OPERATION OF THE UNIFIED POWER CONTROLLER AS HARMONIC ISOLATOR

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Abstract- The Unified Power Controller (UPC) is a tool in the implementation of Flexible AC Transmission Systems (FACTS). It provides for the equivalent of static VAr compensation and series injection using back-to-back force commutated converters. This paper proposes a control strategy to extend UPC operation to allow for the isolation of harmonics due to non-linear loads. Simulation results based on the Electromagnetic Transients Program (EMTP) are used to illustrate device performance in a power system environment. Experimental results based on a single phase laboratory implementation verify the proposed control algorithm.

INTRODUCTION

Concepts relating to Flexible AC Transmission Systems (FACTS) are gaining popularity internationally for enhancing steady state power transfer limits as well as improving power system dynamic response [1,2,3,4,5]. FACTS devices include solid state phase shifters [1,2], thyristor-controlled series capacitors [3,4] and static VAr devices [5,6]. First generation installations using phase controlled series compensators are currently being commissioned [4,14]. Recent efforts have addressed the synthesis of FACTS-controllers using converter-based topologies. The Unified Power Controller (UPC) [5,6,7] provides for the equivalent of static VAr compensation and series injection using back-to-back force-commutated converters [6,7]. With an increasing emphasis on power quality [8,12], harmonic isolation [8-11] and harmonic compensation [12,13] issues are also being investigated for high power applications [12,13].

The present paper discusses the extension of UPC operation to include not only fundamental phase shift and reactive power compensation, but to also provide for harmonic isolation in the presence of non-linear loads. This is performed using a combined harmonic/fundamental control strategy in a single converter topology. This approach allows for the optimum use of installed converter kVA with a potentially attractive cost/performance characteristic. Simulation results using the Electromagnetic Transients Program (EMTP) illustrate device performance of a 120 kVA converter implementation. This converter system is suitable for a 1.3 MVA non-linear load, implementing both fundamental phase shift and harmonic isolation. Experimental results are presented for a low power, single phase laboratory prototype. Both simulation and laboratory data show the capability of the proposed combined control approach.

Current power electronic device and micro-controller developments make this new principle already applicable to the multi-megawatt power range. Some first applications to be considered are controlling power flow and stabilizing distribution networks in the presence of harmonic generating industrial loads. Transmission system applications to be considered include the isolation of harmonic power flows and the stabilization of geographically separate power systems.

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UNIFIED POWER CONTROL CONCEPTS

Flexible AC Transmission (FACTS)

Consider power flow over an AC line, in Eq.1 and Fig.1.

$$P = \frac{V_s \cdot V_r}{X_s} \cdot \sin\delta_{rs} \tag{1}$$

The power flow depends on transmission angle, δ_{rs}, between the line-end voltages, the sending-end voltage, V_s, the receiving-end voltage, V_r, and line impedance, X_s. Currently, only limited high speed control over any one of these parameters is used. In homogeneous electromechanical power systems, the operators arrive at the required steady state power flow while maintaining voltages and angles within safe tolerable limits. These levels are well below the peak stability limits of the power system. The consequences of the lack of fast, reliable control are stability problems, power flowing through other than the intended lines, the inability to fully utilize the transmission resources to its thermal and/or economic limits, undesirable VAr flows, higher losses, bad voltage regulation, cascade tripping and long restoration times [1,2].

Figure 1 shows a representation of a phase shifter in one transmission line. This phase shifter can be realized with a high speed thyristor based converter [1,5]. With this arrangement, one can obtain substantially the same advantages as with an HVDC

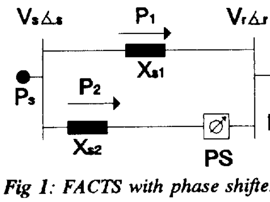


Fig 1: FACTS with phase shifter

line but at a fraction of the cost, since not all power is processed through the power electronic converter. This phase controller forms the basis of the Unified Power Controller (UPC) [5]. All the network parameters in Eq. 1 can now be controlled by means of this equivalent Unified Power Controller.

Basic Principle of UPC Operation

The basic equivalent circuit of the UPC is shown in Fig. 2. A fully controllable voltage source, V_{pq}, is injected in series with the transmission line, and a controllable shunt current source, I_q, is connected in parallel with the transmission line. The modes of operation are summarized in Fig. 2(b). For generalized series (shunt) compensation, the source I_q (V_{pq}), could be omitted if a sufficient dc energy storage device was coupled to the controlled voltage (current) source. The UPC then operates either as a converter based series compensator or static VAr compensator [6,7].

