# Damping Algorithm based on Phasor Estimation

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Abstract: The paper describes a new method to generate the reactance reference for a TCSC, which has been installed in order to provide damping in a power system. The knowledge of the expected oscillation frequency in the power system is used to create a coordinate system, which rotates with that frequency. In this coordinate system a phasor representing the power swing is being extracted from the input power signal. A reactance reference signal with arbitrary gain and phase shift can easily be created using the phasor. The phase of the reactance reference is preserved during limiting. Gain and phase-shift may comfortably be scheduled due to measured parameters like average power, power swing amplitude etc. Frequency compensation has been implemented, and adapts the frequency in the measuring system when a power oscillation occurs. The new approach has been implemented and successfully tested in the North-South Interconnection in Brazil in March 1999 and has been in operation since then. The scheme is applicable for PSS and other FACTS damping systems.

Keywords: FACTS, TCSC, Controller Design, Power Oscillation Damping

## I. INTRODUCTION

The integration of two neighbouring power systems by an interconnecting line may often offer attractive benefits to both parties. The use of an AC intertie permits the investments to be spread in time to make pace with the growing demand and opens the possibility to connect generation and/or load along the power line corridor. However, in the initial stage of the power system integration, the power transfer capability of the interconnecting line may be low as compared to the installed power in the connected systems in the line terminals. The integrated power system therefore is prone to low-frequency "inter-area" power swings, when the equilibrium between generation/load balance in each system and the power transfer along the interconnection line is being disturbed. Such disturbances may e.g. be caused by trip of a generator or loss of a main transmission line. The frequency of such inter-area oscillations is low, typically in the range 0.1-0.4 Hz. The very low frequency makes Power System Stabilisers (PSS) less effective as the reactance between the inner emf in the generator and the terminal rather is the synchronous reactance than the transient reactance. FACTS devices can be used to provide damping in this situation. Thyristor Controlled Series Capacitor (TCSC) has proven to be an effective means for this purpose [1-3]. The TCSC is being installed directly in the high-voltage circuit without any need for high-voltage interfacing transformer. By thyristor control the inserted (capacitive) reactance can be varied in order to dampen power oscillations. When a power oscillation occurs it is varied in pace with the power swing and with a phase shift of -90°.

A power disturbance in the interconnection line typically appears as in figure 1.

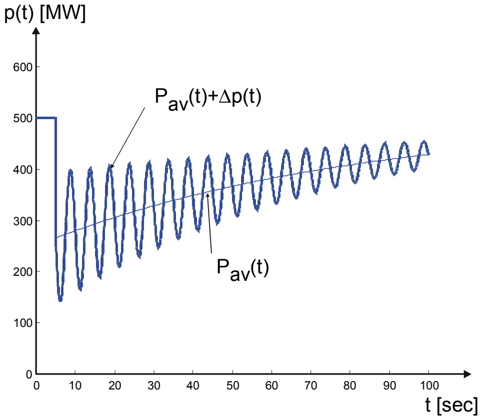

Fig. 1. Typical power disturbance.

A sudden change of the average power occurs at the onset of the power oscillation. A high-level power control system slowly restores the average power towards a new equilibrium level by intervention to the power dispatch control. The TCSC of course can not change the average power and it is supposed to react on the oscillation only. In order to control the TCSC so that it brings about damping of the power oscillation it is crucial that the oscillation part of the measured line power signal can immediately be extracted and separated from the change in average power. A further requirement is that correct phase shift shall be preserved even when the reactance command is being limited to respect the maximum permitted main circuit stress in the TCSC.

In this paper a new approach, here called the Phasor-POD, to solve this problem will be reported. It is based on the fact that the frequency of the potential inter-area power oscillation normally is quite well known. The new method takes advantage of this information and continuously extracts a phasor that represents the existing power swing with the expected oscillation frequency from the measured power signal. In normal operation this phasor is zero, but when a power oscillation occurs the extracted phasor magnitude increseases in proportion to the swing amplitude. Its phase corresponds to the phase of the oscillation in the rotating coordinate system. The phasor representation is advantageous because a reactance command signal for the TCSC with arbitrary gain and phase shift can easily be generated.

