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STEADY STATE OPERATION OF INTERPHASE POWER CONTROLLER (IPC) USING POWER ELECTRONIC CONVERTER

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***Abstract*-- The paper described the variant of Interphase Power Controller (IPC) conjugated with power electronic converter. This form of IPC provides more independent control both active and reactive power flows. Schematic configuration of device is described. The control strategy for the steady state operation to maintain the required power characteristic of IPC is outlined. The preliminary results confirm the expected behavior of device.**

***Index Terms*-- Interphase Power Controller, power electronic converter, power transmission, control strategy, phasor diagram, control strategy, operating area.**

I. INTRODUCTION

THE power flow distribution at the interconnected power systems is a function of the networks phase shift angle (δ) between the voltages at the input and output terminals of each transmission line. Any fluctuation in this angle is accompanied by corresponding fluctuation of active power exchanged through transmission. In some cases this leads to undesirable effects. Particularly, dangerous oscillatory processes can be initiated when you synchronize power systems with equipment of different standards of devices for control the system frequency, for example in situation concerning the coupling of Eastern and Western Europe. Some of these, and similar, problems can be reduced through the use of IPC.

The inherent power characteristics of Interphase Power Controller [1,2,3,4] are passive in nature. Therefore it does not interact with other power flow devices. Because of the high values of its internal impedances, the IPC limits the contribution to a short circuit. The controller can prevent undesirable loop flows and may also be used to reduce mutual impact in the possible contingencies affecting the basic transmission lines of interconnected power systems. In addition, the IPC provides decoupling effect which limits the spread of the transient oscillations processes to neighboring areas of network. The substantial improvement of power systems efficiency can be provided by a rational allocation of such devices at the appropriate transmission terminals. More favorable operating conditions will be achieved with the applying of additional power electronic converter.

II. SCHEMATIC CONFIGURATION OF DEVICE

Figure 1 shows the schematic configuration of IPC conjugated with power electronic converter UPFC (Unified Power Flow Controller). It is a series-connected controller consisting phase shifting transformer (ET) with fixed internal phase shift $(\psi = 30^\circ)$ which provided by its high voltage windings W_1 and W_2, two conjugated susceptances $|-B_1| = |B_2| = B$ (one of them is inductive of nature, another is capacitive), boosting transformer (BT) and two back-to-back connected inverters (Inv.1 and Inv.2) which forms the power electronic converter.

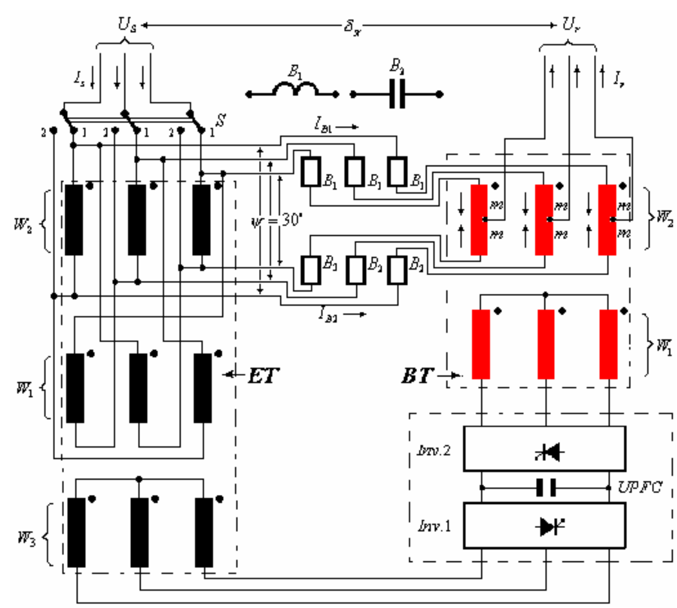

Fig. 1. Schematic diagram illustrating the IPC using power electronic converter

The switch S performs the reversal of sign of the angle ψ that allows adapting the working area of IPC to the operation conditions of networks. Submitted version of power flow

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controller belongs to a family of IPC with the shifted characteristics. It should be noted that output contacts of device are positioned at the middle points of high-voltage windings W_2 which belongs to the booster transformer BT. This is a quite different way for voltage injection into UPFC practice in comparison with the well-known method.