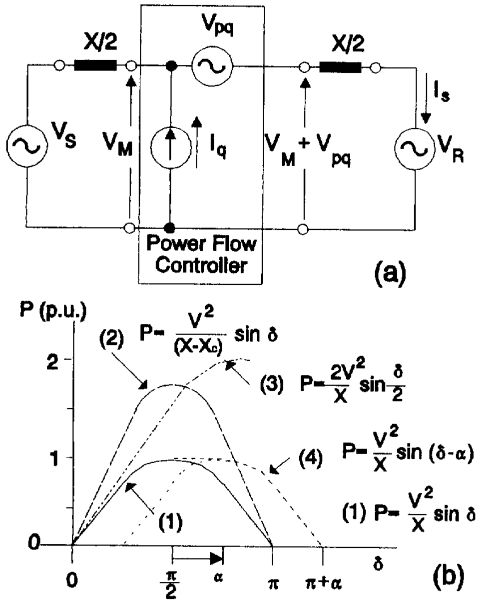


Fig 2: Equivalent circuit and operating modes of the UPC [6]

Table I: Modes of Unified Power Controller (UPC) Operation

MODES OF OPERATION	Power Controller Output	
	V_{pq}	I_q
1) No Compensation	0	0
2) Series Compensation	$-jX_c \cdot I_s$	0
3) Shunt Compensation	0	$-j4V/X(1-\cos\delta/2)$
4) Phase Shift Control	$\pm jV_M \tan\alpha$	No Reactive Current

The different UPC modes of operation are plotted in the power flow diagram, depicted in Fig. 2(b), while the appropriate values for I_q and V_{pq} are shown in Table I [6].

Multiple power flow control functions can be achieved by adding an appropriate voltage phasor V_{pq} to the terminal voltage phasor V_0 as shown in Fig. 3. Specifically, by appropriate control of phasor V_{pq}, i.e, by synthesizing V_{pq} from phasors ΔV_0 (representing voltage magnitude), V_C (representing series impedance compensation), and V_α (representing phase shift), the following power flow control functions can be accomplished [6,7]:

a) Dedicated terminal *voltage* regulation or control of ΔV_0.
b) Combined *series* line compensation V_C *and* terminal voltage control, ΔV_0.
c) Combined *angle* regulation, V_α, *and* terminal voltage control, ΔV_0.
d) Combined terminal voltage regulation ΔV_0, *and* series line compensation V_C *and* angle regulation V_α.

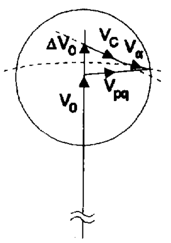


Fig 3: Multiple control modes [6]

The Unified Power Flow Controller [6,7] can control transmission line voltage, transmission angle and impedance, thus operating as a converter based SVC and Series Compensator. This implies that the UPC structure has the possibility of controlling all relevant fundamental frequency parameters of the power transmission network, as shown in Eq. 1.

OPERATION OF UPC AS HARMONIC ISOLATOR

The Unified Power Controller (UPC) can be considered as a controlled shunt current source and a series voltage source with adequate dynamic response, as is shown in the equivalent circuit of Fig. 4(a).

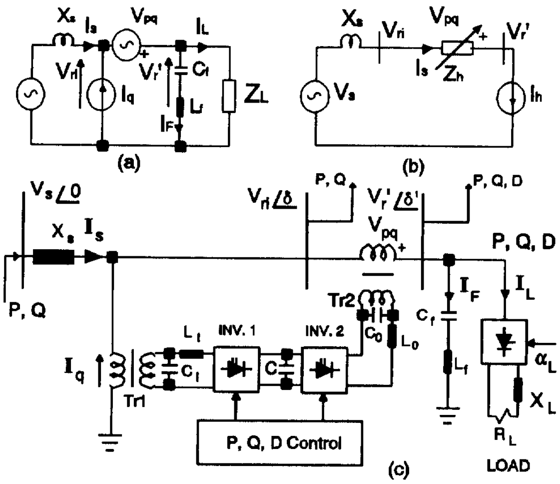


Fig 4: Unified Power Flow Controller as Harmonic Isolator.
(a) Equivalent Circuit; (b) Principle of Operation;
(c) Power Electronics Implementation

When considering the UPC as a pure harmonic isolator, no active power is flowing in the circuit, and the equivalent circuit, plotted in Fig. 4(b), is considered at the higher frequency components. Fig. 4(b) illustrates that the injected voltage, V_{pq}, is controlled to have a high impedance (Z_h) at the system harmonic frequencies, while being a short circuit at the fundamental system frequency.

As shown in Fig. 4(b), the UPC as harmonic isolator uses the same series voltage source, V_{pq}, in yet another mode. In this mode the voltage harmonics associated with the non-linear load, depicted in Fig. 4(c), are isolated. This isolating voltage source now prevents the load harmonics from penetrating back into the power system onto the voltage receiving bus, V_{ri}. This injected voltage source, V_{pq}, can also be used to isolate incoming network harmonics from penetrating to local harmonic filters and sensitive loads. At the fundamental frequency, the series impedance, Z_h, should be near to zero and only power flow is controlled.

