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INTERPHASE POWER CONTROLLER (IPC) USING ROTARY TRANSFORMERS

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Abstract **– This paper introduces a new variant of IPC using rotary transformers for independent control of active and reactive output power, the control strategy is presented to maintain the required power characteristics.**

Keywords: *phase shifting transformer, susceptances, rotary transformers, injected voltage.*

1. INTRODUCTION

The IPC technolody is designed to improve the management of power flow in AC networks.The controller uses conventional elements only:a phase shifting transformers, two susceptances (one inductive and the other capacitive) and circuit breakers. The desired power level can be adjusted by changing either the internal phase shift angles or the values of the susceptances. Greater operating flexibility can be achieved by the use of rotary transformers.

2. PRINCIPLE OF OPERATION AND POWER CHARACTERISTICS

The power characteristics of an IPC with the use of rotary transformers can be demonstrated on the base of device [1] where the position of the power control characteristic is offset and where its useful portion is shifted with the level of the power set point (Adapted IPC).

Figure 1 illustrates the internal connections of Interphase Power Controller with shifted characteristics and the use of rotary transformers. It is a series-connected controller consisting of phase shifting transformer (ET) with fixed internal phase shift (ψ), two conjugated susceptances (B_1 and B_2), booster transformer (BT) and two rotary transformers (RT1 and RT2).

Rotary transformers [2] are constructed similarly to a wound-rotor induction machines. By connecting the stator windings (W_S) in parallel and the rotor windings (W) in series, it is possible to control the magnitude (m) and phase shift (α) of the generalised voltage injection as shown in Figure 2.

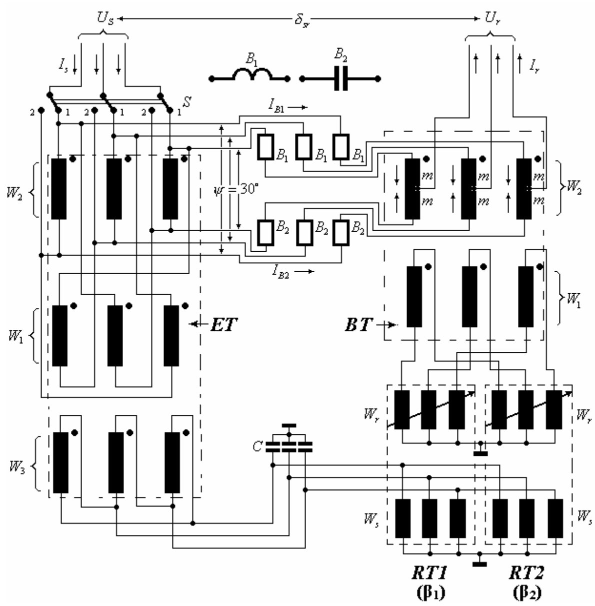

Figure 1. Schematic diagram illustrating the IPC using rotary transformers

The variation of m and α by mechanical adjusting of rotary transformers angular turnings $\beta 1$ and $\beta 2$, makes it possible to control both the magnitude and the angle of the line current without the need for more expensive power electronic devices.

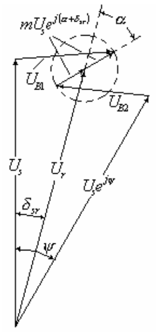

Figure 2. Phasor diagram illustrating the regulation of injected voltage

Phasor diagram shown in Figure 2 (for condition $\left|-B_1\right| = \left|B_2\right| = B$) determines the operating output current $\left(I_r\right)$ of IPC by following equation:

$$I_r = I_{B1} + I_{B2} = jB\left(U_{B2} - U_{B1}\right) = \\ = 2BU_s\left[\sin\frac{\psi}{2}e^{j\frac{\psi}{2}} - jme^{j\left(\alpha+\delta_{sr}\right)}\right],$$

where:

$$I_{B1} = \text{-}jB_1U_{B1};$$

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

$$I_{B2} = jB_2U_{B2};$$

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

The apparent output power $\left(S_r\right)$ of IPC:

$$S_r = I_r \cdot \overset{*}{U_r} = I_r \cdot U_re^{-j\delta_{sr}} = \\ = 2BU_sU_r\sin\frac{\psi}{2}\left[e^{j\left(\frac{\psi}{2}-\delta_{sr}\right)} - j\frac{m}{\sin\frac{\psi}{2}}e^{j\alpha}\right].$$