Converter is powered by additional winding (W_3) of transformer ET. The boosting transformer BT is powered by inverter Inv.2. This boosting transformer in due course provides injection of control voltage $mU_S e^{j(\alpha+\delta_{sr})}$. The generalized voltage injection, which allows the full 360 degrees variation of the angle α as well as simultaneous control of magnitude m, makes it possible to control both the real and reactive power flow in the transmission line. Phasor diagram, illustrating the general concept of voltage injection, is shown on Figure 2.

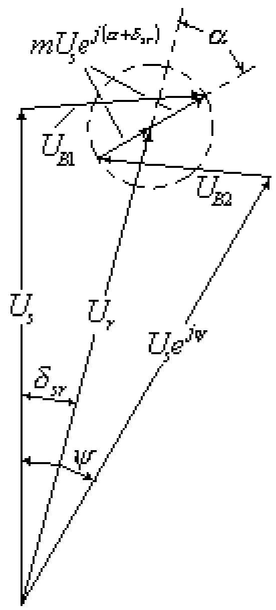

Fig. 2. Phasor diagram illustrating the regulation of injected voltage

To both sides of the network the IPC is appears as a voltage-dependent current source. Therefore, the more significant controlled parameter of the device is its output operating current (I_r) which depend from injected control voltage $mU_S e^{j(\alpha+\delta_{sr})}$.

The geometric relationships, as defined by the phasor diagram in Figure 2, allow us to present the following equations (1):

$$\begin{aligned} &U_s + U_{B1} - mU_s e^{j(\alpha+\delta_{sr})} - U_r e^{j\delta sr} = 0, \\ &U_s e^{j\psi} + U_{B2} + mU_s e^{j(\alpha+\delta_{sr})} - U_r e^{j\delta sr} = 0. \end{aligned} \tag{1}$$

Then the applied voltages on the conjugated susceptances B_1 and B_2 would obey the conditions (2):

$$\begin{aligned} U_{B1} &= U_r e^{j\delta_{sr}} - U_s\left[1 - me^{j(\alpha+\delta_{sr})}\right], \\ U_{B2} &= U_r e^{j\delta_{sr}} - U_s\left[e^{j\psi} + me^{j(\alpha+\delta_{sr})}\right]. \end{aligned} \tag{2}$$

The currents of susceptances (3):

$$\begin{aligned} I_{B1} &= -jB_1 U_{B1}, \\ I_{B2} &= jB_2 U_{B2}, \end{aligned} \tag{3}$$

where:

$$I_{B1} = -jB_1 U_{B1}; \quad U_{B1} = U_r e^{j\delta_{sr}} - U_s\left[1 - me^{j(\alpha+\delta_{sr})}\right];$$

$$I_{B2} = jB_2 U_{B2}; \quad U_{B2} = U_r e^{j\delta_{sr}} - U_s\left[e^{j\psi} + me^{j(\alpha+\delta_{sr})}\right].$$

The sum of these conjugated currents is the output current (I_r) of IPC (4):

$$\begin{aligned} I_r &= I_{B1} + I_{B2} = jB\left(U_{B2} - U_{B1}\right) = \\ &= 2BU_s\left[\sin\frac{\psi}{2} e^{j\frac{\psi}{2}} - jme^{j(\alpha+\delta_{sr})}\right]. \end{aligned} \tag{4}$$

Similarly can be presented the input current (I_s) of IPC (5):

$$I_s = 2BU_r\left[\sin\frac{\psi}{2} e^{j\left(\delta_{sr}-\frac{\psi}{2}\right)} - jm\frac{U_s}{U_r}\cos\frac{\psi}{2} e^{j\left(\delta_{sr}-\frac{\psi}{2}+\alpha\right)}\right]. \tag{5}$$

Under these conditions the apparent power S_r at the output terminals of the device can be expressed as follows (6):

$$\begin{aligned} S_r &= I_r \overset{*}{U}_r = I_r U_r e^{-j\delta_{sr}} = \\ &= 2BU_s U_r \sin\frac{\psi}{2}\left[e^{j\left(\frac{\psi}{2}-\delta_{sr}\right)} - j\frac{m}{\sin\frac{\psi}{2}} e^{j\alpha}\right]. \end{aligned} \tag{6}$$

Active and reactive components (P_r and Q_r) (7,8) of the apparent output power S_r:

$$P_r = S_m\left[\cos\left(\frac{\psi}{2} - \delta_{sr}\right) + \frac{m}{\sin\frac{\psi}{2}}\sin\alpha\right], \tag{7}$$

$$Q_r = S_m\left[\sin\left(\frac{\psi}{2} - \delta_{sr}\right) - \frac{m}{\sin\frac{\psi}{2}}\cos\alpha\right], \tag{8}$$

where $S_m = 2BU_s U_r \sin\frac{\psi}{2}$.