It is proposed here that the harmonic isolation control mode can be implemented concurrently with the conventional UPC modes described previously. Figure 4(c) illustrates the power electronic implementation of the Unified Power Controller in a contaminated power system as a Unified Power Controller and a harmonic isolator using the four quadrant converter topology as proposed by Gyugyi [6,7]. Another harmonic isolating topologies may also be considered for this converter, as described by Malesani [9], and others [8,11]. Several controllers for harmonic isolators have been proposed as indicated in references [8-11]. The present paper integrates the harmonic isolator within the Unified Power Controller, without any added hardware.

The sample power system described in Fig. 4(c) consists of a standard two machine system, with a non-linear load (phase controlled rectifier) and the implemented unified controller. In this equivalent circuit the system is represented by the series voltage source, V_{pq}, the shunt current source, I_q and the non-linear load with injected current harmonics, I_h. It is now possible to control fundamental power flow in the power system as described in the previous paragraph, while isolating the harmonics with the injected voltage source. This will be possible if the converter system (Inverter 2) has an adequate dynamic response. The voltage source (Inverter 2) is controlled in the mode of a harmonic isolator, by injecting a voltage, V_{pq}. A high impedance at the harmonic frequencies is thus injected while controlling the fundamental phase shift, δ_{rs}, between sending-end voltage, V_s, and receiving-end voltage, V_r.

The power rating of the Unified Power Controller is still determined for the amount of fundamental phase shift anticipated for a given location, while the dynamic response of the converter need not to be much higher than in the regular UPC, since a high quality sinusoidal injected voltage is required in any case. When considering Fig. 2, the harmonic isolation mode can now be added as the 5 th mode. The system forms in this mode an isolating active impedance, Z_h, in series with the transmission line at the harmonic frequencies. If only harmonic isolation is performed and no cross-correlation between voltage and current harmonics exists [12,13], Table II determines the value of the series injected voltage, V_{pq}, and shunt current, I_q.

***Table II**: Extended Mode for UPC Operation*

EXTENDED MODES OF OPERATION	Power Controller Output	
	V_{pq}	I_q
5) Harmonic Isolation	$Z_h \cdot I_s$	0

SIMULATION OF UPC AS HARMONIC ISOLATOR AND DYNAMIC POWER FLOW CONTROLLER

System Parameters with Simulations

The three phase unified controller as a phase shifting controller and harmonic isolator for a non-linear load is simulated using EMTP. The three phase circuit shown in Fig. 4(c), is simulated using two 120 kVA IGBT inverters (Inv. 1 and 2) with a 1.3 MVA non-linear load. Passive harmonic filters for the 5 th, 7 th and 11 th harmonics are included on the bus V_r'. The harmonic isolator, V_{pq}, is placed in series with the transmission line to isolate the harmonic voltages produced by the non-linear load on bus V_r'. A large portion of the harmonic currents, I_h, is thus confined to the non-linear load and passive filters, C_f and L_f. It is assumed that the DC link voltage in the UPC circuit is kept constant at 400V by inverter 1. In order to simulate the circuit under the same defined conditions, the load current, I_L, filter current, I_F, and line current, I_s, are kept constant. The sending-end voltage, V_s, is also kept constant at 6.35 kV (rms). The load current is the current produced by the phase controlled rectifier circuit. A clean sinusoidal voltage at V_s is assumed on the sending-end power bus. The main parameters of the simulations are shown in Table III.

***Table III**: Main Power System Parameters*

Transm. line Ind L_s	6 mH	Load Ind. L_L	80 mH
UPC Filter Ind. L_0	50 μH	UPC Filter Cap. C_0	5mF
Trans. 2 Leakage	30 μH	Trans. 2 Wind. ratio	2.5:28
Load R_L *	15-25Ω	Load Firing Angle	82-84°

* R_L is adjusted to keep load current, I_{Ldc}, constant (83 Adc)

Case 1: Small Phase Compensation and Harmonic Isolation

No fundamental phase shift between V_{ri} and V_r' is implemented in the controller of the UPC for the first simulation case. Thus, the UPC is operating mainly as harmonic isolator. The EMTP output is plotted in Fig. 5. For this case, the power rating of the UPC (Inv. 2) is very small compared to the transmission rating. The waveform of V_{pq} still has a small fundamental component, which is included to compensate the internal leakage reactance of the injecting transformer, Tr2. The load voltage V_r before harmonic isolation (resulting from the 6 pulse load converter and network impedance X_s) exhibits the well-known distortion of 5 th, 7 th 11 th, 13 th, etc., harmonics.