Any implementation of FACTS apparatus reaches some maximum permitted stress when the power swing amplitude and/or the gain is sufficiently high. Its command signal then must be limited accordingly. It is important that the phase of the reactance control signal is not deteriorated by such limiting actions.

Although the power oscillation frequency is fairly well known some variations are caused by changing network configurations loading conditions etc. In order to exhaust the maximum available damping performance of the installed TCSC the desired phase shift between the power oscillation and the reactance modulation signal shall be sustained in spite of small frequency variations. The Phasor-POD concept compensates such variations when real power oscillations occur in the power system.

## II. CONVENTIONAL APPROACH

The traditional method to generate command signal for damping devices like Power System Stabilisers (PSS) and Static Var Compensators (SVC) is to filter the power signal in a number of cascaded links. On or more washout filters are used to remove the power average. The necessary phase-shift is provided by lead-lag links. The setup is depicted in figure 2.

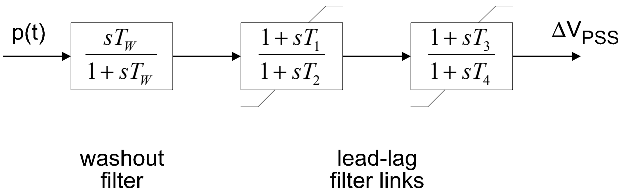

Fig. 2. Conventional filter setup to create damping signal.

Additional links may be inserted to suppress interaction at lower or higher frequencies than the intended ones. It should be noted that the design of the filters inherently utilises knowledge about the expected frequency of the power system oscillation and they provide correct phase shift only at one specific frequency given by the design.

Two major obstacles are encountered in this approach:

- the cut-off frequency in the washout filter must be well below the power oscillation frequency. Accordingly the (unwanted) output signal caused by the average power step does not disappear very fast
- at high power swing amplitude it is necessary to limit the damping output signal so that the main circuit of the damping equipment (TCSC, SVC or generator excitation system) remains within its dynamical range. It has proven to be difficult to accomplish adequate limitation and simultaneously provide the correct phase shift with respect to the power oscillation

## III. PHASOR ESTIMATION

The Phasor-POD approach focusses on the problem of separating the power oscillation from the measured average power. This is done by representing the measured line power in the form

$$p(t)=P_{av}+\mathrm{Re}\left\{\Delta\vec{P}e^{j\Omega t}\right\} \qquad (1)$$

where *p(t)* is the measured line power, $P_{av}$ is the average line power and $\Delta\vec{P}$ is a complex phasor that represents the power oscillation in a coordinate system, which rotates with frequency $\Omega$. Thus the idea is to extract the quantities $P_{av}, \Delta\vec{P}$, which are "constants" or at least "slowly varying functions of time". Because as soon as the constants in (1) have been obtained it is an easy task to provide a damping signal *D(t)* with any gain and with arbitrary phase. In the rotating coordinate system where $\Delta\vec{P}$ resides the damping signal is represented by the phasor $k_G\Delta\vec{P}e^{j\beta}$ where $k_G$ is the gain and $\beta$ is the desired phase shift. The damping signal *D(t)* can be obtained by transformation back from the original fixed coordinate system

$$D(t)=\mathrm{Re}\left\{\left(k_G\Delta\vec{P}e^{j\beta}\right)e^{j\Omega t}\right\} \qquad (2)$$

The principle is illustrated in figure 3.