Similarly the apparent power S_s at the input terminals of the device (9):

$$\begin{aligned} S_s &= I_s U_s = \\ &= 2BU_s U_r \sin\frac{\psi}{2}\left[e^{j\left(\delta_{sr}-\frac{\psi}{2}\right)} - j\frac{m}{tg\frac{\psi}{2}}\frac{U_s}{U_r} e^{j\left(\delta_{sr}-\frac{\psi}{2}+\alpha\right)}\right]. \end{aligned} \tag{9}$$

Active and reactive components (P_s and Q_s) of the apparent output power S_s (10):

$$\begin{aligned} P_s &= S_m\left[\cos\left(\delta_{sr} - \frac{\psi}{2}\right) + \frac{m}{tg\frac{\psi}{2}}\frac{U_s}{U_r}\sin\left(\delta_{sr} - \frac{\psi}{2} + \alpha\right)\right], \\ Q_s &= S_m\left[\sin\left(\delta_{sr} - \frac{\psi}{2}\right) - \frac{m}{tg\frac{\psi}{2}}\frac{U_s}{U_r}\cos\left(\delta_{sr} - \frac{\psi}{2} + \alpha\right)\right]. \end{aligned} \tag{10}$$

Assuming m=0, we obtain the well-known equations that determine the response of usual IPC to variations of phase angle δ_{sr} between input voltage U_s and output voltage U_r (11,12):

$$P_r = S_m\cos\left(\frac{\psi}{2} - \delta_{sr}\right); \quad Q_r = S_m\sin\left(\frac{\psi}{2} - \delta_{sr}\right); \tag{11}$$

$$P_s = S_m \cos\left(\delta_{sr} - \frac{\psi}{2}\right); \quad Q_s = S_m \sin\left(\delta_{sr} - \frac{\psi}{2}\right). \qquad (12)$$

Thus we come to a result ($P_s = P_r$ and $Q_s = -Q_r$) which correspond with power characteristics presented in [2].

III. Steady State Operation Of IPC With Power Electronic Converter

Figure 3 shows the simplest situation that allows us to analyze the main features of steady state operation with IPC and power electronic converter in order to control power flow of transmission line.

Sending end of transmission system is presented by voltage $U_1 = U_s$, receiving end – by the voltage $U_2 = U_1 e^{j\delta}$. In so doing we assume that the two connected subsystems are able to accurately maintain the equality of modules $|U_1| = |U_2|$. This precondition can be satisfied if the potential power capacities of subsystems are much higher of transmitted by the line or through the use of appropriate Var compensators The phase shift δ between these voltages U_1 and U_2 is arbitrary. It is defined as result of the common power flows distribution in the system. To simplify the situation the transmission line is presented only by reactance X, that in turn, determines the angle γ caused by load current I_r. So the phase angle δ_{sr} between U_s and U_r is given: $\delta_{sr} = \delta - \gamma$.

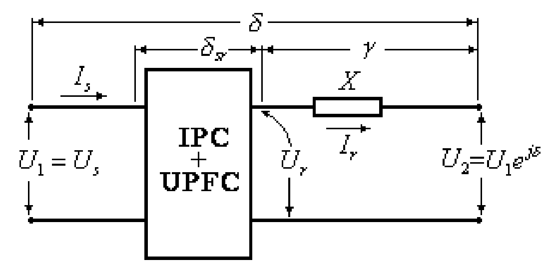

Fig. 3. Operating conditions of IPC with power electronic converter

Due to the high internal impedance of IPC its output voltage obtains an uncertain character. The voltage in question is very perceptible to the modulus and phase shift of load current I_r. To demonstrate how the IPC with power electronic converter can be used for the management of power flow within the alternative current network, it is necessary to formulate the requirements for the output voltage U_r. The voltage stability when applied to power systems is the most typical and frequent requirement. Therefore, for our examples we assume the situation of equality of input and output voltages of device $|U_r| = |U_s|$. Phasor diagram showing the method of stabilizing the output voltage U_r is shown on Figure 4.