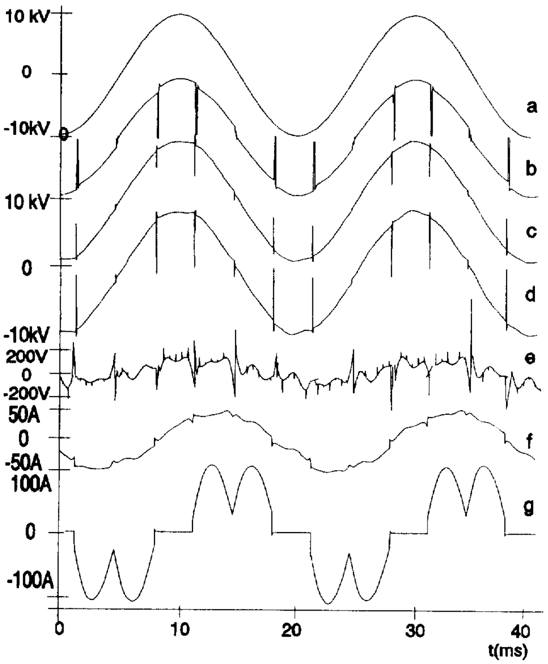


Fig 5: EMTP Simulation of UPC as Harmonic Isolator
(a) (V_s): Source Sending-end Voltage and Reference {6.35 kV}
(b) (V_r): Receiving and Load Voltages without Compensation {6.22 kV}
(c) (V_{ri}): Receiving Voltage with Harmonic Isolation {6.31 kV}
(d) (V_r'): Load Voltage with Harmonic Isolation {6.28 kV}
(e) (V_{pq}): Injected Harmonic Isolation Voltage {70 V}
(f) (I_s): Source Current through UPC and Line after Compensation {32 A}
(g) (I_L): Current through Non-linear Load {68 A}
$R_L = 25\ \Omega$; $I_{Ldc} = 83\ A$ {$R_L = 20\ \Omega$ - *Without Harm. Iso.*}

After the unified converter has injected the voltage V_{pq}, the voltage harmonics are isolated as shown in the V_{ri} waveform. The small fundamental component to cancel the leakage impedance voltage drop is clearly visible in the injected V_{pq} (Fig. 5(e)) waveform. For this case, no phase shift exists between V_{ri} and V_r'. A passive filter is also added in order to keep the power rating of the UPC small compared to the transmission system. The passive filter compensates the load current, I_L, to the transmission line current, I_s, as shown in Figs. 5(f) and (g). In the process, the load voltage is affected as shown in V_r'.

Case 2: Phase Compensation with Harmonic Isolation

Operation of the Unified Power Controller as a phase shifter and harmonic isolator is considered in Fig. 6, using EMTP. The load current is the same as in the previous simulations. The original phase shift between V_s and V_r, due to X_s, is now completely compensated by means of the injected voltage V_{pq}. The receiving-end voltage, V_r', is also controlled to be lower than in Case (i) {5.08kV v/s 6.28kV}. Energy is thus withdrawn from the transmission system through V_{pq}, and injected back by inverter 1, using I_q.

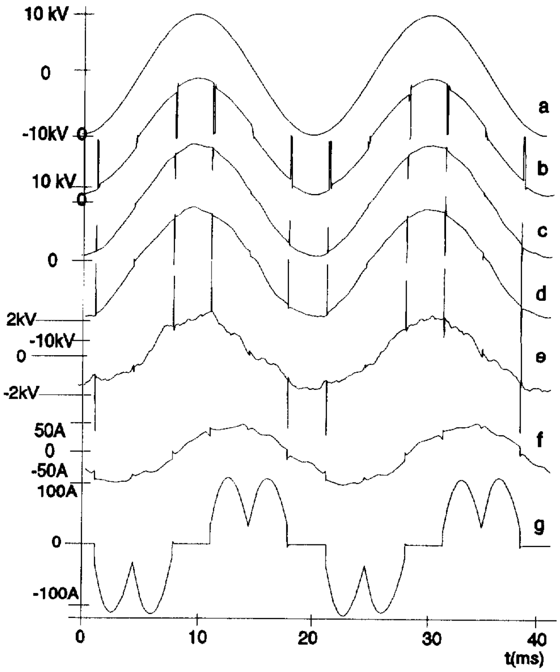


Fig 6: EMTP Simulation of UPC as Harmonic Isolator and Phase Shift Compensator
(a) (V_s): Source Sending-end Voltage and Reference {6.35 kV}
(b) (V_r): Receiving and Load Voltages without Compensation {6.22 kV}
(c) (V_{ri}): Receiving Voltage with Harmonic Isolation {6.304 kV}
(d) (V_r'): Load Voltage with Phase Shift and Harmonic Isolation {5.08kV}
(e) (V_{pq}): Injected Phase Shift and Harmonic Isolation Voltage {1.25 kV}
(f) (I_s): Source Current through UPC and Line after Compensation {32 A}
(g) (I_L): Current through Non-linear Load before Compensation {68 A}
$R_L = 15\ \Omega$; $I_{Ldc} = 83\ A$ {$R_L = 20\ \Omega$ - *Without Compensation*}

For this case, there is active and reactive power flow through the UPC. This is also evident from the large fundamental frequency voltage {1.25 kV} injected at V_{pq}. The UPC operates simultaneously in modes 2, 4 and 5.

