TECHNIQUES FOR POWER NEGATIVE INDUCTANCE SYNTHESIS AND ITS APPLICATIONS

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Abstract – **This article presents some methods for generating power negative inductance, as well as possible applications, and the resulting circuits stability analysis. Such non-natural behavior is analyzed based on mathematical modeling, circuit simulations and experimental results. Previously synthesis methods, VAPAR and BVI are briefly described, and another strategy, the Direct Reactance Synthesis (DRS) is introduced. The DRS method is useful when the negative inductance is connected in series to an electrical circuit. All the methods use a DC-AC switching converter for synthesizing the necessary voltage. The applications include displacement factor correction, voltage regulation and transmission line compensation.**

KEYWORDS

Negative Inductance, Reactive power compensation, Power factor compensation.

I. INTRODUCTION

DC-AC converters with PWM (Pulse Width Modulation) techniques can produce any current or voltage waveform. In applications like active power filters and inverters for uninterruptible power supplies and AC motors drive, the control strategy determines a reference signal for the PWM modulator. The fidelity of the resulting signal depends on the power switches switching frequency and low-pass output filter response, which determines the output signal spectrum.
This article presents the use of a VSI for synthesizing a voltage, whose waveform is proportional to the derivative of the current through its terminals, characterizing an inductive behavior. It is presented and discussed the synthesis of negative inductance, showing the advantages if compared with capacitive compensations for some typical applications.

II. SYNTHESIS OF NEGATIVE INDUCTANCE

The literature shows different approaches for synthesizing the behavior of passive dipoles using DC-to-AC converters. The VAPAR (Variable Active-Passive Reactance) [1] was initially presented as an alternative for synthesizing high value inductances and capacitances with advantages respect to real components (inductors and capacitors). Afterwards it was identified the possibility of produce non-natural dipoles, as a negative inductance [2], or coupled inductances with negative coupling factor [3].
The VAPAR basic operation is shown in figure 1. It produces a current that follows the integral of the terminal voltage (for an inductance synthesis). Since it is used a VSI, it is necessary to work in closed loop in order to produce the desired current waveform. In figure 1 a proportional regulator is used to process the current error.
Another strategy is the Bootstrap Variable Inductance (BVI) [4]. As shown in figure 2, the objective is to control the voltage applied to the one of the terminals of a known dipole. The controlled voltage reproduces the same waveforms of the voltage on the other terminal with a gain G. If G is zero the dipole reflected to the rest of the circuit is the proper model component, in this example, the inductor L_a. If G=1, no current flows through the device, reflecting an infinity inductance to the circuit. When G>1 there is an inversion in the current sense, what means, from the rest of the circuit point of view, that the device works as a negative inductance. Controlling the gain G it is possible to vary the inductance value since a minimum positive (L_a), increase its value up to the infinity and then, inverting the signal, reduce it up to the limit given by the amplifier voltage. In practice, for power applications, the amplifier is a PWM inverter.
The natural use of such device is in shunt applications [5]. Series applications are not convenient due to the impossibility of reducing the value bellow a minimum.
A low-pass filter is necessary at the inverter output or in the reference signal path, in order to avoid that the switching noise produced by the inverter affects the generated voltage.

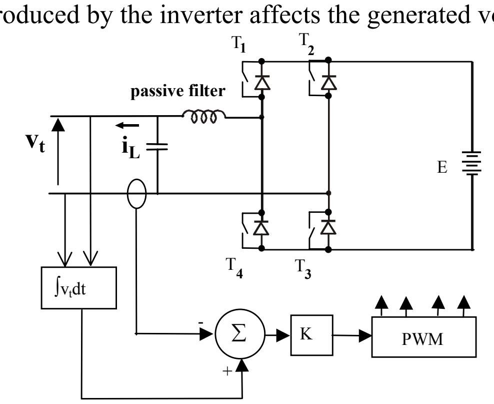


Fig. 1. VAPAR basic circuit.