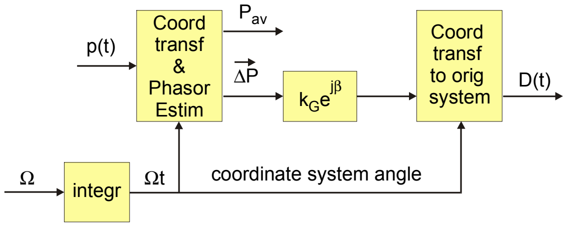

Fig. 3. Principle for creating the damping signal.

The damping signal *D(t)* represents the desired power modulation to be used for creating damping to the power system. In the case of a pure two-mass inter-area oscillation the phase shift will be selected to $\beta=90°$, but for more complex swing patterns another phase shift may be preferred.

It should be noted that the transfer function from intput *p(t)* to *D(t)* involves a coordinate transformation to and from the same rotating coordinate system. Thus, if the input signal varies sinusoidally with frequency $\omega$ then the output signal varies with the same frequency $\omega$. In other words the relation between the output signal $D$ and the input signal $p$ can be described by a linear transfer function.

Different techniques may be used to extract the phasor. A straight-forward engineering approach taking the expression (1) as its starting point is derived in Appendix A. Its transfer function is given in Appendix B. An example of a transfer function has been depicted in figure 4.

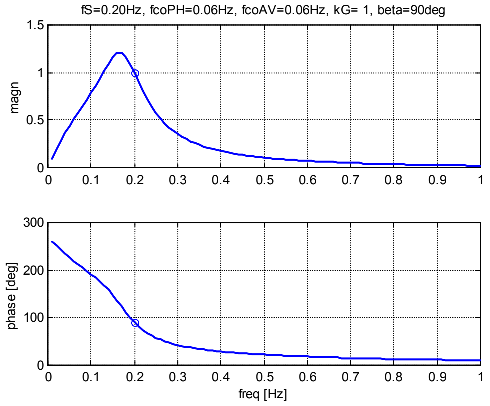

Fig. 4. Transfer function (D/p) in frequency domain.

In the example the nominal frequency is 0.20 Hz and the phase shift is $\beta=90°$. First order filters with cutoff frequency 0.06 Hz are used. The plots show that the Phasor Estimator has unity gain and the desired 90° phase shift at its nominal search frequency. The magnitude curve peaks at a somewhat lower frequency. A more symmetrical characteristics around the nominal frequency can be obtained by using second-order filters. The gain at DC is zero.

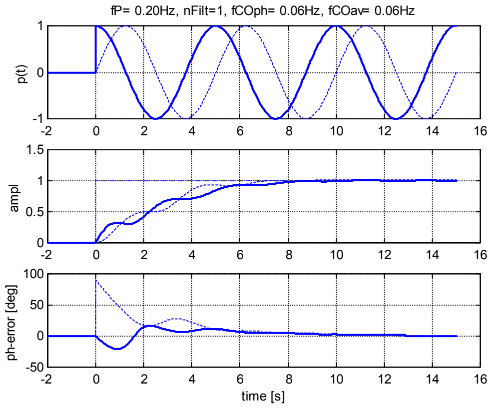

Fig. 5. Time-domain response to suddenly applied sinusoidal signal

Figure 5 shows the response $\Delta\vec{P}$ in the phasor estimator when a sinusoidal signal with unity amplitude and nominal frequency is suddenly applied on its input.

The upper diagram shows the input signal in two cases with different phase at the onset of the oscillation. The diagram in the middle shows the estimated swing amplitude and the lower diagram shows the error of the estimated phasor. It can be seen that almost correct amplitude and phase is obtained after approximately one cycle after the initiation of the oscillation.

It was pointed out earlier (figure 1) that in a typical disturbance in the power transmission system a change of the average power appears at the onset of the oscillation. The simulated response of the estimated phasor $\Delta\vec{P}$ for such a disturbance is depicted in figure 6, where the input signal appears at the top and the diagrams below show the estimated average power, the swing amplitude and the error in phase error in the estimated phasor. The thin curves indicate the ideal response.

