Interphase Power Controllers
complementing the family of FACTS controllers

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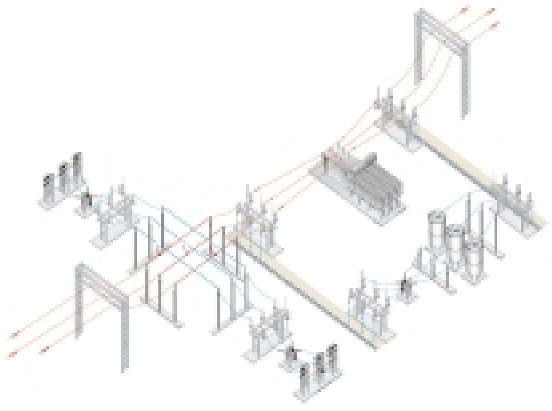
The current application of Flexible AC Transmission Systems, or FACTS, solutions does not address the widespread problem of excessive short-circuit levels, for which the only conventional solution is to break up networks, thus reducing operating flexibility, if not reliability. Interphase Power Controller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

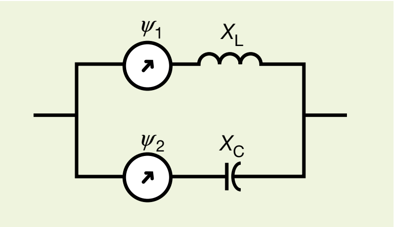


The Interphase Power Controller (IPC) does not have a fixed configuration, being more a technology for creating different, innovative power flow controllers with diverse characteristics and configurations. Generically, it is a series-connected device consisting of two parallel branches, each with an impedance in series with a phase-shifting element 1 [2–8]. The four design parameters (two impedances and two phase shifts) allow enormous flexibility and make a wide variety of applications possible. Since these IPC applications can have different characteristics, they have their own specific names.

A good idea of how IPCs can be adapted to specific operating conditions is given in [4]. 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 in a more favorable position in the power angle plane [10]. 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.

1 Generic single-line diagram of the interphase power controller. The four design parameters allow enormous flexibility at the design stage.

ψ_1, ψ_2	*Internal phase shifts*
X_C	*Capacitive reactance*
X_L	*Inductive reactance*



Three categories of IPC applications are commercially available today:

- The IPCs described in references [2] to [4] are a subset of the technology in which the impedances form a parallel cir-

Why IPC?

One of the main reasons for developing 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.

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 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.

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cuit tuned to the fundamental frequency of the network. These high-impedance IPCs have the unique properties of limiting their own contribution to a fault and of decoupling the voltages at their terminals, hence their name *'decoupling interconnectors'* (DI). 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 IPC in the USA, 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 [5].) As co-developer of the technology, ABB holds a unique worldwide license for marketing all three IPC applications.

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.

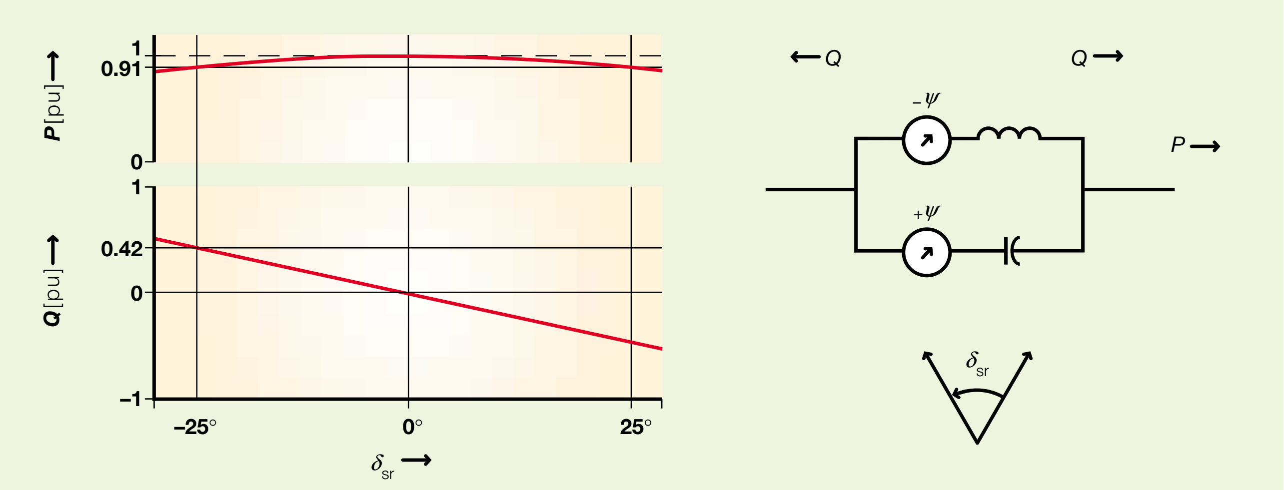
In normal operating conditions, the DI provides bidirectional power flow control and voltage support through the generation and absorption of reactive power. The desired operating levels are obtained by adjusting the phase shifts, using either using tap-changers or switches. During perturbations, there 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 2 are obtained by passive means using conventional elements, ie 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.