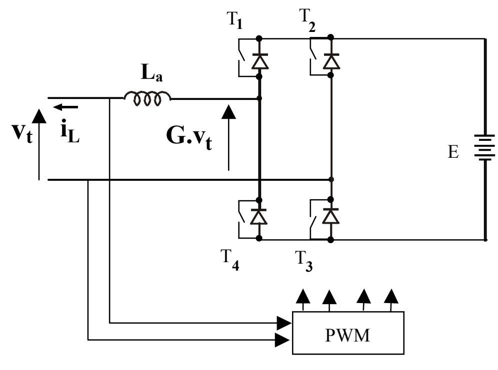


Fig. 2. BVI basic circuit.

If at the DC side of the inverter there is a power source, the VAPAR and the BVI can deliver real power to the circuit. The circuits can operate with only a capacitor at the DC link since the converter process only reactive power. In fact, due to the inverter losses, it is necessary to absorb some amount of real power in order to maintain constant DC voltage. This can be done, for example, adjusting the phase of the synthesized voltage.

1) *Direct Reactance Synthesis*

The method presented in this article is the Direct Reactance Synthesis (DRS). This strategy solves the dipole differential equation in order to obtain the reference signal for the PWM inverter. Using a VSI, an inductance is obtained measuring the current at the inverter output (after the low-pass filter) and producing a voltage proportional to its derivative. The value can be chosen, from zero to a maximum, adjusting the PWM modulation index. To obtain a negative inductance, it is only necessary to change the polarity of the reference. The basic topology is shown in figure 3.

The DRS also works in open loop if synthesizing a voltage using a VSI, which is the case of inductance synthesis. As a voltage source, its natural application is in series. For shunt applications it needs a current feedback and, in practice, behaves like the VAPAR.

For synthesizing a capacitance it would be necessary to measure the voltage and produce the current. This can be done in open loop only if using a current source inverter.

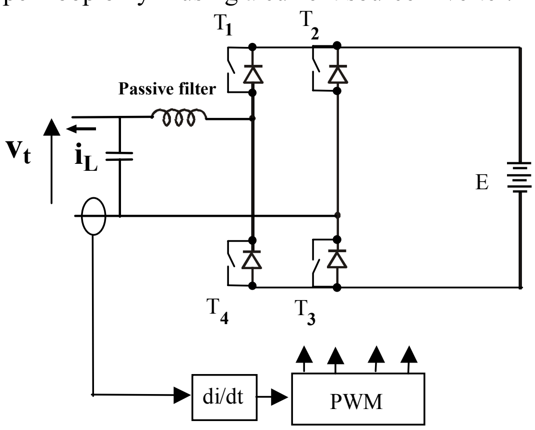


Fig. 3. DRS basic circuit.

The derivative operation necessary to the inductance synthesis asks for filters in order to reduce the high-frequency current components, especially that produced by the switching.

At the DC link it is possible to have a power source or a simple capacitor. In the first case the device can deliver real power. In the second one, it is necessary to absorb a small amount of real power from the circuit in order to regulate the DC voltage.

Three-phase converters for all the mentioned topologies are easily obtained using three-phase inverters for balanced signals. If unbalanced reactances must be produced it is necessary to use single-phase converters, or a four-leg inverter.

For medium or high power applications, the power switches available limits the switching frequency to a few kHz, making more restrictive the passive filter design.

For effectively attenuate the switching components, it is necessary to use a high order filter. A good design, that maximizes the bandwidth, will result in a resonance around 1/5 of the switching frequency [6] that must be adequately damped. Passive damping is viable only in low-power applications due to the losses. For medium or high power applications it is necessary to provide some active strategy to damp the filter response.

Such design considerations will not be discussed further in this article, whose goal is to present the DRS method, to study some circuit stability problems and to expose some typical applications.

III. APPLICATIONS OF THE NEGATIVE INDUCTANCE

The applications shown in the sequence do not intend to be complete, but only to indicate some situations in which the use of a negative inductance can be advantageous if compared with the traditional solution based on capacitors.

In fact, in sinusoidal steady state a capacitance and a negative inductance present the same waveforms. However in transients their behaviors are completely different.

1) *Displacement Factor Correction*

The figure 4 shows a sinusoidal source feeding a resistive-inductive parallel load. The full compensation of the power factor, which in this case coincides with the displacement factor, asks for a reactive power source to supply the inductive part of the load.