Power Flow and Rating Calculations

When considering the power ratings of the different components in the simulation cases, the power rating of the Unified Power Controller is mainly a function of the phase shift effort required in the power flow control strategy. The power requirements for the UPC in the harmonic isolating mode is only a fraction of the total power system requirements when passive filters are also integrated. However, the minimum dynamic response of the UPC is determined by the harmonic spectrum of the load to be isolated. Table IV shows the power flows and rating requirements for inverters 1 & 2 in the different simulation cases. In case (ii) the equivalent network impedance, Z_s, has a resistive and capacitive portion, which indicates the amount of active power removed from the system at point V_{ri}, and injected back by means of I_q.

Table IV: Relative Power Calculations

Description	No Compensation	(i) Harmonic Isolation	(ii) Phase Contr. & Harm. Iso.
Load Apparent Power $[S_L]$	1.27 MVA	1.28 MVA	1.04 MVA
Load Active Power $[P_L]$	140 kW	173 kW	104 kW
Transmission Apparent Power	1.27 MVA	602 kVA	602 kVA
UPC Inv. 2 Power Rating	0	7 kVA	120 kVA (Rect.)
UPC Inv. 1 Power Rating	0	0	36 kVA (Inv.)
Passive Filters	0	770 kVA	625 kVA
Eqv. Impd. Z_s	$X_s = j1.88\ \Omega$	$X_s = j1.88\ \Omega$	$Z_s = 12\text{-}j38\ \Omega$

EXPERIMENTAL VERIFICATION

Power Electronic System for Experimental Verification

In order to evaluate the concept of harmonic isolation using a unified power controller experimentally, a small single phase experimental UPC has been developed using an IGBT inverter. The basic experimental converter system is shown in Fig. 7, and represents a portion of the system shown in Fig. 4(c).

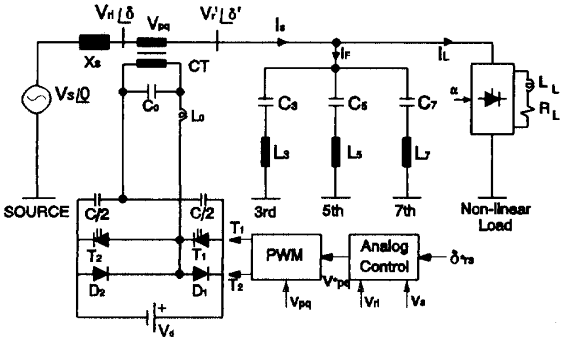


Fig 7: Simplified Circuit of UPC as Harmonic Isolator

The parameters of the experimental system are included in Table V and refer to Fig. 7 and Fig. 4(c). Only Inverter 2, reference to Fig. 4(c), is integrated using IGBT devices with associated gate-drives and controllers. The active power is directly supplied to the DC bus V_d, from a separate DC power supply. Due to the harmonic isolator topology and series transformer, a half-bridge power electronic converter implementation was adequate for this application. The IGBT inverter is rated for 100 V, 10 A. Controller inputs are the desired angle, δ_{rs}^*, and the instantaneous values of sending-end voltage, $v_s(t)$, and receiving-end voltage, $v_{ri}(t)$. The passive filters are designed as tuned harmonic traps for the 3rd, 5th and 7th current harmonics and are connected on the load voltage bus V_r'. The single phase implementation also requires a 3 rd harmonic passive filter.

Table V: Power Electronics Parameters

Transm. line Ind L_s	11.9mH	Load Ind. L_L	28 mH
UPC Filter Ind L_0	56 μH	UPC Filter Cap C_0	800 μF
Trans. 2 Leakage L_L	12 μH	Trans. 2 Turnratio	1:2.13
Nom. Load Current I_L	5 A	Nominal Voltage V_s	220 V
3rd Passive Filter	42μF 27mH	5th Passive Filter	7.1μF 57mH
7th Passive Filter	3.56μF 57mH	DC Bus V_d	50 Vdc
IGBT Current Limit	10 A	Load Firing Angle	95°
Load R_L *	10-16Ω * Adjusted to keep I_L constant		

Controller for UPC as Harmonic Isolator

A simple analog controller was implemented to derive the reference signal for $v_{pq}(t)$. The block diagram for this simple controller is shown in Fig. 8. Inputs to the controller are the angle reference δ_{rs}^*, the receiving-end voltage, $v_r(t)$, and sending-end voltage, $v_s(t)$. The control function is shown in Eq. 2.

$$v_{pq}(t) = A \cdot \sin(\omega t + \delta_{rs}) - B \cdot v_r(t) \qquad (2)$$
$$A; B \equiv Constants$$

The inner control loops shown in Fig. 8 force the reference voltage and current to the desired values.

