# *Interphase Power Controllers - complementing the family of FACTS controllers*

## 1.0 Why the IPC?

O ne of the main reasons for developing the Interphase Power Controller (IPC) technology was to create new power flow controllers that would overcome the limitations on system operation caused by high short-circuit levels. In fact, excessive short-circuit levels constitute a widespread problem that has been almost completely overlooked in the development of FACTS controllers [1]. The flexibility of transmission and distribution systems can be greatly enhanced when circuits or interconnections can be added without significantly increasing the short-circuit levels. Despite worldwide efforts being made to develop fault-current limitation devices, the IPC is still the only such device available today at a competitive price.

The conventional solution to the problem of high short-circuit levels is to break up the network, for example by leaving a bus-tie breaker open to allow a new supply, generation or line. Another example is the radial operation of subtransmission systems, however with a loss of flexibility, if not reliability. A third example is the increase in transformer station capacity that can be achieved only by splitting the lower voltage bus. Such network degrading situations are widespread, underscoring the need in T&D systems for fault-current limiting power flow controllers.

## 2.0 Overview of the IPC technology

The basic design goal in IPC technology is to find passive solutions to fundamental frequency problems. Power electronics modules can be added in situations where rapid control action is required to damp oscillations or prevent excessive voltage variations. Hence, basic IPC solutions utilize only conventional equipment, such as capacitors, inductors and phase-shifting transformers. They generate no harmonics and have no commutation losses. Robustly built, they require much less maintenance than power electronics-based devices.

The IPC does not have a fixed configuration, being more a technology for creating different and innovative power flow controllers with diverse characteristics and configurations. Generically, it is a series-connected device consisting of two parallel branches, each with an impedance in series with a phase-shifting element (Figure 1). The four design parameters (two impedances and two phase shifts) allow enormous design flexibility and make a wide variety of applications possible. Because of the different characteristics these IPC applications can have, they have their own specific names.
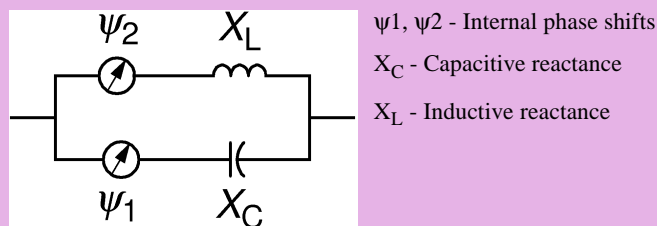


$\psi1, \psi2$ - Internal phase shifts

$X_C$ - Capacitive reactance

$X_L$ - Inductive reactance

**Figure 1: Generic single-line diagram of the interphase power controller.**

IPCs can be adapted to specific operating conditions. In general, the adaptation also results in an optimization. For example, the removal of the phase shift in one of the two branches of the IPC reduces the amount of equipment and relocates the control characteristic to a more

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### Abstract

The current application of Flexible AC Transmission Systems, or FACTS, solutions does not address the widespread problem of excessive short-circuit levels, for which the only conventional solution is to break up networks, thus reducing operating flexibility if not reliability. The Interphase Power Controller (IPC) technology offers innovative solutions for high short-circuit environments. IPCs provide passive solutions for normal and contingency conditions. Power electronics modules can be added as necessary for dynamic conditions. At the present time, there are three commercially available IPC applications.

### Sommaire

Les Systèmes de Transmission Flexibles en Courant Alternatif (FACTS) actuels ne permettent pas de gérer le problème largement répandu des niveaux de court-circuit trop élevés. La solution traditionnelle, qui consiste à fractionner les réseaux, nuit à leur flexibilité d'exploitation, voire à leur fiabilité. Le Régulateur de Puissance Interphases (RPI) constitue une solution innovatrice pour les environnements à niveaux de court-circuit élevés. Le RPI gère, de manière passive, les régimes permanent et post-contingence. On peut aussi lui adjoindre des modules d'électronique de puissance, selon les besoins en régime dynamique. Trois types de RPI sont actuellement disponibles sur le marché.

favorable position in the power-angle plane. The adaptability of the IPC technology is also demonstrated by the various ways in which the internal phase shifts can be implemented. Conventional phase-shifting transformers (PST) are the first obvious choice, but the IPC characteristics can also be obtained using conventional transformers which have auxiliary windings added to create the desired internal phase shift by injecting series voltages from other phases.