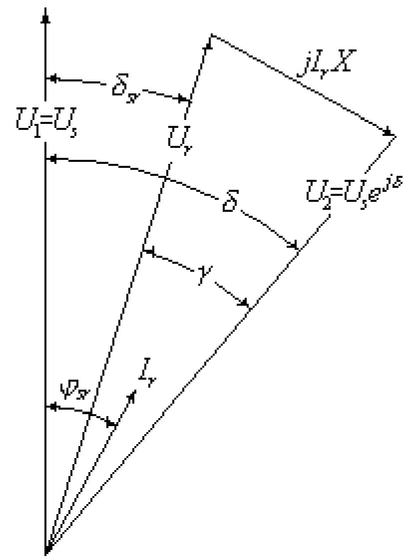

Fig. 4. Phasor diagram showing the method of stabilizing the output voltage U_r

This requirement will be fulfilled if, during the change of the angle δ, you will observe the conditions (13):

$$\varphi_{sr} = \delta - \frac{\gamma}{2};$$

$$\alpha_{1,2} = \frac{\gamma}{2} \pm \arccos\left[\frac{\sin\frac{\psi}{2}}{m}\sin\left(\frac{\psi}{2} + \frac{\gamma}{2} - \delta\right)\right], \qquad (13)$$

where:

$$\varphi_{sr} = arctg\frac{\operatorname{Im}(I_r)}{\operatorname{Re}(I_r)}$$

and $\gamma = arc\cos\left(1 - \frac{I_r^2 X^2}{2U_s^2}\right)$.

Figure 5 shows the $\alpha(\delta)$, $\gamma(\delta)$ and $I_r(\delta)$ characteristics to illustrate the control strategy $|U_r| = |U_s|$. These characteristics correspond to three different angular length (γ_0) of the transmission line: $\gamma_0 = 0^\circ$, $\gamma_0 = 15^\circ$ and $\gamma_0 = 30^\circ$. The angular offset for characteristics is depending on the angular length which can be determined as $\gamma_0 = \gamma$ on condition $I_r = 1$ and $U_s = 1$. All these and the next ensuing characteristics are obtained with $m = 0,068 = const$. This value of m is minimal if necessary to ensure the continuity of control, when we alter the sign of ψ through the use of switch S. The main (lower) scale of angle δ variation in Figure 5 belong to position 1 of network switch S while the additional (upper) scale correspond to position 2.

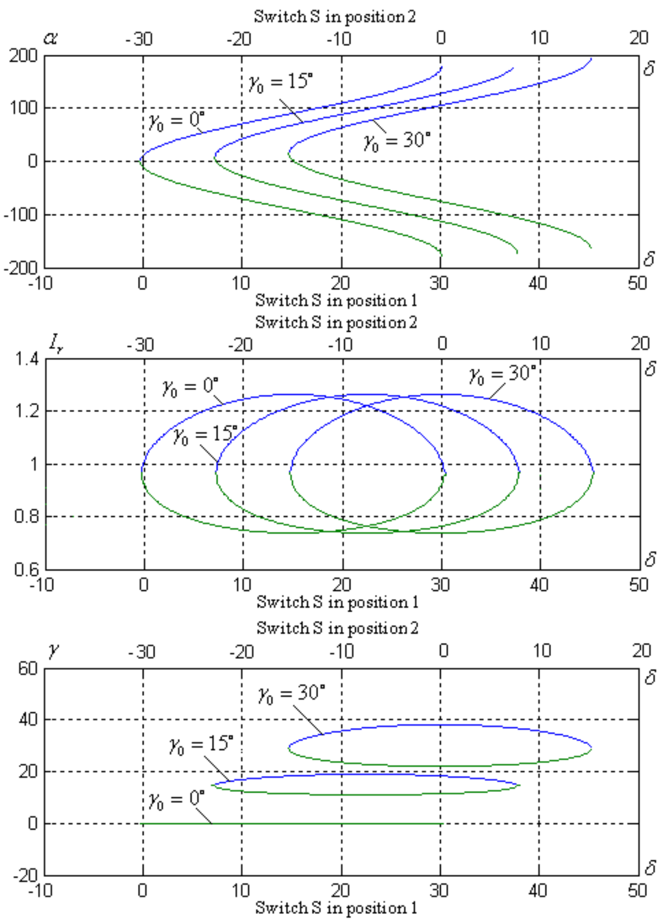

Fig. 5. The $\alpha(\delta)$, $\gamma(\delta)$ and $I_r(\delta)$ characteristics illustrating the control strategy $|U_r| = |U_s|$

Operation capability of IPC equipped with power electronic converter is illustrated in Figure 6. As it follows from pointed figure, the operating area of input active power $P_s = f(\delta)$ as well as operating area of output active power $P_r = f(\delta)$ of controller could be depicted as configuration that resembles an ellipsis. So the operating level of active power flow can be continuously controlled within the each of selected operating area. Power characteristics $Q_r = f(\delta)$ describes the operative areas for reactive power at the output terminals of IPC. This reactive power is concentrated in the reactance of transmission. It decreases with the decreasing of transmission length and becomes zero when $\gamma_0 = 0$.