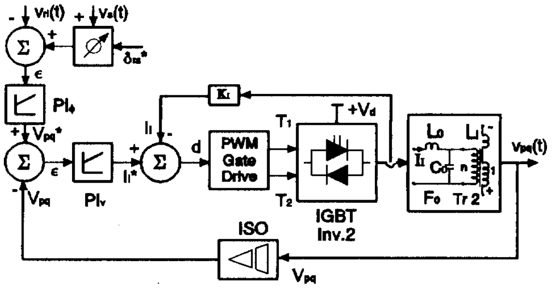
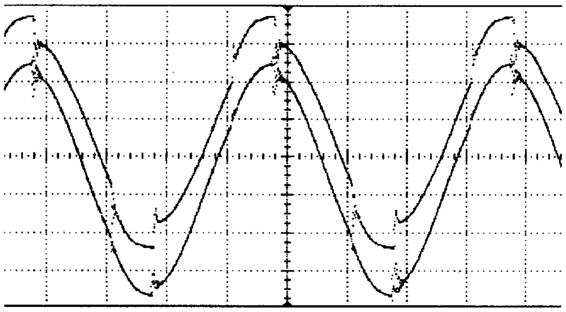


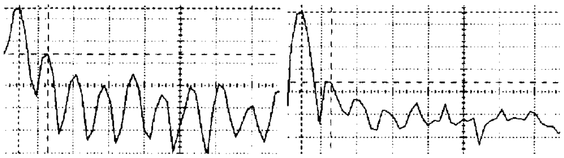
Fig 8: Block diagram of Simplistic Harmonic Isolator & UPC

Case 1: Unified Power Controller as Harmonic Isolator

No fundamental phase shift ($\delta_{rs}^* = 0$) is implemented to illustrate the UPC as a harmonic isolator. There is therefore no compensation of the line impedance X_s, and the experimental results in Fig. 9 show the operation of the UPC mainly as harmonic isolator. In most cases the frequency spectra (in dB) of the waveforms are also included to indicate the effect of the harmonic isolator on the waveforms. For this case, the power rating of the UPC is very small compared to the rating of the transmission line since mainly harmonic isolation is considered. This operating mode corresponds to the defined mode 5 in Table II, and simulation case (i). No fundamental component is visible in Fig. 9(d).

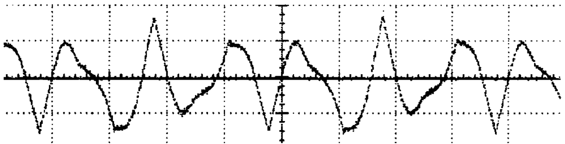


(a) V_r *{Top};* V_{ri} *{Bottom} - 100V/div; 5ms/div*
$V_{r(rms)}=201.4$ V; $V_{ri(rms)}=213.4$ V; $\delta=1.4°$

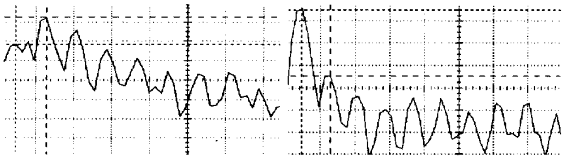


(b): FFT{V_r*};* $\Delta=21dB$ *10dB/div; 120 Hz/div*

(c): FFT{V_{ri}*};* $\Delta=32dB$ *10dB/div; 120 Hz/div*

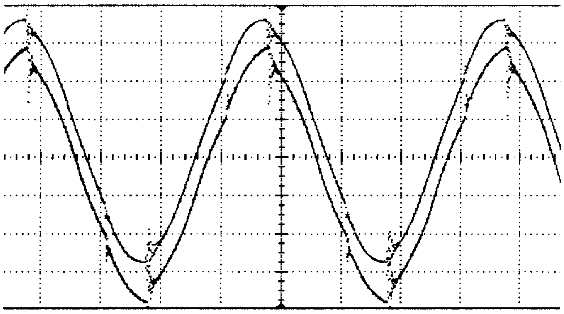


(d):V_{pq} *- 2V/div; 5 ms/div;* ($V_{pq(rms)}=1.76$ V)



(e): FFT{V_{pq}*};* $\Delta=15dB$ *10dB/div; 120 Hz/div*

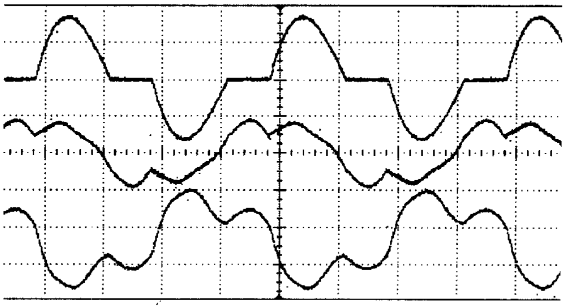
(g): FFT{V_r*'};* $\Delta=29dB$ *10dB/div; 120 Hz/div*



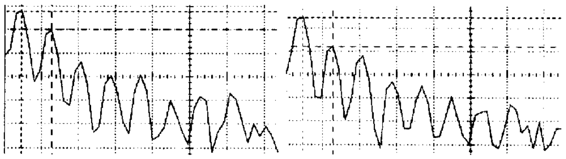
(f): V_{ri} *{Top};* V_r*' {Bottom} - 100V/div; 5ms/div*
$V_{ri(rms)}=213.4$ V; $V_{r(rms)}'=211.7$ V; $\delta\approx0°$

Fig 9: (a-g): Experimental Results of UPC as Harmonic Isolator (Zero Phase Compensation)

The effect of the harmonic isolation is evident from the suppression of the 3 rd voltage harmonic from 21 dB to 32 dB in V_r, shown in Fig. 9(a-c).



