Understanding Interphase Power Controller: A Description

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Abstract – **Interphase Power Controller (IPC) is defined
as a Flexible Alternative Current for Transmission
System (FACTS) device, that functions as an integrated
concept. Its constitution revolves mainly around this
following key equipment: phase shifting transformers
(PST), inductive reactors, shunt capacitors and circuit
breakers. IPC devices are used for non-harmonic
operations, such as stable control of power flow and
mitigation of fault current. The evolution of this
technology is part of the Assisted Phase Shifting
Transformer (APST), which increases the transit
capacity of transmission lines, the IPC 240 which has an
additional property, that of allowing the mitigation of
the fault current. Although they have identical
functions, the IPC 120 is preferred to the IPC 240
because of the lower values of its reactors. On the other
hand, Unified Interphase Power Controller (UIPC)
came to raise the limit of the control of flow of power
thanks to the presence in its structure of Static
Synchronous Series Compensators (SSSC) instead of
PST.**

*Keywords- Assisted Phase Shifting Transformer
(APST); Power flow control; Interphase Power Controller
(IPC); Fault current mitigation; Unified Interphase
Power Controller (UIPC)*

I.   INTRODUCTION

Interphase Power Controller (IPC) is an innovative
technology that is growing significantly. Indeed, the
first document to introduce the IPC technology was
published in the middle 1990 [1]. The world's first
IPC, an Assisted Phase Shifting Transformer (APST),
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, 3-phase, 60 Hz, Phase Shifting Transformer
(PST) [2]. Asian Brown Bowori (ABB) Energy
Company is the holder of a license for the
development and application of IPC technology [3].
The first book to describe IPC technology was
presented by Jacques BROCHU of the Center for
Innovation in Energy Transmission (CITEQ) of
Quebec, Canada, in January, 1999 [4].

This technology remains the best alternative to the
problem of limiting the fault current compared to the
solutions used, but uneconomical: splitting of existing
bus, using standby conductors or others FACTS. They
therefore generate no harmonic and have no switching

loss [5]. Several devices resulting from this technology
are currently under development.

The remaining sections of the paper are organized
as follows: Section II focusses on the presentation of
the various types of IPC. Then, in Section III, the
benefits of IPC are mentioned. The paper is concluded
in Section IV.

II.   DEFINITIONS AND TYPOLOGY

The main IPC are thus given:
- Assisted Phase Shifting Transformer (APST)
- Interphase Power Controller 240 (IPC 240)
- Interphase Power Controller 120 (IPC 120)
- Unified Interphase Power Controller (UIPC)

A.   Assisted Phase Shifting Transformer (APST)

The active and reactive power transported over a
transmission line is given by the following equations:

$$P = 3\frac{|V_S||V_r|}{X_L}\sin\delta \qquad (1)$$

$$Q = 3\frac{|V_S||V_r|}{X_L}\left(\cos\delta - \frac{|V_r|}{|V_S|}\right) \qquad (2)$$

Where:
Vs: Sending end source phase voltage;
Vr : Receiving end source phase voltage;
XL: Total reactance of the line;
δ: Power angle of the line.

Altering the active power can be done by altering
the voltages, but this has a bigger influence on the
reactive power, so this method is not very effective.
The total line reactance can be lowered by placing a
series capacitor in order to compensate for the
inductance of the line.

The Phase Shifting Transformer (PST) is modeled
as a reactance in series with a phase shift as showed in
Fig 1.

Figure 1.   Model of a transmission line with and without a PST
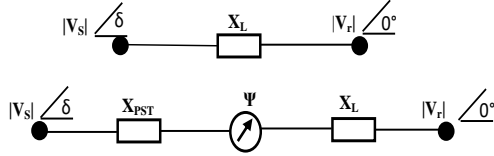
The power flow through the line is increased by adding an angle Ψ to the existing angle δ.

