle.

These bi-directional power flow situations are especially common in modern power drive systems, with either AC or DC motors. Examples are plentiful, with brake energy being returned to the "DC bus" in hybrid automobiles, or lightly loaded AC motors reversing power flow during part of the half cycle. With AC systems, one generally speaks about 4 quadrant operation, while DC systems are generally limited to just 2 quadrants. To characterize the behavior of the MX45-3Pi AC power source under these conditions, a series of tests were performed which are described in this article.

Basic test setup and power source configuration

Even though some of the technical details are complex, the basic structure of a 3 phase programmable AC power source is not so difficult to explain. The figure below shows the general architecture. In principle, the 3 phase input power is rectified and controlled – via an active PFC circuit – to provide the "plus" and "minus" DC bus voltages. These DC buses are used to generate the desired output waveforms and frequency. Normally, the programmed output voltage will be a sine wave, such as 120 V – 60 Hz, 230 V – 50 Hz etc. It is also possible however, to produce a DC voltage, or simulate various distortions and voltage interruptions that occur on the low voltage distribution network. The arbitrary waveform generator can produce virtually any waveform that the user requires, within the resolution and bandwidth limitations of the power amplifier.

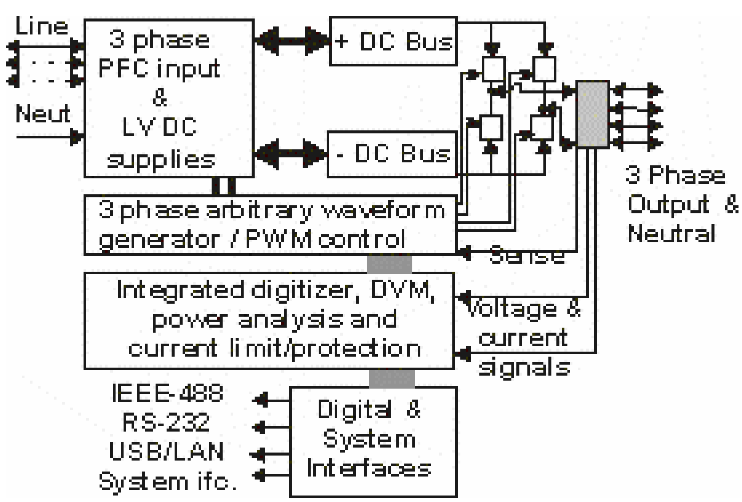


Fig. 1 Basic structure of a modern programmable AC power source, with integrated digitizer/analyzer

Note that the input section, the DC buses, as well as the output section are all bi-directional. In other words, the power source can supply power to a unit that is connected to the output, but it can also absorb power coming back from the unit under test. This return power can, in turn, be supplied back into the “low voltage grid” via the active PFC front end of the programmable AC source.

To test the bi-directional power flow capability of the AC source, two identical MX45-3Pi units were connected via programmable loads in Phase-A and B, and a high power carbon stack resistor, as shown in Figure 2. A fast circuit breaker (42 amp rms) was installed in-line for protection purposes. This circuit breaker is not shown in the figure in order to keep the illustration simple.

In addition to the interconnections and the loads, various digital voltmeters, a power analyzer, and an oscilloscope were used to observe/measure the voltages, currents, and power flow. These measurement instruments are not shown in Fig. 2 for clarity purposes, but they are repeatedly shown in several of the pictures showing the test data etc. Fig. 3 shows the actual units in the laboratory.