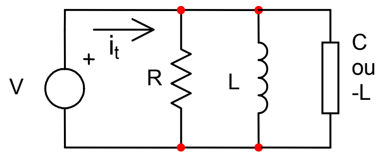


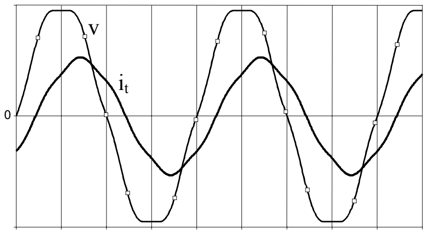
Fig. 4. Displacement factor correction circuit.

For a 30 mH inductance it is necessary to use a 234 μF capacitor (at 60 Hz). Alternatively the same result would be obtained with a –30 mH inductance.

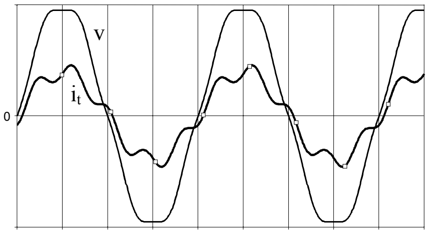
Very different results would be got if the source presents harmonic distortion, as shown in figure 5.a. In the first case, without compensation, current and voltage were displaced. It is possible to use a capacitor to correct the first harmonic displacement factor, as shown in fig. 5.b. However there is an amplification of the voltage harmonics because the capacitive reactance decreases with the frequency increase.

Using a negative inductance the displacement factor becomes unitary, and also the power factor. There is a complete cancellation of the inductance effect, as shown in figure 5.c.

As it is clear, these devices for negative inductance synthesis are not able to compensate for the distortions produced by non-linear loads, what is done by the power active filters. Consequently, the applications should focus in low-distortion systems, what normally happens in the distribution level, or even in higher voltage.



a)



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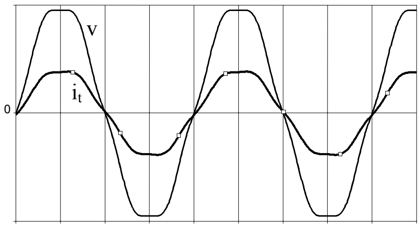

c)

Fig. 5. Voltage and current waveforms for displacement factor compensation: a) Without compensation; b) Capacitive compensation; c) Negative inductance compensation. R=10Ω, L=30mH C=234μF.

2) *Voltage Regulation*

Figure 6 shows a sinusoidal source in series with a RL circuit, which represents the Thevenin equivalent internal source impedance. Shunt compensation can be used for compensating the voltage drop associated with the source regulation, as shown in figure 7. After a load demand increment, there would be a voltage reduction at the point of common coupling (PCC). The converter control circuit (using a PI regulator) detects such voltage decrease and adjusts the synthesized inductance in order to stabilize the voltage. In this simulation, the synthesized inductance varies from a positive to a negative value, as can be noticed by the current and voltage phase displacement shown in figure 7.

Figure 8 shows the different behavior between a capacitive and an inductive (negative) compensation if a voltage step is applied by the source in the circuit of figure 6. In the capacitive case the resonance between the capacitor and the source impedance produces the ringing, while with the negative inductance, as the circuit maintains its first order behavior, there is no oscillation.

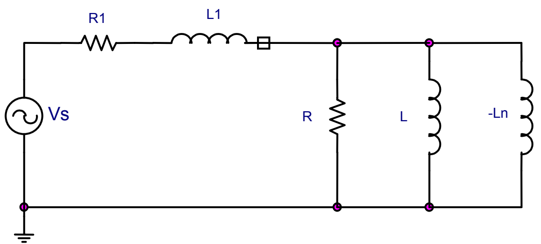

Fig. 6. Circuit for voltage regulation analysis.

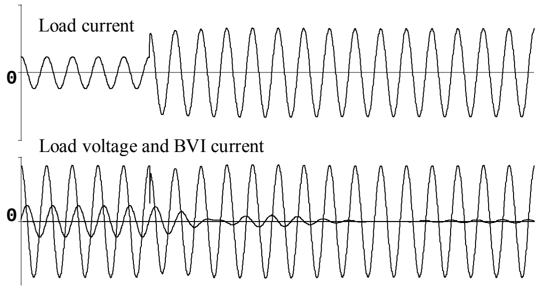

Fig. 7. Voltage regulation by negative inductance.