Power characteristics $Q_s = f(\delta)$ describes the operative areas for reactive power at the input terminals of IPC. This reactive power defines the capacity of the shunting Var compensation if it needs to support voltage U_s at the bus of feeding substation. Additional opportunities for control of reactive power by means of invertors (Inv.1 and Inv.2) are not considered.

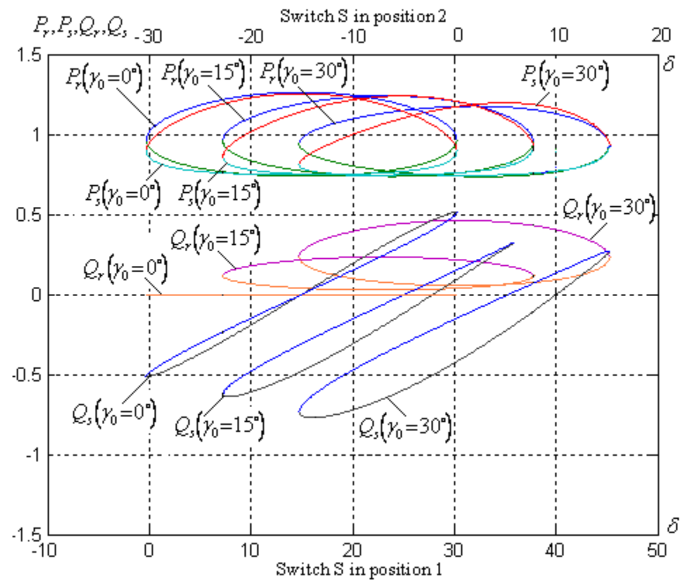

Fig. 6. Operation capability of IPC equipped with power electronic convtrter

Power electronic converter (UPFC) is a device which can transmit the active power only. Therefore, the difference $(P_r - P_s)$ will determine the active power transmitted through the converter. Maximum of this difference should be considered as the rated capacity of the converter. At the pieces where $P_r \succ P_s$ the power transfer through converter is coincides with the power transfer through IPC. At the pieces where $P_r \prec P_s$ is backwards. The graphs describing the difference $(P_r - P_s)$ for the three taken variants of power transmission angular length γ_0 are represented in Figure 7.

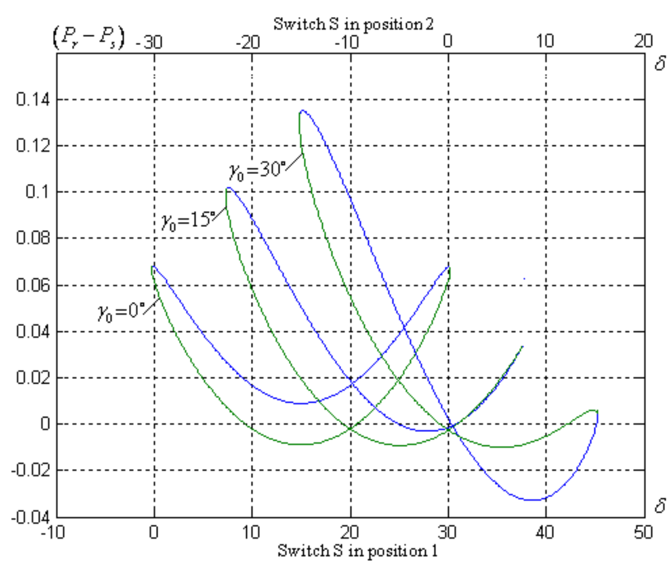

Fig. 7. Rated capacity of power electronic converter with different angular length (γ_0) of transmission and $m = 0{,}068 = const$

Consideration of these graphs shows that the increase in the angular length of the transmission line is accompanied by increased rated capacity of power electronic converter.