APST, on the other hand, is defined as a device, equipment, or dynamic electrical system capable of increasing or reducing the power flow of an electrical power transmission line in normal and post-contingency operations. The simplest configuration of the APST given in figure 2, shows that it consists of a phase shifting transformer connected in parallel with a reactance.

Figure 2.   APST Single-line diagram [3]
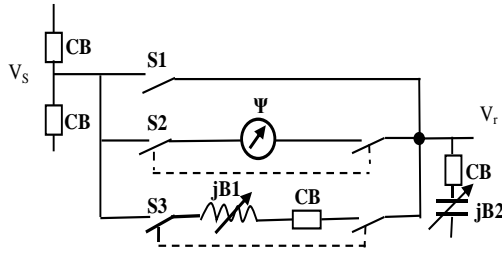
CB: Circuit breaker
S1, S2, and S3: Switches
ψ: Phase shifting
B1: Inductive susceptance
B2: Capacitive susceptance

The power transmitted by the line is now given by equation (3) which follows from equation (1).

$$P = 3 \frac{|V_S||V_r| \sin(\delta + \Psi)}{X_{PST} + X_L + \left(\frac{1}{B_1} + \frac{1}{B_2}\right)} \qquad (3)$$

The nature of this susceptances (B1, B2) depends on the operating quadrant of APST: capacitors to increase power flow and inductive reactors if APST is working to reduce it.

B. Interphase Power Controller 240 (IPC 240)

IPC 240, which consists solely of passive elements, is the main device of this family. As shown in its three-phase diagram given in figure 3, it is connected in series and consists of two parallel branches per phase, each having a susceptance (inductive or shunt capacitor) with a phase shifting element. This phase shifting element may be a conventional phase-shifting transformer, a conventional transformer provided with auxiliary winding to produce the desired internal phase shift, or a rotary transformer.

Figure 3.   Three phase diagram of IPC 240
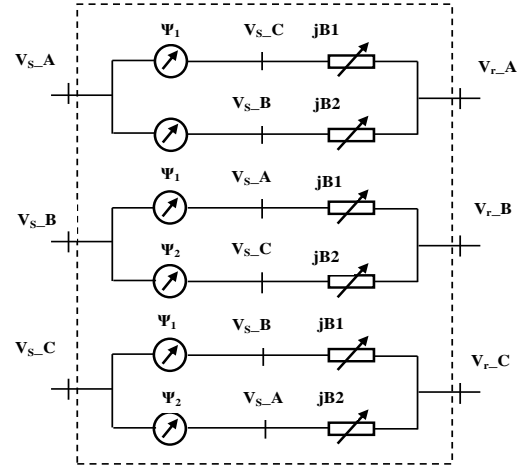
B1: Mutual susceptance1 (inductive or shunt capacitor)

B2: Mutual susceptance2 (inductive or shunt capacitor)

ψ1,2: Phase shifting

This IPC is characterized by its angle, 240°, which represents the angle difference between the sending end voltage applied to the susceptances. This angle can be determined according to table 1, this IPC is said to type 240 with two branches.

In the absence of contingency, this IPC provides robust and bidirectional control of power flow by absorbing or generating reactive power. The desired operating levels are obtained by adjusting the phase shifts, by tap changer adjusting or by variation of the susceptances [4].

One of the properties of this IPC, and its superiority over APST, is its ability to limit the fault current. Indeed, during this contingency, the susceptances are set such that |B1| = |B2|, and the device imposes an infinite impedance to the short circuit, thus relieving the circuit breakers.

TABLE I.   ANGLE CHARACTERISTIC OF THE IPC 240 SEEN PHASES A, B AND C OF A THREE-PHASE LINE

Sending end phase side	Receiving end phase side	Phase shift ψ	Angle of the IPC ($\gamma = \psi_2 - \psi_1$)
C	A	$-120° = \psi_1$	
B		$120° = \psi_2$	
A	B	$-120° = \psi_1$	240°
C		$120° = \psi_2$	
B	C	$-120° = \psi_1$	
A		$120° = \psi_2$	

Recently again, a new IPC 240 model with three branches this time, has been analyzed. This new model fulfills the properties of the IPC 240 with two branches, but in addition, has an asymmetrical operating capacity to ensure during a single-phase short circuit (the occurrence of which is highest in the

transmission lines), continuity of three-phase power supply to the load [6-8]. The diagram of a single IPC 240 with three branches is presented in Fig 4.