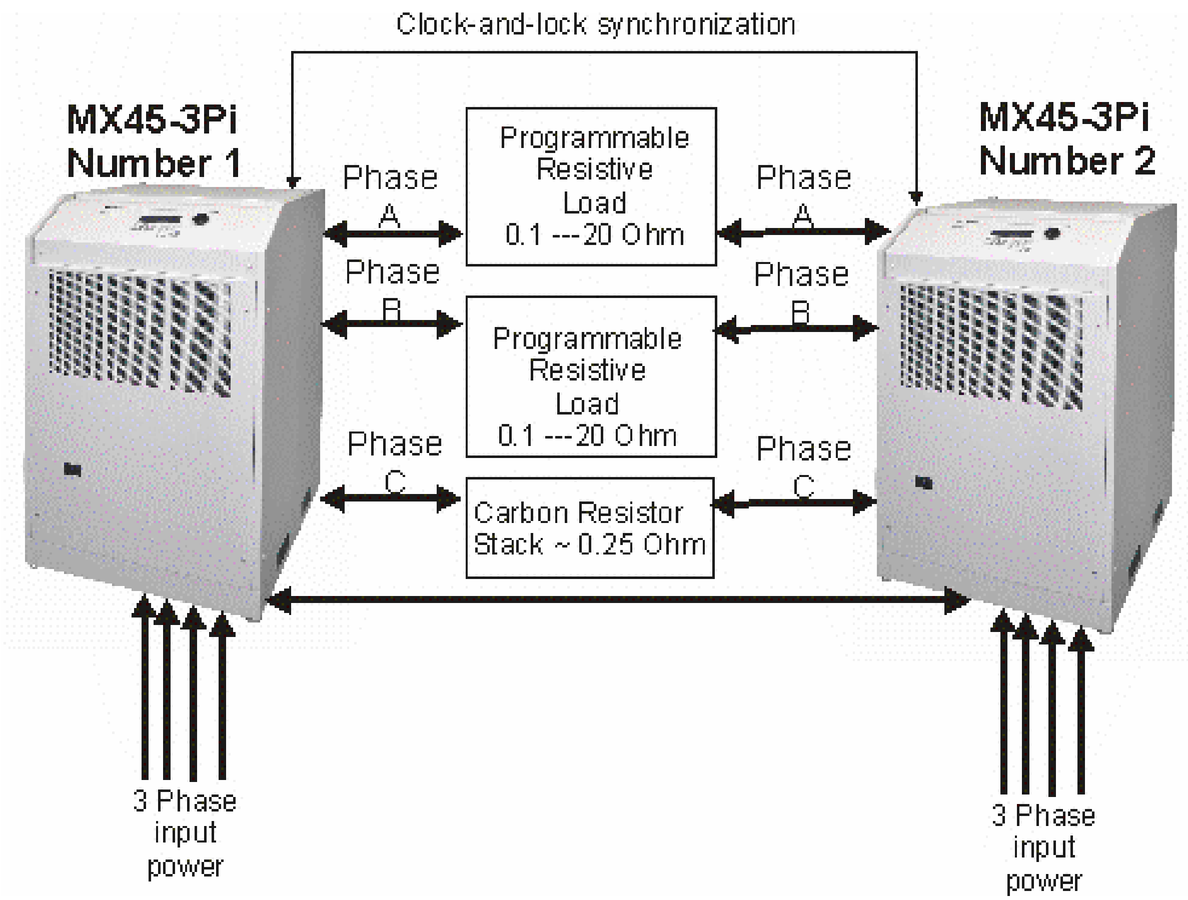


Fig. 2 Test setup with 2 ea. MX45-3Pi power sources – interconnected through loads

With the two MX45-3Pi units interconnected as shown, a series of tests were performed with different voltages, load levels, and with a phase differential programmed between source number 1 and 2. Via the “clock-and-lock” interface, the two power sources can be synchronized (MX45 number 2 is programmed to have its frequency reference set to “External”). Thus, the two units are synchronized, i.e. have the same phase (for all 3 phases). The tests were generally run at a nominal voltage level of 230 Volt – 50 Hz, simulating the European low voltage levels, but some tests at 120 Volt – 60 Hz were run as well. Initially, both units were set to the same voltage, and thus the current flow between the two units is very small, and basically determined by the small differences in amplifier response and the interconnect impedance.