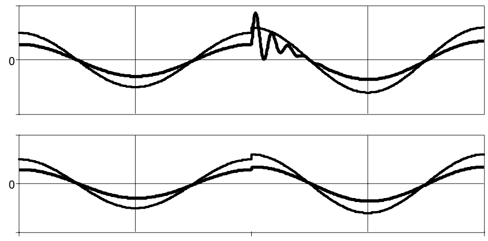

Fig. 8. Response to a voltage step: Top: capacitive compensation. Bottom: negative inductance compensation.

3) *Series compensation of a transmission line*

Figure 9 shows a circuit in which the series impedance between both voltage sources, Vs and Vr, should be varied in order to control the power flow. A device to perform such compensation could be a DRS converter. In the simulation, both sources present the same RMS voltage but there is a 5^{o} phase difference.

This kind of compensation can be useful to adjust the phase mismatch between two transmission lines before connecting them in a ring. It could also be used for controlling the power flow simple varying the line impedance.

Figure 10 compares the responses of capacitive and negative inductance compensation. The capacitive circuit introduces oscillation in the current, which does not appear in the other situation because the system maintains its first order behavior

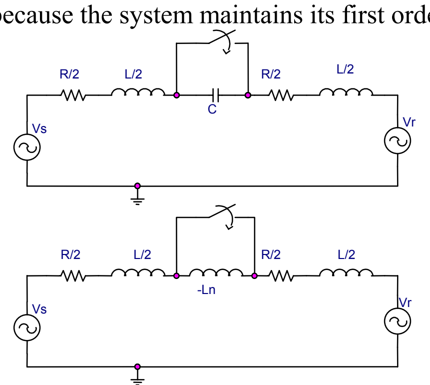

Fig. 9. Circuit for series compensation analysis.

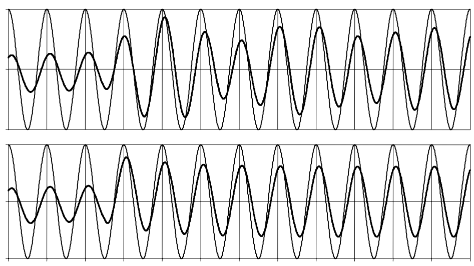

Fig. 10. Vs current and voltage waveforms for 50% line reactance reduction. Top: capacitive compensation. Bottom: negative inductance compensation.

IV. STABILITY ANALYSIS

The use of devices that present a negative inductance dynamic behavior discloses new questions for the stability of electrical circuits. This section will study the stability of some simple circuits. Notice that the stability analysis does not refer to operation of the converters but exclusively considers the presence of a negative inductance in an electrical circuit.

The following analysis is based on the system transfer function or characteristic equation, studying the behavior of its roots. The presence of a negative root in the characteristic equation indicates the system instability.

1) *Series connection*

Considering the circuit shown in figure 9, and making Vr=0, the transfer function between the source current and its voltage is:

$$G(s)=\frac{I(s)}{V(s)}=\frac{1}{R+sL-sLn} \tag{1}$$

The root of the characteristic equation is:

$$s=\frac{-R}{L-Ln} \tag{2}$$

that will be positive is Ln>L, what means, to guarantee the stability the overall inductance in a circuit must be positive.

2) *Shunt connection with ideal source*

Consider the circuit shown in figure 4 with a negative inductance. The transfer function between the source current and its voltage is:

$$G(s)=\frac{I(s)}{V(s)}=\frac{s\{sLLn-R(L-Ln)\}}{s^2LLnR} \tag{3}$$

There is a pole and zero cancellation at s=0, remaining another pole at the origin. The zero position depends on the negative inductance value. If L>Ln this zero will be in the right half-plane, characterizing a non-minimal phase system.

In sinusoidal steady state the currents that flow through the source and the inductances (positive and negative) can present a DC level. In the positive inductance this DC component tends to zero in the presence of a series positive resistance (what normally occurs due to the wiring resistance). For the negative inductance it is necessary to provide some kind of active compensation to eliminate such DC current.