Figure 4.   Topology of an IPC 240 with three branches
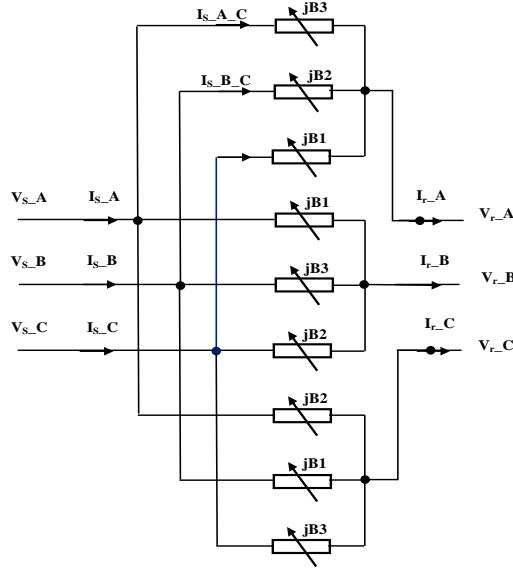
B3: Serial susceptance

For each reverse sequence compensator (B1, B2 and B3) at the input side, the following equation should be satisfied:

$$\frac{1}{B_1} + \frac{1}{B_2} + \frac{1}{B_3} = 0 \qquad (4)$$

As an implication, it might be built using either two inductances and a capacitance, or one inductance and two capacitances. Hence, the relations to be used for computing the values of reactances are as follows:

- Currents Is_X_C in the reverse sequence compensator for X ε {A, B, C}:

$$Is\_A\_C = -Is\_A/3$$
$$Is\_B\_C = -Is\_B/3$$
$$Is\_C\_C = -Is\_C/3 \qquad (5)$$

- Resistance R2_CI and reactance X2_CI in the reverse sequence compensator:

$$R_2\_CI = RealPart(Vs\_A/(-Is\_A\_C))$$
$$X_2\_CI = ImagPart(Vs\_A/(-Is\_A\_C)) \qquad (6)$$

- Serial and mutual (interphase) susceptances of the reverse sequence compensator.

$$B_1 = \frac{1}{2 * X_2\_CI}$$
$$B_2 = \frac{1}{\sqrt{3} * R_2\_CI - X_2\_CI}$$
$$B_3 = \frac{1}{-\sqrt{3} * R_2\_CI - X_2\_CI} \qquad (7)$$

The same reasoning from equation (4) to (7) could be used to obtain similar expressions of the susceptance B_{11}, B_{22} and B_{33} at the output side (Dual IPC 240). In (6), Vs_A = Vs $\angle\delta sr°$, δsr being a power angle. Consequently, each inverse sequence reactance defined in (6) given (3), evolves according to a real function of δsr. The graph of functions B_1 (δsr), B_2 (δsr), B_3 (δsr), B_{11} (δsr), B_{22} (δsr) and B_{33} (δsr), obtained using a simple Matlab program from the following set of data {voltage Vs = Vr = 225 kV, line impedance Z = 10.49 + j 40.90, δsr ε [1° - 30°]}, are represented in Fig 5 [7].