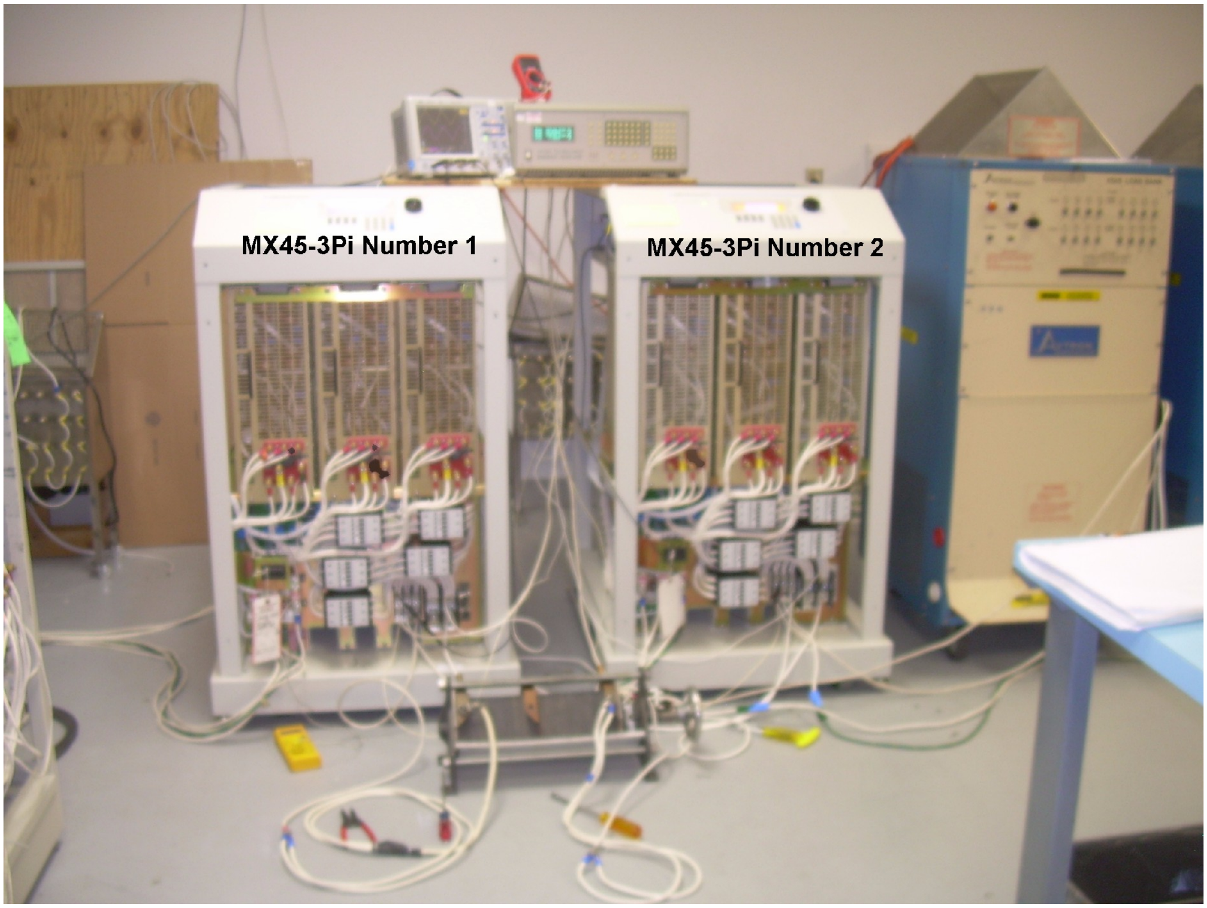


Fig. 3 The two MX45-3Pi units with front panels removed. One of the programmable loads is visible on the right, and the carbon stack resistor is on the floor in the foreground.

The MX45 itself has a very low output impedance, in the order of a few milli-Ohms and the output inductance is approximately 40 micro-Henry in the 300 Volt AC range while it is only 10 micro-Henry in the 150 Volt range.

Description and results of the tests

Initially, MX45-3Pi number 2 (right hand side unit) was operated as the "supply" while MX45-3Pi number 1 was operated as the "load" – in conjunction with the interconnect load resistance. For these tests, MX45 no. 2 was kept at 230 Volt, while the voltage of MX45 no. 1 was lowered. In addition, the interconnect load values were changed to simulate different test objects (motor or UPS size etc.). As the load resistance values were lowered, the current flow from one MX45 into the other increased. For example, with one MX45 set to 230 Volt, the other set to 225 Volt, and the interconnect load set to 0.1 Ω, one MX power source "delivered" a net output level of 8.1 kWatt for Phase–A while the other "received" 7.9 kWatt and delivered this back (less internal losses) into the mains supply. Thus, the net consumption from the mains supply was in fact just the 0.2 kWatt dissipated in the 0.1 Ohm load, plus the internal consumption (for control circuitry and switching losses) of the two MX units.

Table 1 below shows some of the recorded voltage and load settings, and their associated power flow. For simplicity purposes, the readings for just one phase (Phase-A) are displayed. In 3 phase mode, with the two programmable loads set to 0.2 Ohm, and the carbon resistor stack at approximately 0.25 Ohm, the "received' power in MX45-3Pi no. 1 was about 21 kW (7.5 kW ea. in Phase-A and B, and 6.2 kW in Phase C). This is almost 50 % of the rated power the MX45-3Pi can deliver. Since the range of the current readings had to accommodate current in excess of 40 amp rms, the low power readings are shown as approximate. The uncertainty of the current readings was at least 0.05 amp rms and thus the power reading uncertainty was at least +/- 10 Watt.