3) *Shunt compensation with non-ideal source*

Consider the circuit of figure 6. Its characteristic equation is:

$$s^3+s^2\left[R\left(\frac{1}{L}-\frac{1}{Ln}\right)+\frac{R_1+R}{L_1}\right]+s\left[\frac{RR_1}{LL_1}-\frac{RR_1}{LLn}\right]=0 \tag{4}$$

The system is stable if the negative inductance absolute value is higher than the positive inductance. Another stable situation is when the absolute value of the negative inductance is lower than the parallel association of the positive inductances. This second case normally does not present practical applications because the source series inductance is low, what results in very low negative inductances. The behavior of the root that can cause instability is shown in figure 11.

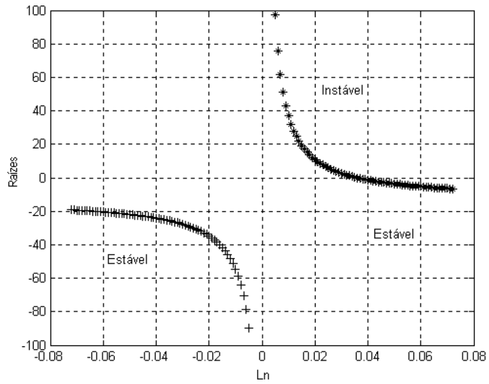

Fig. 11. Real part of eq. (4) root x Negative inductance (L_n)

4) *Parallel compensation of a RL series circuit*

Let us consider the circuit shown in figure 12. A non-ideal source feeds a RL series branch, and a negative inductance is used for compensating the displacement factor. The resulting characteristic equation is:

$$s^2+s\left[\frac{R+R_1}{L}-\frac{R_1}{Ln}\right]-\frac{RR_1}{LLn}=0 \tag{5}$$

The roots indicate that one of them always has positive real part, what means the system is unstable, independently of the negative inductance value.

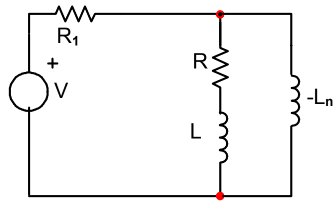

Fig. 12. Circuit with RL branch.

5) *Stabilizing effect of a negative resistance*

Doing again the previous analysis but including a negative resistance ($-R_n$) in series with the negative inductance, the characteristic equation becomes:

$$s^2+s\left[\frac{R_n-R_1}{L_n}+\frac{R+R_1}{L}\right]+\frac{R_n(R+R_1)-RR_1}{LL_n}=0 \tag{6}$$

The system becomes stable for any value of negative inductance since the negative resistance is higher than the parallel association of R and R_1, as shown in figure 13, in which the value of both roots are plotted for different R_n values. The existence of a negative resistance additionally allows canceling the DC current term, as presented earlier, following a time constant of $-L_n/-R_n$.

The inclusion of a negative resistance in series with the negative inductance expands the stability range of all the circuits in which the L_n is shunt connected. In such cases it is possible to get overcompensation, what means, the current through the negative inductance can be higher than the current through the branch with the positive inductance. The resulting source current will be in advance respect its voltage. From another point of view, a negative resistance is equivalent to delivering real power to the system. In this case it is necessary to have a power supply at the inverter DC side.

Many other circuits could be analyzed. Nevertheless, by reducing more complex topologies to the equivalent Thèvenin circuit, the presented results describe the more important properties of the circuits with negative inductance. Additionally, if the converter uses some closed loop control strategy, the overall stability must be checked.

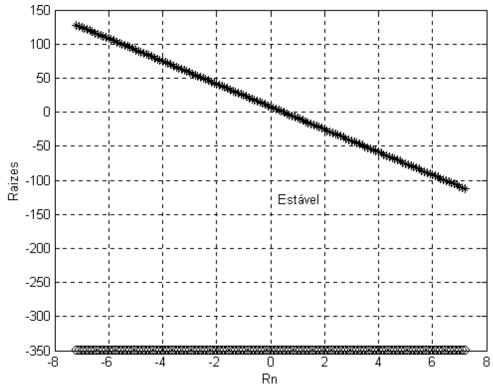

Fig. 13. Equation (6) roots (real part) x negative resistance (R_n).