Operation capability of IPC equipped with power electronic converter can be expanded by changing the control strategy for maintenance of output voltage U_r. Unlike to the previously adopted situation $|U_r| = |U_s|$, one can formulate any other conditions for maintenance of U_r, not inconsistent with the processes in the power systems. For illustration, let us consider two additional possible options of control strategy U_r.

The first one relates to situation, where $|U_r| \prec |U_s| = 1$. Phasor diagram for this situation is shown in Figure 8.

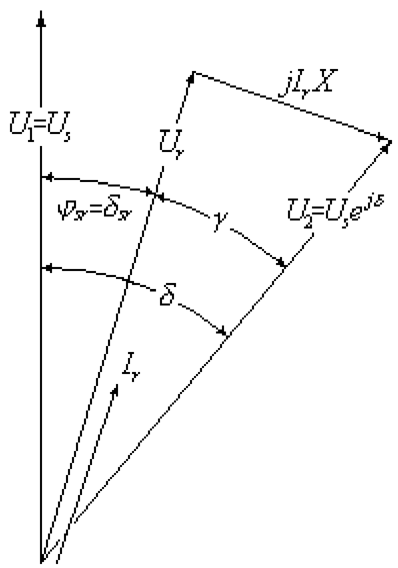

Fig. 8. Phasor diagram showing the method of control output voltage $|U_r| \prec |U_s| = 1$

The control strategy, corresponding to this phasor diagram, can be mathematically represented as follows (14):

$$U_r = U_s \cos\gamma;\ \ \varphi_{sr} = \delta_{sr} = \delta - \gamma;\ \ \gamma = \arcsin\frac{I_r X}{U_s};$$
$$\alpha_{1,2} = \gamma \pm \arccos\left[\frac{\sin\frac{\psi}{2}}{m}\sin\left(\frac{\psi}{2} - \delta\right)\right]. \tag{14}$$

The second option relate to situation, where $|U_r| \succ |U_s| = 1$. Phasor diagram for this situation is shown in Figure 9. The control strategy, corresponding to this phasor diagram, can be mathematically represented as follows (15):

$$U_r = \frac{U_s}{\cos\gamma};\ \ \varphi_{sr} = \delta;\ \ \gamma = \mathrm{arc}\,tg\frac{I_r X}{U_s};$$
$$\alpha_{1,2} = \pm\arccos\left[\frac{\sin\frac{\psi}{2}}{m}\sin\left(\frac{\psi}{2} + \gamma - \delta\right)\right]. \tag{15}$$

Computational characteristics of $U_r = f(\delta)$ for both assumed conditions, with angular transmission length $\gamma_0 = 15^\circ$ and $m = 0{,}068$, are depicted in Figure 10. It is evident that under these conditions the voltage deviation of U_r is in the permissible limits.

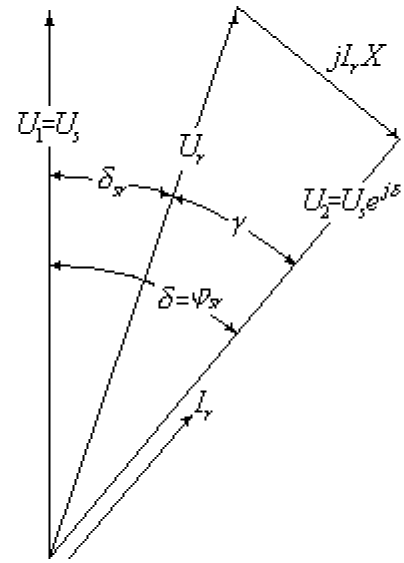

Fig. 9. Phasor diagram showing the method of control output voltage $|U_r| \succ |U_s| = 1$

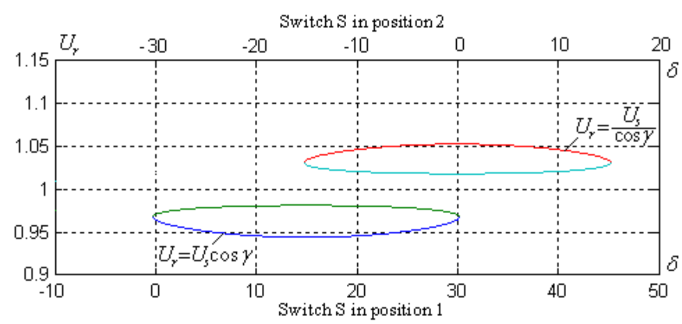

Fig. 10. Computational characteristics of $U_r = f(\delta)$.