MX45 no.1 Voltage	MX45 no.2 Voltage	Phase of MX45 no. 2 relative to MX45 no. 1 (Deg)	MX45 -no.1 Power absorbed	MX45 – no.2 Power delivered	Load value (Ohms)
230.0	230.0	0	~ 55 W	~ 60 W	0.2
230.0	230.0	0	~ 120 W	~ 110 W	0.1
225.0	230.0	0	1.95 kW	2.09 kW	0.5
225.0	230.0	0	2.44 kW	2.61 kW	0.4
225.0	230.0	0	3.10 kW	3.33 kW	0.3
225.0	230.0	0	4.43 kW	4.77 kW	0.2
225.0	230.0	0	7.60 kW	8.13 kW	0.1
222.0	230.0	0	7.50 kW @ 33 amp	8.10 kW @ 33 amp	0.2
219.8	228.0	0	7.7 kW	8.1 kW	0.2
220.0	230.0	0	10.1 kW	10.7 kW	0.2
230.0	225.0	0	8.10 kW	7.55 kW	0.1
230.0	230.0	1.3 degrees	0.43 kW @ 40 amp	0.25 kW @ 40 amp	0.1

Table-1 Voltage levels for both power sources, and delivered/absorbed power

The last line in the table is for the condition where both power sources are set to 230 V-rms, but the phase angle of the voltage of MX45-3Pi no. 2 is shifted. The phase shift was gradually increased (in 0.1 degree steps) until the maximum current – permitted by the circuit breaker – was achieved. Note that with both power sources set to 230 Volt rms, and the current at 40 amp rms, the apparent power level is about 9.2 kW, but the real power is just a couple hundred Watt. This is of course due to the fact that both power sources alternatively supply and absorb power in successive 10 ms half cycles.