V. EXPERIMENTAL RESULTS

In order to verify the BVI and DRS devices, an experimental setup was built, using the DSP ADMC401, to make the measurements, calculations and power circuit driving.

The signals are measured by Hall sensors and applied to the AD DSP inputs. There is an digital filter, whose cutoff frequency is 1 kHz.

The results were obtained in low voltage with the objective of verifying if the converters and the respective control strategies are able to realize a negative inductance. The inverter switching frequency is 10 kHz.

Figure 14 shows the displacement factor compensation of a circuit as the displayed in figure 4 (R=11Ω, L=36mH). The BVI current is leading the reference voltage, characterizing the negative inductance. The BVI sample inductor is 2 mH.

Figure 15 shows a similar result, but including a 5% of the 5th harmonic in the voltage source. The BVI allows obtaining unity power factor. In the presence of a voltage step the BVI is able to maintain the correct compensation.

Figure 16 shows the same situation of figure 15 but the displacement factor is correct with a capacitor (200 μF). The amplification of the voltage harmonic is clear in the resulting current, in which the 5th component is 25% of the fundamental. Also at the step voltage there is an oscillation due to the resonance between the capacitance and the source inductance (30 μH).

Figure 17 shows the PCC voltage regulation with a BVI. The circuit is the same shown in figure 6 with: R_l=0,5Ω e L_l=1mH. The PCC voltage is measured and compared with the reference. A PI regulator defines the BVI gain and, consequently, the value of the synthesized inductance, positive or negative. In this figure, initially the BVI gain is less than unity, and the inductance is positive. An additional load reduces the PCC voltage; the gain is increased up to obtain the desired voltage level. The synthesized inductance becomes negative.

For test circuit of the DRS the device is series connected with an 11Ω resistance and a 20 mH inductance. At the inverter output there is a suitable passive filter. Figure 18 shows a full compensation of the reactive part. The resulting circuit is resistive from the source point of view. Notice that the voltage reference and the generated DRS voltage are 90° lagging the current, as expected for a negative inductance.

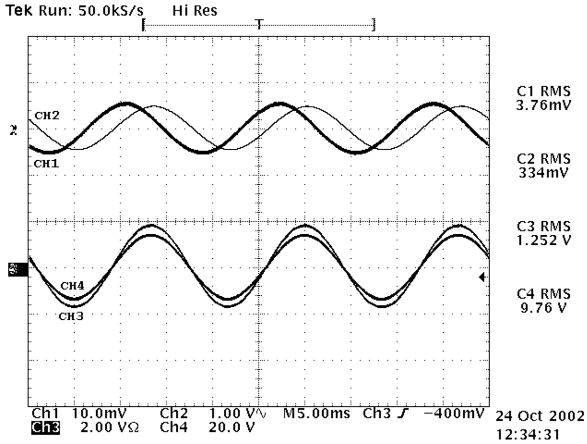

Fig. 14. Displacement factor compensation with BVI.
CH1: BVI current (2 A/div.), CH2: Reference voltage (1V/div.), CH3: Source current (2A/div.), CH4: Source voltage (20V/div.).

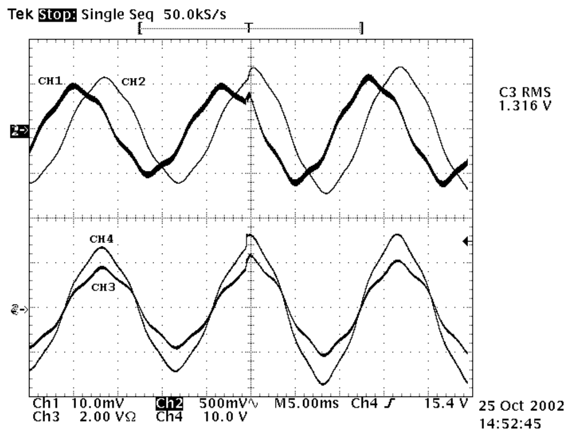

Fig. 15. Displacement factor compensation with BVI.
CH1: BVI current (2 A/div.), CH2: Voltage reference (0.5V/div.), CH3: Source current (2A/div.), CH4: Source voltage (10V/div.).