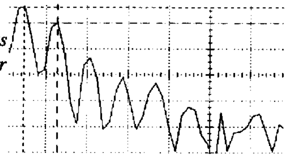
(h): I_L *{Top};* I_s *{Center};* I_F *{Bottom} : 5A/div; 5ms/div;*
$I_{L(rms)} = 4.8$ A; $I_{s(rms)} = 3.23$A; $I_{F(rms)} = 4.31$A; $\alpha_L=95°$



(i): FFT{I_L*};* $\Delta=7.8dB$ *10dB/div; 120 Hz/div*

(j): FFT{I_s*'};* $\Delta=12.5dB$ *10dB/div; 120 Hz/div*

Fig 9: (h-k) Experimental Results of UPC as Harmonic Isolator (Zero Phase Compensation)



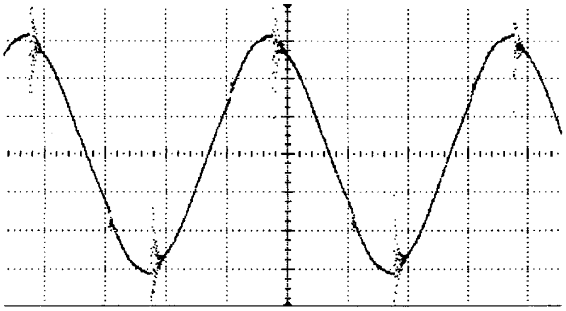
(k): FFT{I_F*'};* $\Delta=6.25dB$ *10dB/div; 120 Hz/div*

The voltages at the isolation point V_{ri}, and receiving end, V_r', after harmonic isolation have no noticeable phase shift, while the RMS receiving end voltage has been raised to 213V from the value of 201 V before harmonic isolation. The system currents and associated spectra are plotted in Fig. 9(h-k). The passive filter current is mainly responsible for the large reduction of the transmission line current from 4.8A to 3.23A.

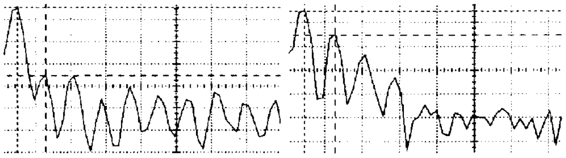
While the concept of harmonic isolation is clearly demonstrated by the results in Fig. 9, it should be noted that the dynamic range of V_{pq} suffers from a low DC bus voltage during the experiment. Thus, appropriate selection of V_d, and filter components L_0 and C_0, will allow for further improvement of waveform quality on the isolated bus, V_{ri}.

Case 2: Unified Power Controller as Harmonic Isolator and Fundamental Phase Shifter

Fundamental phase shift ($\delta_{rs}^*=4°$) is added to the injected voltage, V_{pq}, to illustrate the operation of the UPC as harmonic isolator and fundamental phase shifting device. In this case, line impedance, X_s, is fully compensated, leaving V_s in phase with V_r'. The experimental results of Fig. 10 show the operation of the UPC as harmonic isolator and phase shifter integrated into one power electronic device. Frequency spectra (in dB) for some waveforms are also included to

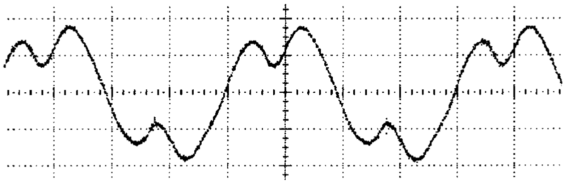


(a) V_{ri} *- 100V/div; 5ms/div*
$V_{ri(rms)}=217.1$ *V;* $\delta_{ris}=3.4°$

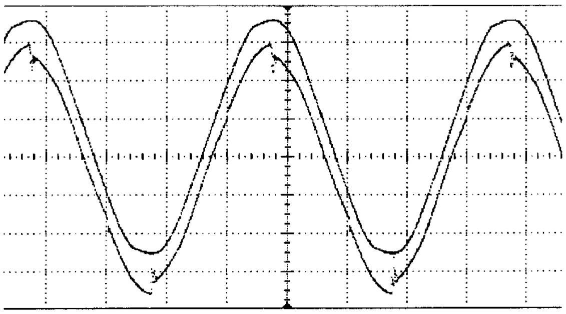


(b): FFT{V_{ri}*}; Δ=31dB*
10dB/div; 120 Hz/div

(c): FFT{V_{pq}*}; Δ=10dB*
10dB/div; 120 Hz/div



(d):V_{pq} *- 10V/div; 5 ms/div; (*$V_{pq(rms)}=12.4$ *V)*



(e): V_s *{Top};* V_r' *{Bottom} - 100V/div; 5ms/div*
$V_{s(rms)}=215.4$ *V;* $V_{r(rms)}'=219.3$ *V;* $\delta_{rs}\approx 0°$