Typical applications

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

- Ties between separate subtransmission systems, for increasing operational flexibility, sharing



2 *Basic control characteristics of the decoupling interconnector*

P Active power Q Reactive power δ_{sr} Phase angle between terminals

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.

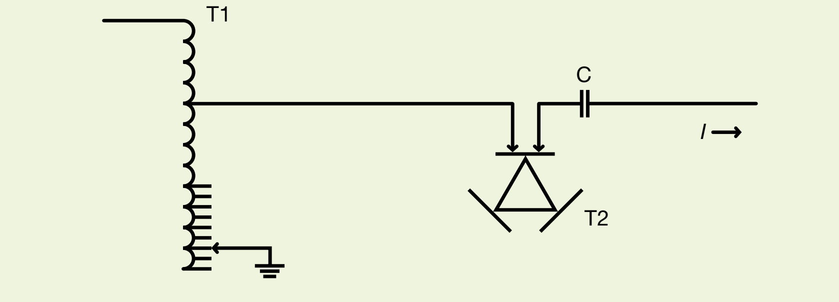
The DI can also be used as a *blocking circuit for preventing overloads* in a subtransmission system following the loss of parallel higher voltage lines. This allows higher pre-contingency loading of the higher voltage lines. Such IPC solutions are expected to be less onerous than increasing the capacity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

The results of an exhaustive prototype demonstration using the power system simulator at the Hydro-Quebec Research Institute are summarized in [6]. 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 makes use of conventional components, such as zinc-oxide energy absorption devices.

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 has ended, the short-circuit level on the secondary side does not allow the addition of transformers unless special measures are taken to cope with or 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 the redundant transformer in a standby mode.

[8] 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. Since [8] 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. 3 shows a typical single-line diagram; the phasor diagrams in 4 illustrate the behavior of the optimized



3 ***Single-line diagram of an optimized fault current limiting transformer, consisting of a conventional transformer (T1) in series with a capacitor bank (C) and a small phase-shifting transformer (T2)***

I Current

FCLT during steady-state and fault conditions.

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. Another advantage is that it avoids the control system required to switch the standby transformer.

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. As demonstrated in [11], there is more equipment involved when the increase in short-circuit level is significant (equipment short-time ratings, electrodynamic forces on busbars, etc).