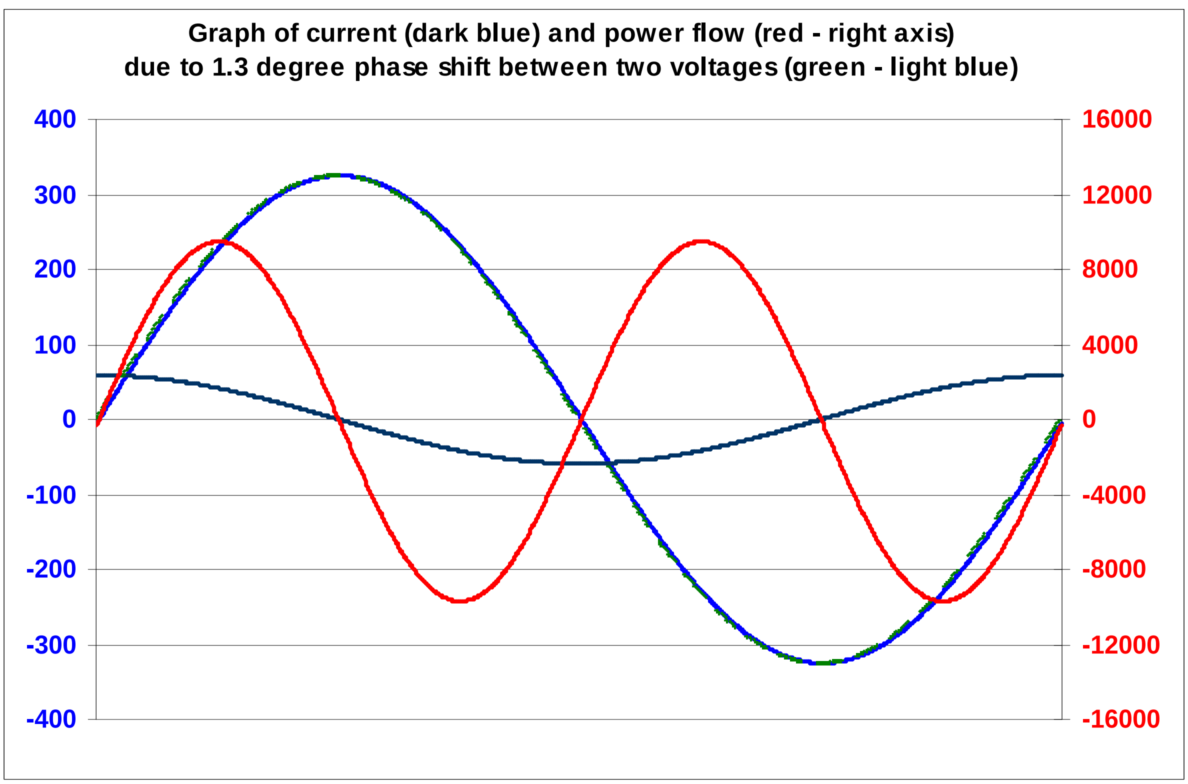


Fig. 4 Alternating positive and negative power flow (red line) due to a 1.3 degree phase shift between two voltage @ 230 V, with a load of 0.1 Ohm between the two power sources.

This power flow is illustrated in Fig. 4 on the previous page and the picture (Fig. 5) below. At about 90 and 270 degrees of the voltage waveforms, the delta between the two instantaneous voltage levels is very small, and thus the current flow is very small, and actually crosses ‘0’ near these points. At “0” and 180 degrees, the 1.3 degree shift results in a substantial delta between the voltage of MX45 no.1 and MX45 no.2, of about 7 volt around the zero crossing. This yields an instantaneous current of almost 60 amp through the 0.125 Ω load (0.1 Ω plus about 50 mΩ in wiring plus circuit breaker) at these points on the waveform. Thus, the net result of the 1.3 degree phase shift between the voltages, is a current phase shift of about 90 degrees , and consequently very little real power is being delivered, while the apparent power is about 9 kVA.