Active and reactive components (P and Q) of the apparent output power S:

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

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

where: $S_m = 2BU_sU_r\sin\frac{\psi}{2}$.

The input operating current of IPC can be expressed as follow:

$$I_s = I_{B1} + I_{B2}e^{-j\psi} = \\ = 2BU_r\left[\sin\frac{\psi}{2}e^{j\left(\delta_{sr}-\frac{\psi}{2}\right)} - jm\frac{U_s}{U_r}\cos\frac{\psi}{2}e^{j\left(\delta_{sr}-\frac{\psi}{2}+\alpha\right)}\right]$$

The apparent input power of IPC:

$$S_s = I_sU_s = \\ = 2BU_sU_r\sin\frac{\psi}{2}\left[e^{j\left(\delta_{sr}-\frac{\psi}{2}\right)} - j\frac{m}{tg\frac{\psi}{2}}\frac{U_s}{U_r}e^{j\left(\delta_{sr}-\frac{\psi}{2}+\alpha\right)}\right]$$

Active and reactive components of the apparent input power:

$$P_s = S_m\left[\cos\left(\delta_{sr} - \frac{\psi}{2}\right) + \frac{m}{tg\frac{\psi}{2}}\cdot\frac{U_s}{U_r}\sin\left(\delta_{sr} - \frac{\psi}{2} + \alpha\right)\right],$$

$$Q_s = S_m\left[\sin\left(\delta_{sr} - \frac{\psi}{2}\right) - \frac{m}{tg\frac{\psi}{2}}\cdot\frac{U_s}{U_r}\cos\left(\delta_{sr} - \frac{\psi}{2} + \alpha\right)\right].$$

Let's assume further that operating problems of IPC are reduced to formation the required output power characteristics in situation where angle δ_s imposed by the network is changing from $\delta_{sr} = 0$ to $\delta_{sr} = 30^\circ$.With a view of simplification of the subsequent calculations all further results correspond to a condition $\left|U_s\right| = \left|U_r\right| = 1$.On the need to support both the requested values of P and Q the control strategy for IPC can be formulated as it follows :

$$m = \frac{P_r\sin\left(\frac{\psi}{2} - \delta_{sr}\right) - Q_r\cos\left(\frac{\psi}{2} - \delta_{sr}\right)}{P_r\cos\alpha + Q_r\sin\alpha}\sin\frac{\psi}{2},$$

$$\alpha = arctg\frac{P_r - S_m\cos\left(\frac{\psi}{2} - \delta_{sr}\right)}{S_m\sin\left(\frac{\psi}{2} - \delta_{sr}\right) - Q_r}.$$

Tuning of a phasor $\dot{m} = me^{j\alpha}$ on a value and on a phase provides the previously settled control conditions for IPC.

The basic equations for real and reactive components of power at the output terminals of IPC also allow to determine the full area of P free control at a preset value of Q or on the contrary - the full area of Q free control at a preset value of P :

$$P_r = S_m \left\{ \cos\left(\frac{\psi}{2} - \delta_{sr}\right) \pm \right.$$

$$\left. \pm \sqrt{\cos^2\left(\frac{\psi}{2} - \delta_{sr}\right) - \frac{Q_r}{S_m}\left[\frac{Q_r}{S_m} - 2\sin\left(\frac{\psi}{2} - \delta_{sr}\right)\right] - \left(1 - \frac{m^2}{\sin^2\frac{\psi}{2}}\right)} \right\}$$

$$Q_r = S_m \left\{ \sin\left(\frac{\psi}{2} - \delta_{sr}\right) \pm \right.$$

$$\left. \pm \sqrt{\sin^2\left(\frac{\psi}{2} - \delta_{sr}\right) - \frac{P_r}{S_m}\left[\frac{P_r}{S_m} - 2\cos\left(\frac{\psi}{2} - \delta_{sr}\right)\right] - \left(1 - \frac{m^2}{\sin^2\frac{\psi}{2}}\right)} \right\}$$