Figure 5.   Graph of the inverse sequence susceptances
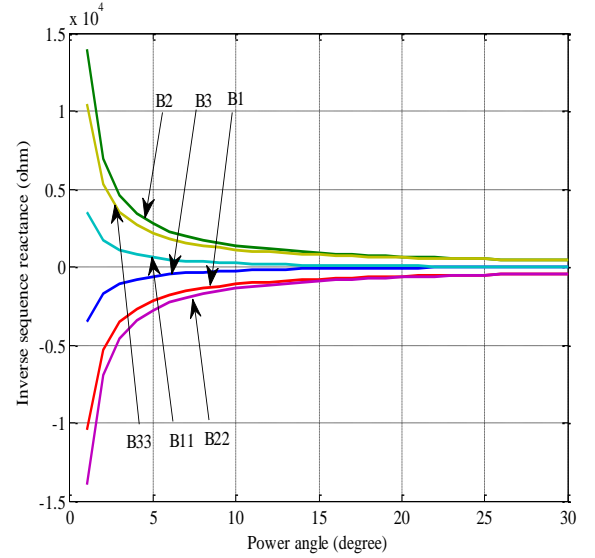
In Fig 5, relation (4), is quite apparent. In addition, a new finding arising from Fig 5 is that, the variations of the reverse sequences susceptances of an IPC 240 with three branches fall into the family of simple exponential or polynomial functions of the power angle δsr.

C.   Interphase Power Controller 120 (IPC 120)

IPC 120 is part of the synchronous topologies of this technology. Figure 6 shows its three-phase diagram, which essentially comprises a multi-tap transformer, three inductive reactors and three capacitors grouped two by two on each phase of the receiving side of the device.

The reactances B_1 and B_2 are connected to the Y-y6 transformer according to Table 2. As long as these forms of voltages are out of phase by 120 °, this IPC is said to be of type 120.

TABLE II.   CONNECTION DIRECTION IN THE IPC 120°

Secondary winding phase of the transformer	Receiving end phase of the reactance	Total angle
$\underline{V}_{bs}$ and $\underline{V}_{cs}$	$\underline{V}_{Ar}$	
$\underline{V}_{cs}$ and $\underline{V}_{as}$	$\underline{V}_{Br}$	120°
$\underline{V}_{as}$ and $\underline{V}_{bs}$	$\underline{V}_{Cr}$	

When this IPC is symmetrical, the current $\underline{I}_{AS}$ is equal to the total of currents $\underline{I}_{B1}$ and $\underline{I}_{B2}$, phase shifted by -60 ° and +60 °, respectively. By adjusting the values of the reactances, this IPC provides full control of the magnitude and phase angle of the currents $\underline{I}_{AS}$, $\underline{I}_{BS}$, and $\underline{I}_{CS}$ or simultaneously, the full control of $\underline{I}_{AR}$, $\underline{I}_{Br}$, and $\underline{I}_{Cr}$. It is then possible to control the power $\underline{S}_S$ and $\underline{S}_r$ [5].

It is important to note that during contingencies of such magnitude, this IPC can help maintain the voltage profile by generating or absorbing reactive power as it reduces power flow between sub-networks. When a short circuit occurs on either side of the IPC 120, these reactances limit the fault current. This IPC is sometimes preferred because of its installed reactive power, which is lower than IPC 240 [5].

By adjusting the value of the susceptances, the IPC thus provides full control of powers as defined in equation (8).

$$P_S = (-V_S\,V_r\,\sin\delta_{B_1})B_1 + (-V_S V_r \sin\delta_{B_2})B_2$$
$$Q_S = (V_S^2 - V_S\,V_r\,\cos\delta_{B_1})B_1 + (V_S^2 - V_S V_r \cos\delta_{B_2})B_2 \quad (8)$$

Figure 6. Three phase diagram of the IPC 120

Is_X: Source current of phase X, for X ∈ {A, B, C}
Ir_X: Receiving current of phase X
I_B1: Inductive reactor current; I_B2: Capacitor current

The angles δ_{B1} and δ_{B2} are the phase shifts appearing between the voltages on the secondary winding side and reception side of susceptance B1 and B2 respectively.

D. United Interphase Power Controller (UIPC)

UIPC is based on an IPC 240 in which the phase-shifting is replaced by Static Synchronous Series Compensators (SSSC). Each phase of UIPC consists of three voltage-source-converters (VSCs) as shown in figure 7. The DC bus of all the three VSC modules is connected to the same bus. VSCs 1 and VSCs 2 are connected to the AC network by two series coupling transformers T_1 and T_2.