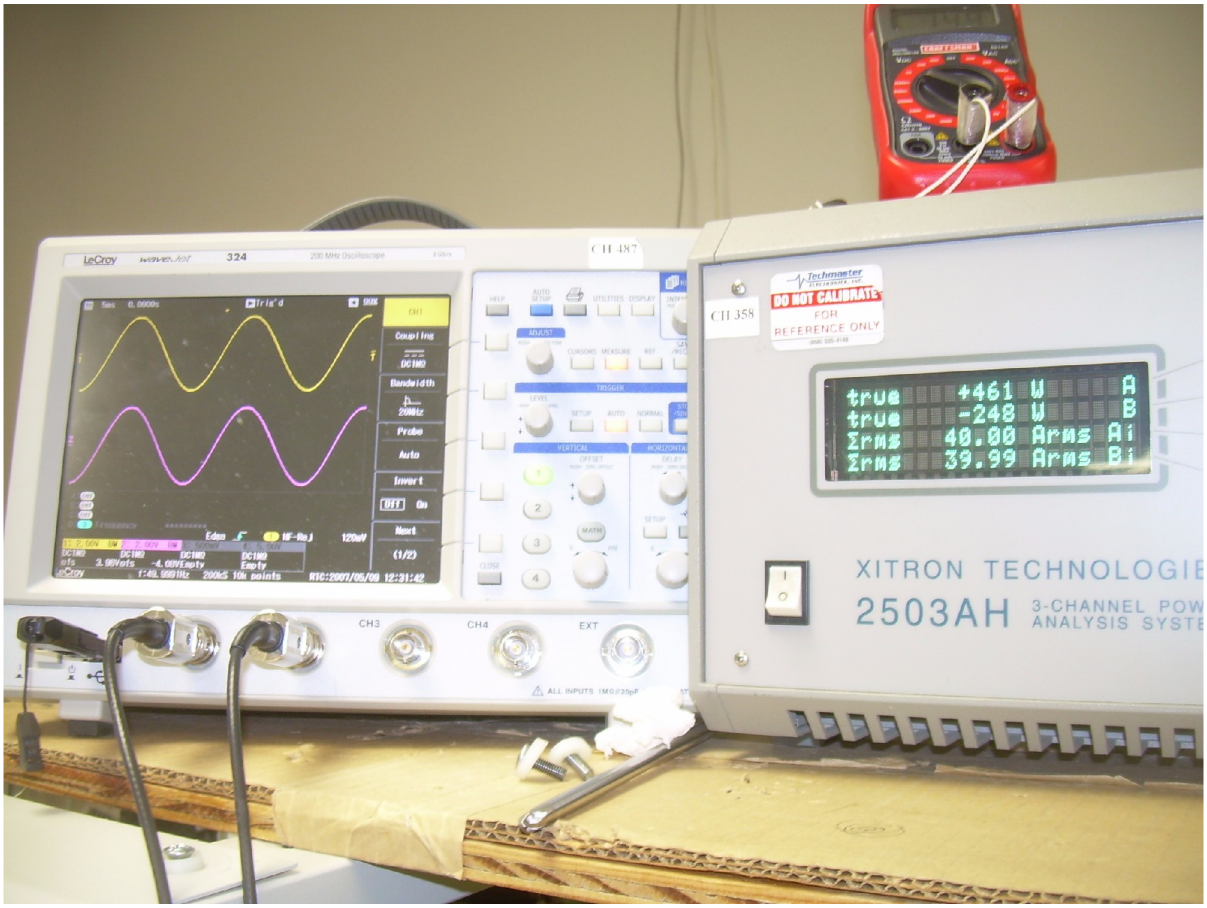


Fig. 5 40 amp rms current @ 230 V-rms and minimal real power flow readings due to 1.3 degree phase shift between the two MX 45 units. The two voltage waveforms are shown as well.

So, in this condition, with both power sources at 230.0 Volt rms, and about 40 amp rms flowing back and forth between the two power sources, there is very little real power “consumed”. The total power consumption consists of the losses in the 0.1 Ohm load – due to the 40 amp rms flowing back and forth – and the internal losses in the two power sources, which have to “transport” the apparent power back-and-forth through the two MX units into (and out of) the mains supply. As will be easy to understand, one can control the apparent power – and the current level - by varying the phase angle (the MX45-3Pi has 0.1 degree resolution) because the phase angle determines the voltage difference, which in turn determines the current flow through the load. This phase-shifted operational mode differs substantially from the mode with both units synchronous, and “zero” phase shift. At “zero” phase shift, the current flow is still determined by the delta in voltage level between the two units. When there is a voltage difference, there is current and real power flow. The losses in the resistive load are simply determined by the current level, as is the case with the current flow due to the phase shift between the voltages. When the two voltages are “in phase” but have a slightly different level, such as 230 V-rms and 225 V-rms, the resulting current flow is in phase with the voltages, and thus there is real power flow.

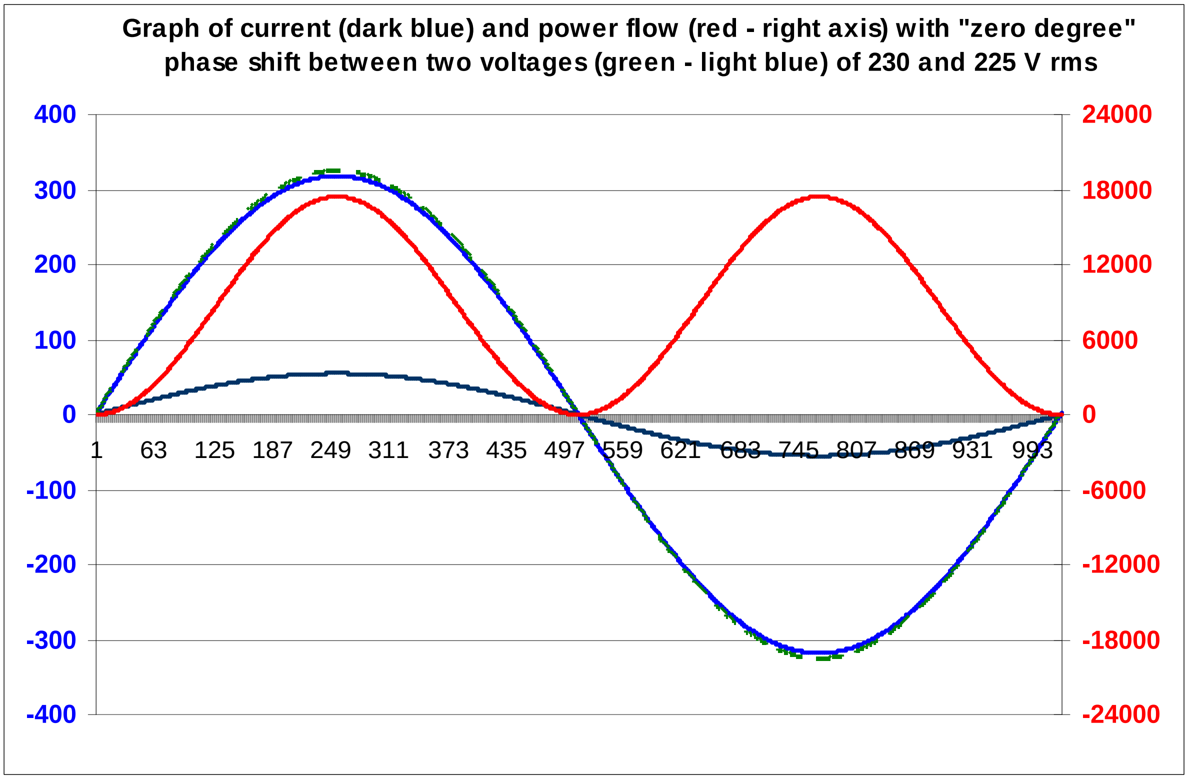
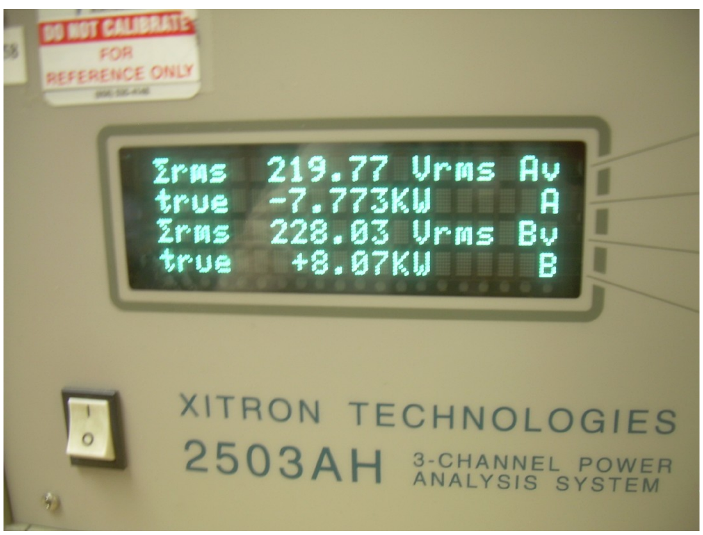