***Fig 10**: Experimental Results of UPC as Harmonic Isolator and Phase shifter (Full* X_s *Compensation)*

indicate clearly the effect of the harmonic isolator on the waveforms. The power rating of the UPC is still small (but larger than in case 1) compared to the rating of the transmission line, since harmonic isolation and phase shifting modes are integrated.

The large fundamental component in V_{pq} is visible in Fig. 10(d). This fundamental component is necessary to control the required phase shift between V_s and V_r'. As shown in Fig. 10(e), the phase shift between V_s and V_r' has been reduced to nearly zero. The large fundamental component is shown in the FFT spectrum of Fig. 10(d). A 31 dB reduction {from the original 21 dB} of the voltage harmonics is still maintained in this mode of operation while performing fundamental phase shift control. System currents are maintained at the same levels as in the previous test case of Fig. 9.

SUMMARY AND RECOMMENDATIONS

The Unified Power Controller provides for excellent control flexibility in AC transmission systems by allowing for static VAr compensation, series compensation and phase shift using the same installed power electronic hardware. The present paper has extended UPC operation to provide for harmonic isolation in the presence of non-linear loads. EMTP studies outline the principle of operation for pure isolation purposes and mixed-mode operation. The latter mode incorporates harmonic isolation with the traditional UPC modes of operation. Experimental results are provided for a low power laboratory prototype. While the practical results shown are far from optimum, they serve well to illustrate the concept developed. Future work will address the optimization of isolation performance by improving the UPC dynamic range. Three phase implementations at more realistic power ratings will also be investigated.

As illustrated in the paper, the UPC does not require a substantial increase in converter kVA to isolate significant harmonic loads when used in conjunction with appropriate passive filters. For example, a converter rating of 120 kVA was shown to be suitable for harmonic isolation of a 1.3 MVA load while providing for fundamental phase shift and voltage control of 0.2 p.u. Thus, UPC operation including harmonic isolation provides for the optimum use of installed converter kVA and offers potentially attractive cost/performance ratios.

Present day power device limitations will initially limit the UPC harmonic isolator concept to several MVA in order to achieve the desired switching frequencies of several kHz. However, there are numerous applications at the distribution level as well as for industrial loads where this concept can already be implemented. Eventually, converter implementations seem feasible for high power applications, such as isolation of harmonics between two power systems while providing for fundamental power flow control. Future work will address application specific design advantages and tradeoffs for the UPC when compared to other, more conventional FACTS devices, such as the TCSC. For example, the absence of capacitor based subsynchronous resonance may make the UPC with harmonic isolation capability a very attractive candidate for systems with high levels of thermal generation in the presence of high power non-linear loads, such as arc-furnaces.

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APPENDIX: NOMENCLATURE

FACTS- Flexible AC Transmission Systems
HVDC - High Voltage Direct Current Transmission
TCSC - Thyristor Controlled Series Compensator
UPC - Unified Power Controller
SVC - Static VAr Compensator
IGBT - Insulated Gate Bipolar Transistor
V_{pq} - Injected Series Voltage [V]
V_s - Sending-end Transmission Line Voltage [V]
V_r - Receiving-end Transmission Line Voltage [V] {BEFORE Harmonic Isolation}
V_{ri} - Isolated Receiving-end Voltage [V] {AFTER Harmonic Isolation}
V_r' - Load-side Receiving-end Voltage [V] {AFTER Harmonic Isolation}
V_c - Injected Voltage with Series Compensation [V]
V_α - Injected Voltage with Angle Compensation [V]
V_M - Transmission Line Midpoint Voltage [V]
V_d - Converter DC Bus Voltage [V]
ΔV - Injected Voltage with Terminal Voltage Compensation [V]
δ - Transmission Power Angle [°]
δ_{sr} - Transmission Power Angle between V_s and V_r [°]
α - Phase Shift Control Angle [°]
α_L - Load Thyristor Firing Angle [°]
I_q - UPC Shunt Current Source [A]
I_L - Load AC Current [A]
I_s - Transmission Line Current [A]
I_F - Passive Filter Current [A]
I_h - Non-linear Load Harmonic Currents [A]
X_s, X - Transmission Line Reactance [Ω]
X_c - Equivalent Series Compensation Reactance [Ω]
L_l - Transformer Leakage Inductance [H]
L_0 - High Frequency Filter Inductance [H]
L_i - Passive Harmonic Filter Inductances [H]
C_0 - High Frequency Filter Capacitance [F]
C_i - Passive Harmonic Filter Capacitances [F]