Potential areas for control of active power in situations relative to different values of preset reactive power at the output terminals of IPC are shown on Figure 3. The first situation relevant to condition $Q_r = 0$, the second - to condition $Q_r = S_m \sin\left(\frac{\psi}{2} - \delta_{sr}\right)$ what is in conformity with the absence of any special request to Q .Oval configuration correspond to a first situation, the full shadowed area describes the full control ability of examined IPC with $S_m = 1$ and $m = 0,075$.

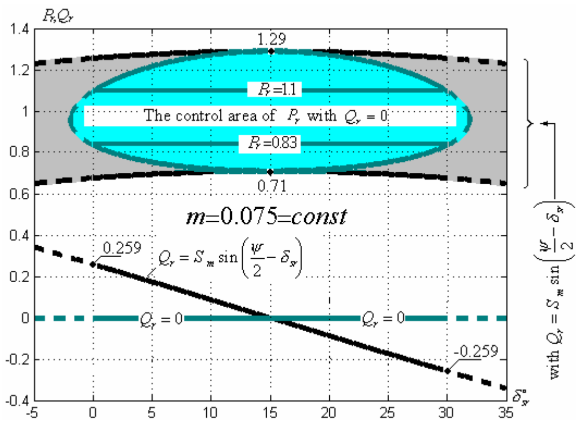

Figure 3. Typical capability P characteristics of IPC using rotary transformers

The chosen on Figure 3 two horizontal lines ($P_r = 0,83$ and $P_r = 1,1$) are define the limits of uninterrupted control within accepted framework of δ_s change $\left(0 \le \delta_{sr} \le 30^\circ\right)$ at $Q_r = 0$. Control strategy for realization of above mentioned conditions by means of tuning phasor **m** is submitted on Figure 4.

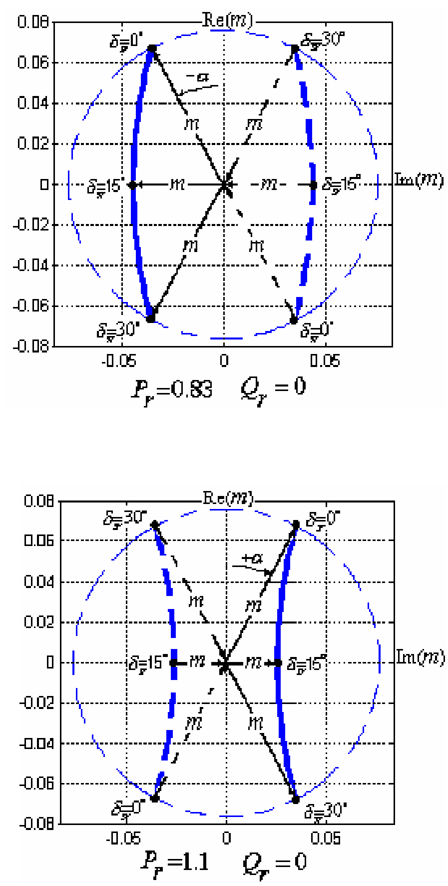

Figure 4. Variations of injected voltage with $P_r = 0,83\ (Q_r = 0)$ and $P_r = 1,1\ (Q_r = 0)$.