Fig. 6 Power flow when the two MX45-3Pi units are "in phase" but have different voltage levels.

This is illustrated in the above Fig. 6. Given that the two MX45-3Pi power sources are connected in series, it will be clear that one MX45 power source delivers the power, while the other absorbs and transfers the power level to the mains supply (less the loss in the 0.125 Ohm load). It should be noted that the 40 µH inductance of the MX45-3Pi – in the 300 Volt range – has negligible effects on any of the foregoing tests, as this 40 µH only represents about 12.6 µΩ at 50 Hz. Given the 100 µΩ resistive part, plus the wiring impedance and the circuit breaker of say 40 – 50 µΩ, the inductance affects the complex impedance vector by just 1 - 2 µΩ and thus there is virtually no phase shift, no resonance, and consequently no impact of such small inductance values.



When the voltages are in phase, the current flow is primarily determined by the delta between the two voltage settings, and is almost independent of the absolute voltage level of the MX45 units. This is illustrated by the two lines in Table -1, showing that the delta of 8 volt results in about the same power levels. The first line to be considered shows the current of 33 amp – rms, due to the 8 volt differential between the two sources. The following line shows the lower absolute voltages, but still the differential of 8 Volt-rms. Consequently, the current through the load is still 33 amp rms (the 0.2 Ω load plus the wiring and circuit breaker are about 0.24 Ω).

This is illustrated in the above Fig. 7, which shows the power analyzer reading with MX45-3Pi no.1 (channel A) having negative power (i.e. absorbing power) while MX45 no. 2 delivers (positive) power.

The maximum current permitted by the circuit breaker was 42 amp rms, and this current is reached at a voltage differential of about 10.5 Volt (load set to 0.2 Ω and thus a total series impedance of between 0.24 – 0.25 Ω). Fig. 8 below illustrates this test, for which MX45-3Pi no.1 was set to deliver power, while MX45-3Pi no. 2 was the “load”. The voltages for both units remained sinusoidal. The current waveforms are not shown, but they were observed to have distortion around the zero crossing, which is easy to understand. Since the MX units are of the switch mode design, they have a “dead zone” around the zero crossing, where no current flow takes place.