Three categories of IPC applications are commercially available today:

■ The first subset of the technology, in which the impedances form a parallel circuit tuned to the fundamental frequency of the network, is called the Decoupling Interconnector (DI). These high-impedance IPCs have the unique properties of limiting their own contribution to a fault and of decoupling the voltages at their terminals. They are intended for implementing ties not otherwise possible because of high short-circuit levels.

■ When a decoupling interconnector linking two voltage levels is in parallel with conventional transformers, its configuration can be simplified and optimized. It is then called a Fault Current Limiting Transformer (FCLT). The purpose of the FCLT is to increase the total capacity of a transformer station without increasing short-circuit levels.

■ In transmission applications, the decoupling characteristics of the DI are detrimental to the stability of the network and the parallel circuit has to be de-tuned. The simplest implementation of a transmission IPC is a phase-shifting transformer (PST) in parallel with a reactive impedance. Called an Assisted Phase-Shifting Transformer

(APST), this device can be used either to increase the normal and contingency transfer capacity of an existing PST or to implement an equivalent high-capacity PST at lower cost. The Plattsburgh APST, in service since June 1998, belongs to this category.

All IPC applications are covered by one or more of five different patents. (The mathematical principles, the method of analysis and basic application examples are found in [2].) As co-developer of the technology, ABB holds a unique worldwide license for marketing all IPC applications.

## 3.0 The Decoupling Interconnector

In the decoupling interconnector (DI), the impedances form a parallel circuit tuned to the fundamental frequency. Each terminal of the DI behaves as a controlled current source.

In normal operating conditions, the DI provides bidirectional power flow control and voltage support through the generation and absorption of reactive power. The desired operating levels are obtained by adjusting the phase shifts, using either tap-changers or switches. During perturbations, there is no short-circuit contribution from the DI and the voltages on each side are decoupled. In other words, the DI does not transfer the impact of perturbations from one side to the other.

The basic control characteristics of the DI (Figure 2) are obtained by passive means using conventional elements, i.e. capacitors, inductors and phase-shifting transformers. The control functions, being inherent to the controller, are robust and predictable for all pre- and post-contingency conditions.
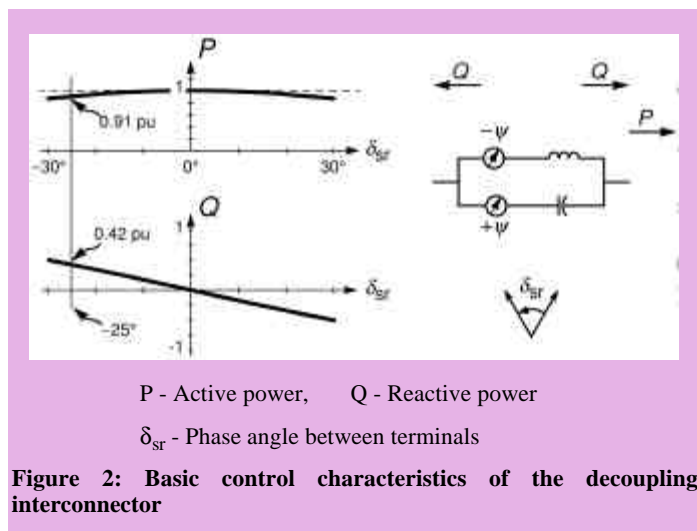


P - Active power,     Q - Reactive power

$\delta_{sr}$ - Phase angle between terminals

**Figure 2: Basic control characteristics of the decoupling interconnector**

### 3.1 Typical applications

The DI allows the implementation of new interconnections, such as:

■ Ties between separate subtransmission systems, for increasing operational flexibility, sharing transmission reserves, and facilitating reactive power management.

■ Bus ties, for paralleling generation or transformation without increasing short-circuit levels.

For such ties, there are no conventional alternatives besides uprating the short-circuit interrupting and withstand capabilities of circuit-breakers and other equipment.