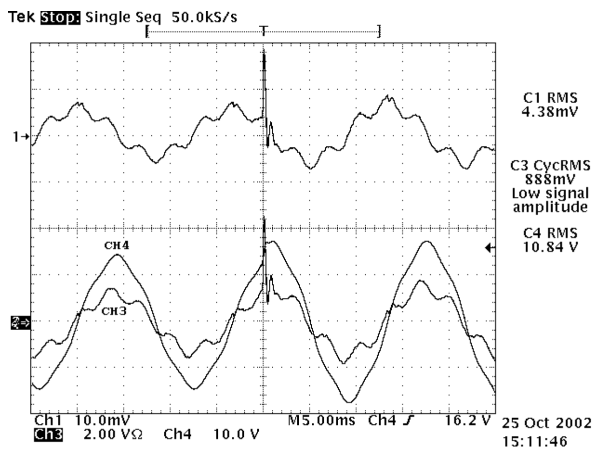

Fig. 16. Displacement factor compensation with capacitor:
CH1: Capacitor current (2 A/div.), CH3: Source current (2A/div.), CH4: Source voltage (10V/div.).

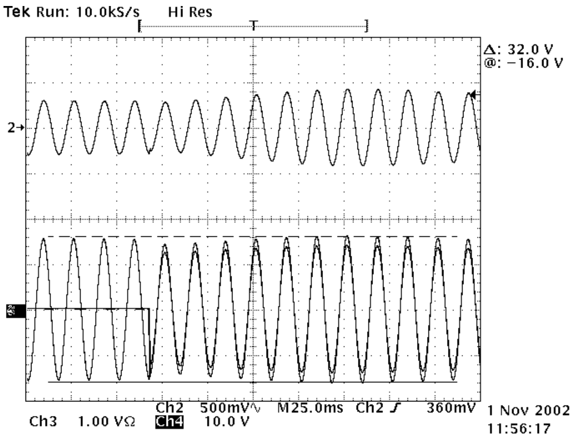

Fig. 17. Voltage regulation with BVI.
CH2: Reference voltage (0.5V/div.), CH3: Resistive branch current (1A/div.), CH4: Source voltage (10V/div.).

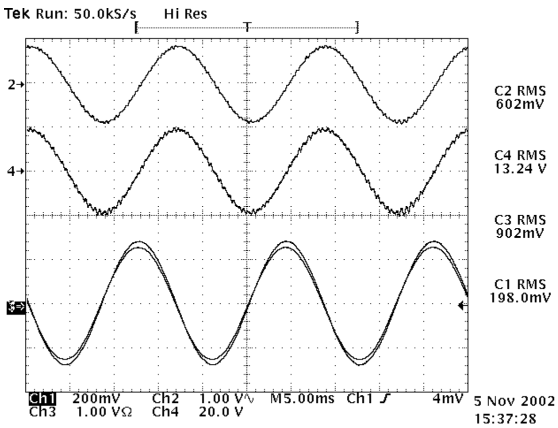

Fig. 18. Power factor compensation with SDR.
From top to bottom: CH2: Reference voltage (1V/div.), CH4: DRS voltage (20V/div.), CH3: Source current (1A/div.), CH1: Source voltage (10V/div.).

VI. CONCLUSIONS

This use of DC-to-AC PWM converters to synthesizing non-natural dipoles was presented, indicating former synthesis strategies and introducing an alternative method, the Direct Reactance Synthesis. Typical applications of the different devices were indicated, and it was shown that the Bootstrap Variable Impedance is indicated for shunt applications, as power factor compensation. For series applications the DRS is the best solution because it can produce positive or negative dipoles just controlling the reference signal. Stability analyses of the resulting circuits show that the use of a negative inductance is limited to the value of the positive inductance present at the circuit. Additionally, the stabilizing effect of a negative resistance was identified. Experimental results confirm the theoretical expectation. This approach (especially the negative inductance synthesis) can be useful for some power systems applications, as voltage regulation and power flow control. The main advantages are that the circuit order does not change (a first order circuit remains first order after compensation) and the non-real power necessity if the converter synthesizes a purely reactive device.

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