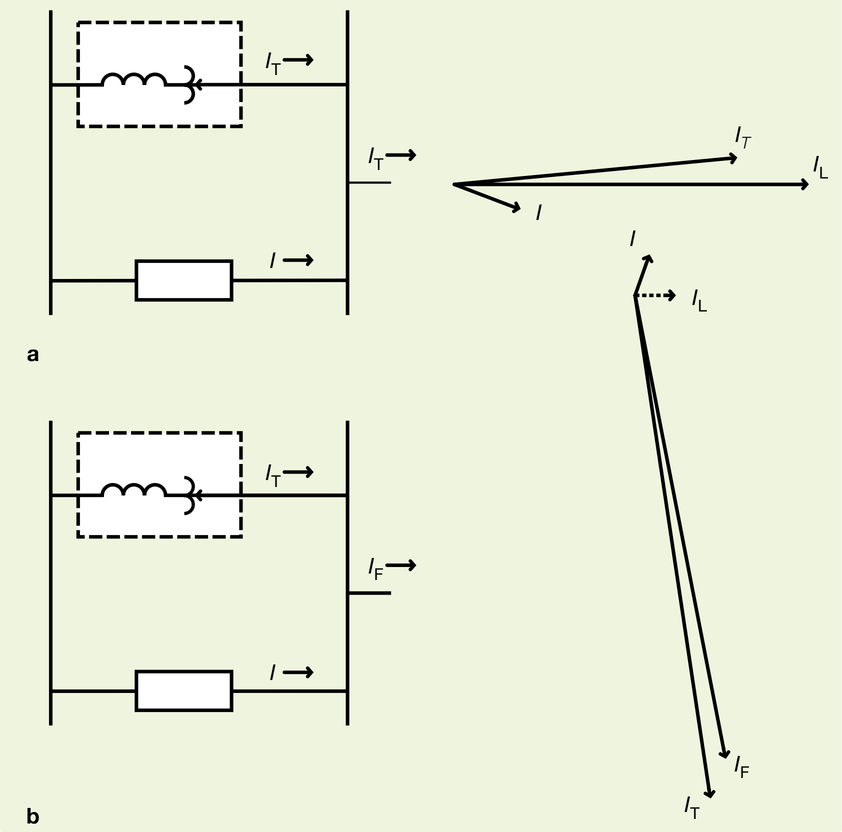
In another application, one of the transformers in a station is converted into an FCLT to reduce the total fault-current contribution. This allows the addition of another source, such as a new generator or a tie line from another network. Both of these options are of interest in the fast-changing open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

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 [7] and [9]. 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.

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

I	*Current flowing in FCLT*	*I_L*	*Load current*
I_F	*Fault current*	*I_T*	*Current flowing in parallel transformers*



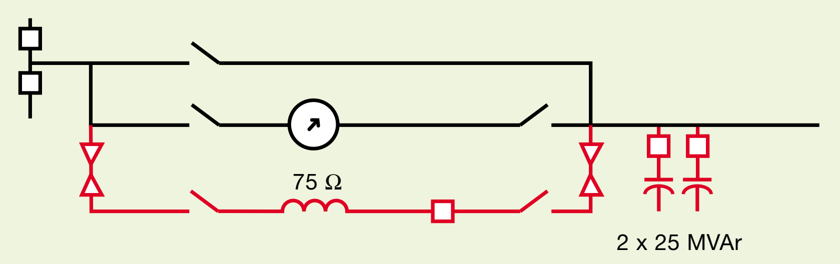
Typical applications

Addition of capacitors for boosting power flows

[7], 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.

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).



5 ***Single-line diagram of the Plattsburgh APST, the world's first interphase power controller. The equipment added to this substation, which connects the systems of the New York Power Authority and Vermont, is shown in red.***

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.

Addition of inductors for bucking power flows

The world's first interphase power controller, an APST [9], 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 increases the summer transfer capacity of the link by 33 %, from 105 to 140 MW **5**. The three single-phase inductors, the circuit-breaker and part of a disconnect switch are seen in **6**. Together with the existing PST, also seen in the background, this equipment constitutes the Plattsburgh IPC. The isometric diagram shown in **7** 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.

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.

6 ***Plattsburgh APST, consisting of three single-phase inductors, a circuit-breaker, part of a disconnect switch, and the existing PST (at rear)***

These two APST applications describe additions to existing PSTs. For a totally new APST installation, it is possible for a lower PST rating to 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. ■