The DI can also be used as a blocking circuit for preventing overloads in a subtransmission system following the loss of parallel higher voltage lines. This allows higher pre-contingency loading of the higher voltage lines. Such IPC solutions are expected to be less onerous than increasing the capacity of the overloaded circuit(s) and will avoid the network degradation resulting from these lines being left normally open.

### 3.2 Demonstration prototype:

The results of an exhaustive prototype demonstration using the power system simulator at the Hydro-Quebec Research Institute are summarized in [3]. The most difficult operating condition for the DI, the one that dictates the final design of the components, is the occurrence of an open circuit on either side of the tuned IPC. In this situation, the two branches of the DI form a series resonant circuit excited by the equivalent voltage source of the phase shift. The design objective is to protect the (already out of service) DI components during shutdown. The solution demonstrated on the simulator uses conventional zinc-oxide energy absorption devices.

## 4.0 Fault Current Limiting Transformer (FCLT)

Normally, the transformers in large T&D substations are operated in parallel for maximum reliability and flexibility. Once the construction of the station is complete, the short-circuit level on the secondary side does not allow the addition of transformers unless special measures are taken to cope with or to avoid the increase in fault currents. Barring either extensive modifications to the substation or the construction of a new one in the immediate vicinity, two conventional options exist: split the low-voltage bus or, if the design of the station is based on the n-1 criterion, operate a redundant transformer in a standby mode.

Reference [5] presents an application in which a fifth transformer is added in a large 315/120 kV transformer station typical of Hydro-Québec installations in the Montréal area. Although more expensive than a conventional transformer, the IPC solution is definitely more advantageous than replacing or uprating a large number of 120-kV breakers and associated equipment. After [5] was written, optimization studies have shown that the configuration of the FCLT can be simplified provided there are at least two conventional transformers in parallel with the FCLT for all contingency conditions. The inductive branch can be removed as it is shorted by the lower impedance of the parallel transformers. The resulting optimized FCLT consists of a conventional transformer in series with a capacitor bank and a small phase-shifting transformer. Figure 3 shows a typical single-line diagram; the phasor diagrams in Figure 4 illustrate the behavior of the optimized FCLT during steady-state and fault conditions.
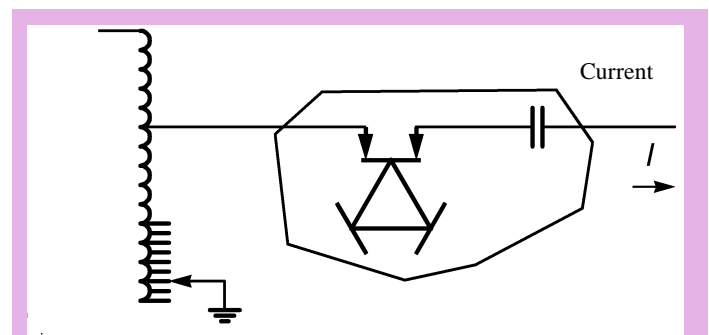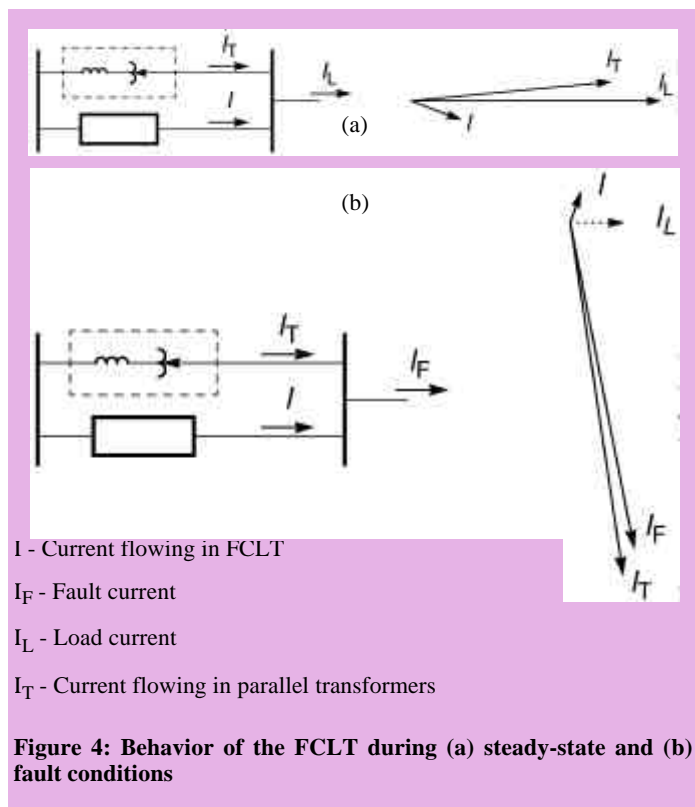