Figure 5 represent the variation of voltages on susceptances U_{B1} and U_{B2} for a limited range of system angles $\delta_{sr} = 0^\circ \div 30^\circ$:

$$U_{B1} = U_r \sqrt{\left[\sin\delta_{sr} + m\sin(\alpha + \delta_{sr})\right]^2 + \left[\cos\delta_{sr} + m\cos(\alpha + \delta_{sr}) - 1\right]^2}\ ,$$

$$U_{B2} = U_r \sqrt{\left[\sin\delta_{sr} - m\sin(\alpha + \delta_{sr}) - \sin\psi\right]^2 + \left[\cos\delta_{sr} - m\cos(\alpha + \delta_{sr}) - \cos\psi\right]^2}\ .$$

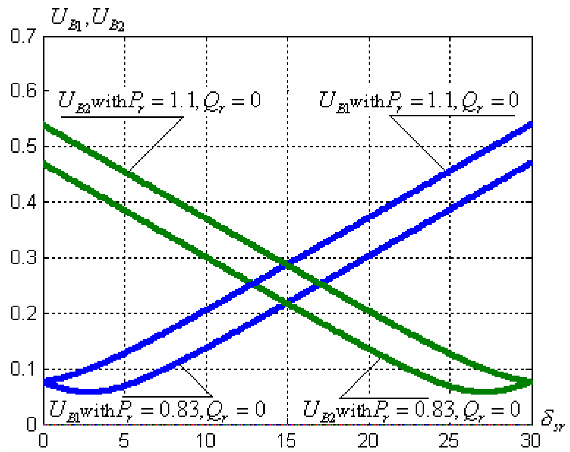

Figure 5. Voltages across susceptances as function of angle δ_S

Settlement borders for independent control of reactive output power at the two indicated limiting levels of active output power ($P_r = 0{,}83$ and $P_r = 1{,}1$) are illustrated with Figure 6 whence follow that within accepted limits of P the full area of Q control changes rather insignificantly.

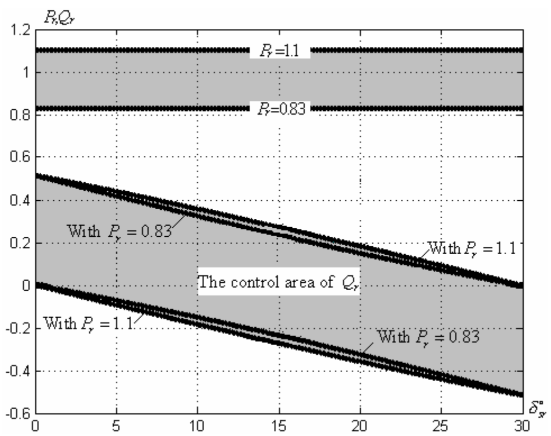

Figure 6. Settlement borders for independent control of reactive output power for condition $P_r = 0{,}83$ and $P_r = 1{,}1$.

3. CONCLUSIONS

Interphase power controller using rotary transformers possesses the ability to generate and absorb both real and reactive power. The new variant of power flow controller, described in this paper, provides a rather simple and potentially less expensive alternative for the smooth power control in comparison with power electronic devices.

Glossary

Per unit values are used throughout the text wherein:

B_1 -negative susceptance;

B_2 -positive susceptance;

I_{B1} -current of susceptance $B1$;

I_{B2} -current of susceptance $B2$;

I_S - input operating current of IPC;

I - output operating current of IPC;

U_{B1} -voltage on susceptance $B1$;

U_{B2} -voltage on susceptance $B2$;

U_s -voltage of sending end;

U_r -voltage of receiving end;

ψ -phase shift created by transformer ET;

S -on-load switch to reverse angle ψ ;

δ_{sr} -phase difference between U_s and U_r ;

C -compensation of magnetizing current;

m -modulus of injected voltage;

α -phase shift of injected voltage.

References

[1] J.Brochu, F.Beauregard, Et al., *Interphase power controller adapted to the operating conditions of networks*, IEEE Trans. on Power Delivery, Vol.10, No.2, April 1995.

[2] H.Fujita, D.H. Baker Et al., Power flow controller using rotary phase-shifting transformers, Session 37-102, CIGRE 2000.