The basic power characteristics of device, taking into account both previous conditions to control the magnitude of output voltage U_r, are shown in Figure 11.

As it follows on consideration of power characteristics, the actual operating areas of device is noticeable changes depending on the accepted control strategy.

The first option provides the noticeable shift of power characteristics to the left side of network angle δ diapason, in the second case - to the right. It should be noted that the power characteristics $P_r = f(\delta)$ and $P_s = f(\delta)$, that correspond to condition $|U_r| \succ |U_s| = 1$, has the broader range of controllability. Additionally, under these conditions, the control area of reactive power $Q_r = f(\delta)$ is significantly narrowed and partially negative.

An adopted control strategy also identifies the rated capacity of power electronic converter. The difference $(P_r - P_s)$ which determine the active power transmitted

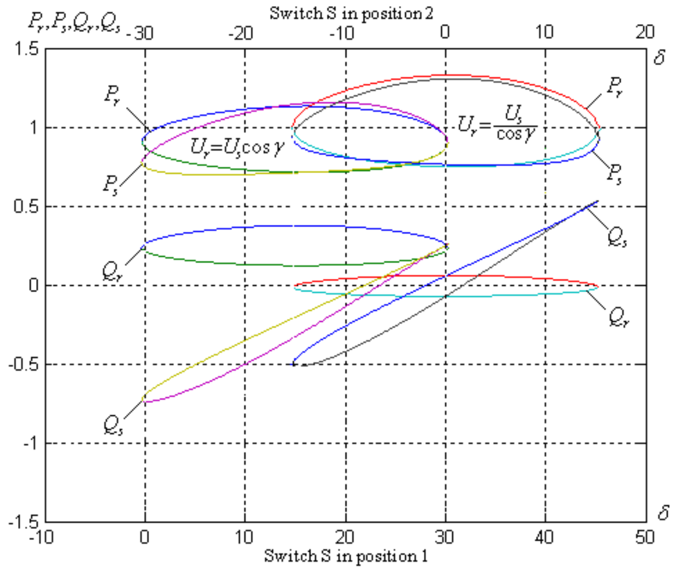

Fig. 11. Power characteristics of device in condition $U_r = U_s \cos(\gamma)$ and $U_r = U_s / \cos\gamma$

through the converter, for the both additional options reviewed, is shown in Figure 12. The representation of these characteristics testifies that in the case $|U_r| \succ |U_s| = 1$, rated capacity of power electronic converter is significantly lower.

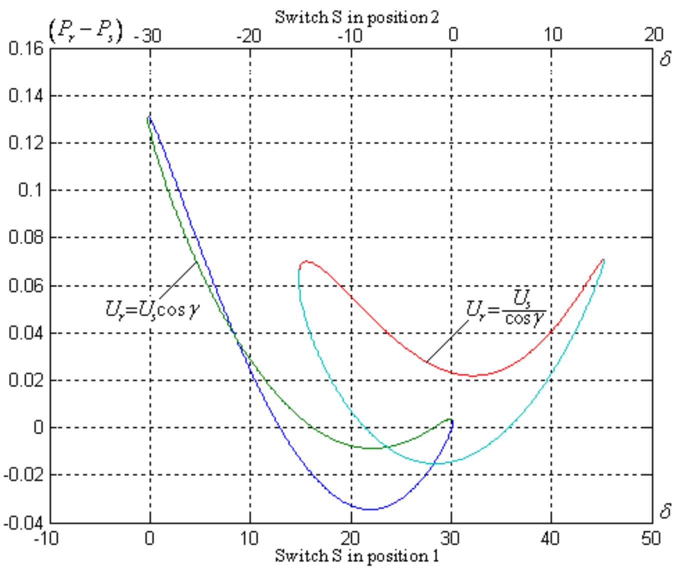

Fig. 12. Rated capacity of power electronic converter in condition $U_r = U_s \cos(\gamma)$ and $U_r = \frac{U_s}{\cos\gamma}$

Thus, introduction and consideration of IPC using power electronic converter shows the expediency of practical application of this device for steady state power flow control in transmission systems.

IV. Conclusion

The paper has defined the principal characteristics of Interphase Power Controller using power electronic converter. The practical realization of device can be implemented by utilization of two well-known FACTS controllers. Thus, the new power flow controller can be constructed for sufficient rating of applications in high voltage power system.

V. References

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