**Figure 3: Single-line diagram of an optimized fault current limiting transformer.**

Thus, the FCLT technology allows one or more transformers to be added without increasing the short-circuit level. Compared with the split-bus approach, the FCLT solution offers flexibility and reliability, exhibits smaller steady-state and transient voltage drops, requires less shunt compensation, and avoids the need for post-contingency redistribution of loads. Compared with the standby mode, it allows the addition of more than one transformer, exhibits lower losses and requires less shunt compensation.

### 4.1 Typical applications

The FCLT is designed to increase the total capacity of transformer stations in cases where the short-circuit level is already close to the rating of the circuit-breakers and other equipment. The economic justification

is based on the replacement cost of breakers and associated equipment. There is more equipment involved when the increase in short-circuit level is significant (equipment short-time ratings, electrodynamic forces on busbars, etc).



I - Current flowing in FCLT

$I_F$ - Fault current

$I_L$ - Load current

$I_T$ - Current flowing in parallel transformers

**Figure 4: Behavior of the FCLT during (a) steady-state and (b) fault conditions**

In another application, one of the transformers in a station is converted into a FCLT to reduce the total fault-current contribution. This allows the addition of another source, such as a new generator or a tie line from another network. Both of these options are of interest in the fast-changing open energy market.

## 5.0 Assisted Phase-Shifting Transformer

The adaptation of IPC technology for an increase in the normal and contingency transfer capability of a transmission line is explained in [4] and [6]. The simplest implementation of an IPC within a transmission system is a reactive impedance in parallel with a conventional phase-shifting transformer (PST). The nature of the impedance depends on the quadrant in which the PST is called upon to operate: capacitors and inductors are used to boost and buck power flows, respectively.

### 5.1 Typical applications

#### 5.1.1 Addition of capacitors for boosting power flows

Reference [4], in which the Mead-Phoenix 500-kV line is discussed, shows that the maximum steady-state transfer capability of the two 500-kV PSTs at Westwing can be increased from 1300 to 1910 MW by adding 125-ohm, 370-MVAr capacitors in parallel. With the capacitors, the effective internal angle of the IPC is 31 degrees, compared with the 25 degrees of the PSTs.

#### 5.1.2 Addition of power electronics for system damping

The main transmission system in Arizona and southern California, of which the Mead-Phoenix 500-kV line is an important component, is subject to low-frequency (0.7 Hz) oscillations. In order to be able to make use of the increase in steady-state capacity, some means of damping these natural oscillations must be provided. One efficient solution is to use thyristor-controlled series capacitors (TCSC).

Preliminary study results are showing that a TCSC module in series

with the two PSTs (one branch of the IPC) can provide as much damping as another TCSC module, of higher rating, in series with the line. Thus, a dynamic APST is possible with conventional components (PST, capacitors) and existing power electronics technology.