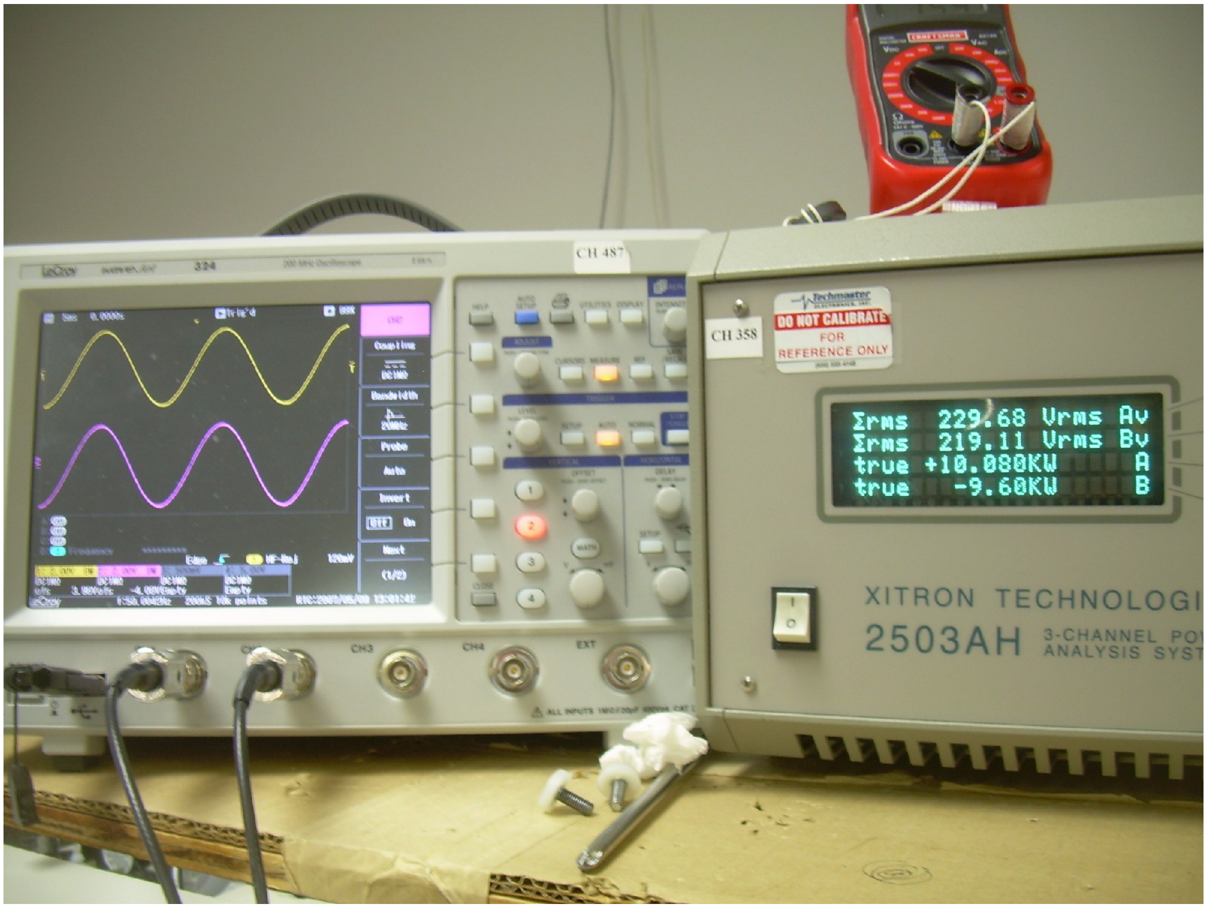


Fig. 8 showing the voltage waveforms and power flow from MX45-3Pi no.1 into MX45-3Pi no.2 with a voltage differential of 10.5 volt.

In order to evaluate the behavior of the MX units, when their maximum current level is exceeded, the current limit was programmed to 25 amp rms max. (to stay under the 42 amp circuit breaker level). Subsequently, the voltage on one of the units was lowered until the 25 amp was exceeded. This caused the “low voltage unit” to fold back its voltage, and consequently the current remains high, and causes the “high voltage unit” to fold back as well. Thus, if one of the two MX units has a voltage delta (or phase shift) that causes the maximum permitted current to be exceeded, one of the two units will fold back. If the unit starting to fold back happens to be the one with the lowest voltage, the resulting behavior is not a reduction in current which would normally result if the unit “supplies power”.

Thus, one cannot “start” with an overload (current) condition and then slowly increase the output voltage of the MX, as the protection circuitry will not permit the voltage to be increased, until the current level is decreased to acceptable levels.

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