Considering the model shown in figure 7, the output apparent power of each UIPC branch is determined as follows:

$$\underline{S}_k = P_k + jQ_k = \underline{V}_r.\underline{I}^*_k \quad (9)$$
$$\underline{I}_k = jB_{eqk}(\underline{V}_s - \underline{V}_{sek} - \underline{V}_r) \; for \; k = 1 \; and \; 2. \quad (10)$$

The main function of transformer is the injection of the voltage which ideally shift the phase angle of Vs. The VSC 3 is connected to the shunt transformer T3 to the input bus of UIPC. VSC 3 provides the active power-exchange between the two VSCs by regulating the DC bus capacitor voltage and the magnitude of Vs.

Figure 7. UIPC Single-line diagram

C1, C2, C3: Signal control of VSC X, for X ∈ {1, 2,3}
Ps + iQs: Input real power
Pr + j Qr: Output real power

Thus, UIPC has the same power flow control properties as well the magnitude of the voltage at the local bus as the mitigation of the fault current. Finally, with the presence of the SSSC in this device, the power controlled by UIPC is greater than that of IPC 240 [9-11].
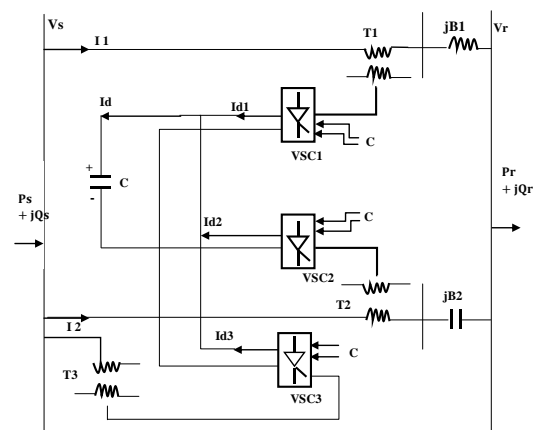
III.   BENEFITS AND COMPARISON

A.   Advantages

IPC technology can be used in several power system applications for harmonic-free operations:
- Active and reactive power control under normal and post contingency conditions,
- Stabilize the flow of power between two sub-networks,
- When this device is tuned, it is used mainly for the fault current mitigation of the short circuit current so that the short circuit on one side of the IPC is not transferred to the other side of this IPC.

In addition, to date, the problem of overvoltage on reactances has already been solved [12].

B. Comparison

Two basic observations can be made such as the behavior of this device compared to a transmission line, with or without series compensation, and a phase-shifting transformer.

TABLE III.   COMPARISON OF IPC SENSITIVITY TO CERTAIN EQUIPMENT

Equipment	Sensitivity to power angle δ	
	P	Q
IPC	Low	High
Series or non-series compensated line	High	Low
Phase-shifting transformer	High	Low

Another comparison of this technology with conventional solutions to solve power system problems is presented in Table 4 [13,14].

TABLE IV.   COMPARISON OF IPC TECHNOLOGY WITH CONVENTIONAL SOLUTIONS

Classic solution	Application	Main advantage of IPC over classic solution
High Voltage Direct Current (HVDC) link	Asynchronous link	No generation of harmonic. No reactive power consumption Robustness.
Phase-shifting transformer	Synchronous link	Passive real power control. Fault current limitation.
System or transformer station redesign	Transformation or capacity increase	Cost reduction in certains cases. Maintenance of operating flexibility.
Phase-shifting transformer	Line power flow control	Cost reduction Lost reduction

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CONCLUSION

With over twenty years of research and development, IPC technology can be considered mature. This paper presents the main features of the main Interphase Power Controller by describing the importance of each property. It also emphasizes the role of IPC devices in power transmission lines to ensure good control and specially to limit fault currents. Finally, a comparison of its functions vis-à-vis traditional solutions was recalled.

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