#### 5.1.3 Addition of inductors for bucking power flows

The world's first interphase power controller, an APST [6], went into commercial operation at the end of June, 1998, in the Plattsburgh substation of the New York Power Authority (NYPA). This substation connects the NYPA and the Vermont systems through a 115-kV PST. Under normal system conditions, the addition of 75-ohm inductors (Figure 5) increases the summer transfer capacity of the link by 33%, from 105 to 140 MW. The three single-phase inductors, the circuit breaker and part of a disconnect switch are seen in the cover picture of this issue of the Review. Together with the existing PST, also seen in the background, this equipment constitutes the Plattsburgh IPC. The isometric diagram of Figure 6 gives a better general impression of the installation. The two shunt capacitor banks are not part of the APST, but are required for voltage support. They were therefore included in the project. The Plattsburgh installation was designed and built by the Systems Division of ABB Canada.
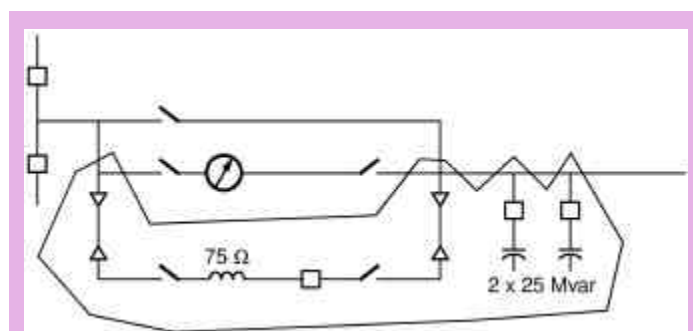


**Figure 5: Single-line diagram of the Plattsburgh APST, the world's first IPC**

The results of the first year of operation of the Plattsburgh APST show that the total energy transfer for the 1998 summer period increased by 77 GWh (25.7%), compared with the previous year. Although these excellent results reflect different market conditions, it can be said that without the higher flows that the APST allows, it would have been physically impossible to transfer at least 40 of these 77 GWh.
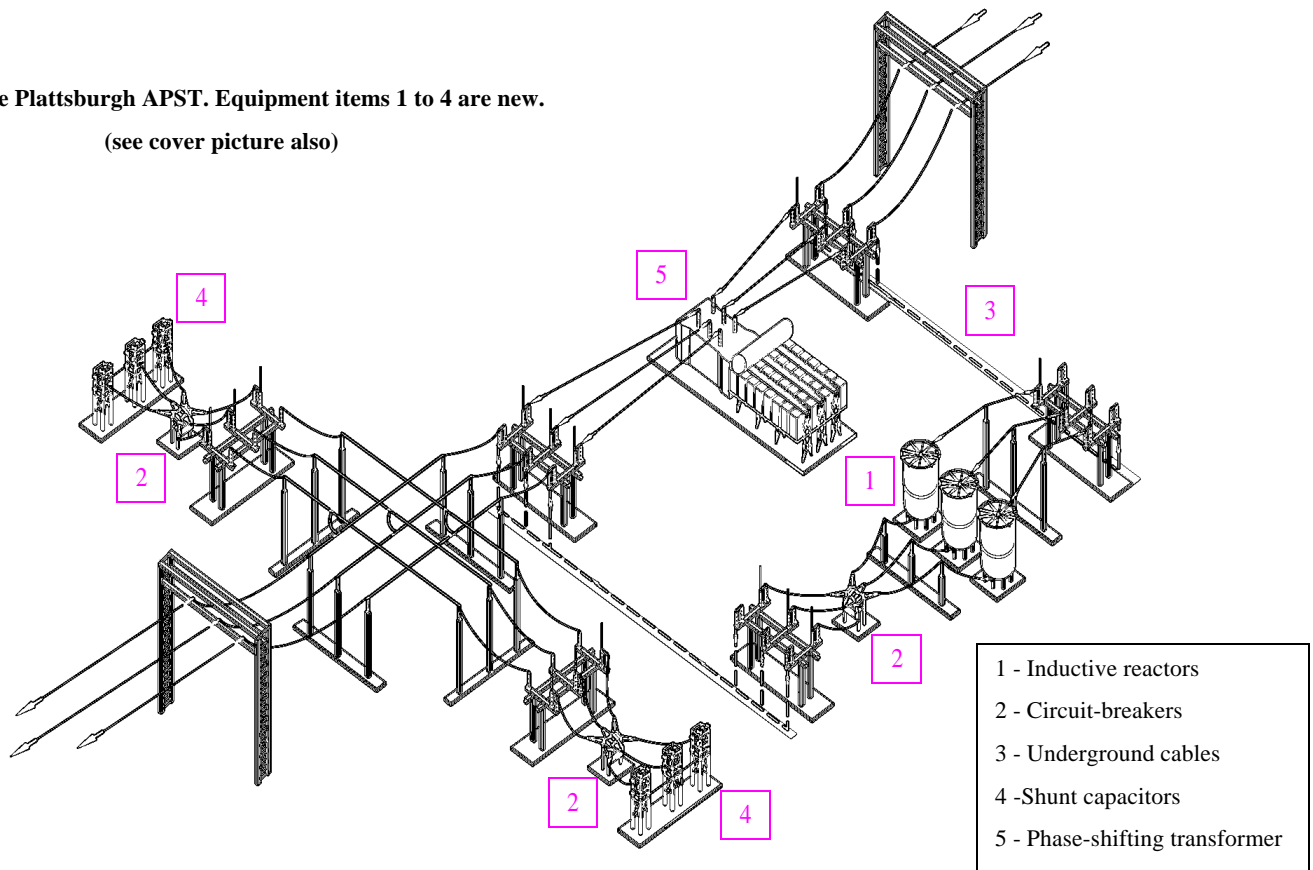
### 5.2 New APST installations