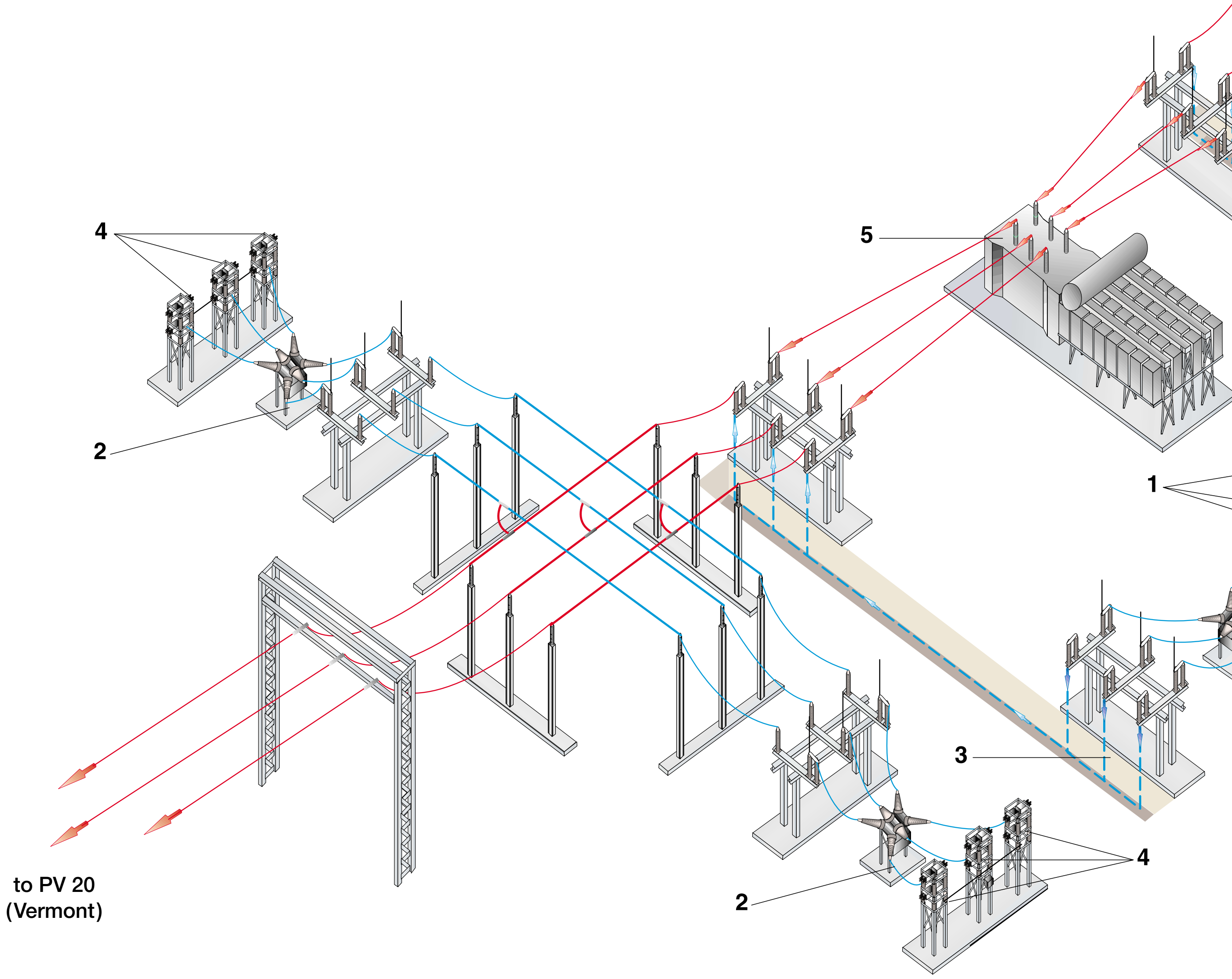
What is CITEQ?

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 and heavy industry. All development activities are closely aligned with market deregulation and other evolving market opportunities.

CITEQ is strategically located in Varennes, close to ABB's Varennes plant and IREQ, Hydro-Québec's high technology research and test center. CITEQ employs at the two parent companies about 20 research specialists who truly 'own' their projects from start to successful completion.

7 ***Plattsburgh APST. Equipment items 1 to 4 are new.***

1 *Inductive reactors*
2 *Circuit-breakers*
3 *Underground cables*
4 *Shunt capacitors*
5 *Phase-shifting transformer*



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The decision-makers get together at the inauguration of the Plattsburgh APST: (from left to right) Jacques Régis of TransEnergie, André Dupont of CITEQ, David Mellor of ABB Canada, Kenneth Haase of NYPA, Richard M. Chapman and George Smith, both of VELCO.

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