These two APST applications describe additions to existing PSTs. For a totally new APST installation, it is possible that a lower PST rating can be used in conjunction with the parallel impedances, so that the total cost of the IPC solution would be less than that of a full-rating conventional PST. This is particularly true of applications in which a wide phase-angle control range is required.

## 6.0 References

[1]. R. Grünbaum, M. Noroozian, B. Thorvaldsson: "FACTS - powerful systems for flexible power transmission", ABB Review 5/99, 4-17.

[2]. J. Brochu, "Interphase Power Controllers", Polytechnic International Press, Montreal, January 1999.

[3]. G. Sybille et al: "Simulator demonstration of the interphase power controller technology", IEEE Trans. on Power Delivery, Vol.11, No.4, Oct. 1996, pp 1985-1992.

[4]. J. Brochu, F. Beauregard, J. Lemay, G. Morin, P. Pelletier, R.S. Thallam, "Application of the interphase power controller technology for transmission line power flow control", IEEE Transactions PWRD, vol 12, no 2, April 1997, pp 888-894.

**Figure 6: The Plattsburgh APST. Equipment items 1 to 4 are new.**

**(see cover picture also)**



1 - Inductive reactors

2 - Circuit-breakers

3 - Underground cables

4 -Shunt capacitors

5 - Phase-shifting transformer

[5]. J. Brochu, F. Beauregard, G. Morin, J. Lemay, P. Pelletier, S. Kheir, "The IPC technology - a new approach for substation uprating with passive short-circuit limitation", Paper PE-830-PWRD-0-04-1997, IEEE/PES 1997 Winter Meeting, Tampa, FL.

[6]. J. Lemay et al, "The Plattsburgh interphase power controller", IEEE/PES 1999 T&D Conference and Exposition, New Orleans, April 11-16, 1999.

**About CITEQ?**

CITEQ (Centre d'innovation sur le transport d'énergie du Québec) is a joint venture between Hydro-Québec and ABB Canada. It concentrates its R&D activities in the areas of high-voltage transmission & distribution equipment. All development activities are closely aligned with market deregulation opportunities.

CITEQ is located in Varennes, close to ABB's Varennes plant and IREQ, Hydro-Québec's high technology research and test center.

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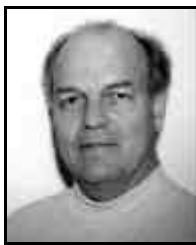
**Jacques Brochu** obtained his B.Sc.A. and M.Sc.A. degrees in electrical engineering from Université Laval of Québec in 1981 and 1986 respectively and his Ph.D. degree from École Polytechnique de Montréal in 1997. From 1981 to 1983, he was production engineer for Canadian General Electric. He is a research engineer at Hydro-Québec's research center (IREQ) since 1985 where his research mainly revolves around power electronic converters and the IPC. Since 1990, he is involved in the IPC development at Centre d'innovation sur le transport d'énergie du Québec (CITEQ). He is co-author of patents and author of a book on the IPC.

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