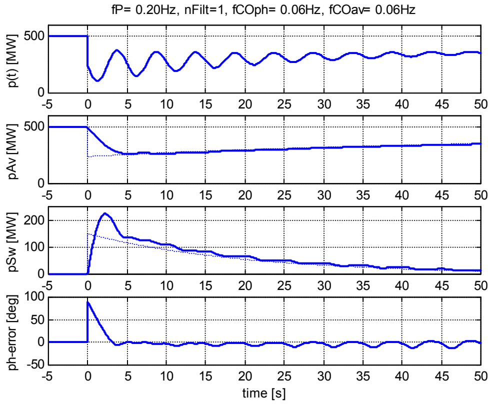

Fig. 6. Phasor Estimator time domain response response to typical power oscillation disturbance.

It can be concluded that the average power and phase information is obtained almost correctly within less than one cycle of the oscillation and that the error in the swing amplitude is relatively small after a few cycles. For damping applications it is most important that the correct phase is obtained. Errors in swing amplitude are less important.

## IV. REACTANCE MODULATION FOR DAMPING

In the Phasor-POD concept the problem of extracting the phasor representing the oscillation has been addressed separately without considering other requirements related to the damping device. Once the phasor has been extracted it is possible to comfortably make the necessary adjustments and adaptations of the damping signal so that it fits with the FACTS device that will be used to bring about the damping action.

In this section adequate adaptations for a TCSC-based damping system will be discussed. Similar adjustments will be applied if the damper is any other FACTS device or PSS.

The TCSC modulates the power flow on the transmission line by varying the inserted capacitive reactance. The magnitude of the total compensating (capacitive) reactance always is kept lower than the inductive reactance of the line. The power flow in the line is proportional to the inverse of the total reactance $X_{\mathrm{LINE}}+X_{\mathrm{TCSC}}$. Thus making the TCSC reactance more capacitive at any instant magnifies the *amount* of power flowing. In order to get a power modulation in accordance with the damping signal the reactance command must be multiplied with the negative sign of the instantaneous power signal.

$$\Delta X_{1TCSC} = -\operatorname{sgn}(p(t)) \times D(t) \tag{3}$$

Figure 7 illustrates equation (3) for three different cases.

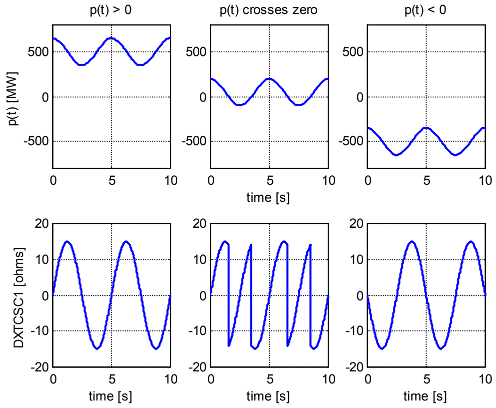

Fig. 7. TCSC reactance order for different power oscillations.

The line current level, or equivalently the average power level, determines the impact of the reactance modulation on the line power. At low current a much larger reactance variation is required to obtain a certain power modulation than at high line current. This fact may be reflected in the selection of the gain for the damper. A multiplicative factor $k_{G1}$ according to figure 8 may be envisaged for this purpose.

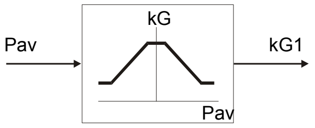

Fig. 8. Gain adaptation with respect to average power transfer level.

The network is small-signal stable under normal operating conditions in any realistic application. The motivation for installing the FACTS damping device is to provide damping at major disturbances like loss of a generator or disconnection of a transmission line. However, even in normal operation small oscillations do occur. The damping equipment gets excited by these small variations if the gain is high. It is appropriate to operate with low gain when the swing amplitude is small and to increase the gain when severe swings really occur. In this way the thermal capability of the TCSC is saved for intervention when it is really required. Figure 9 depicts an example of such a gain scheduling.

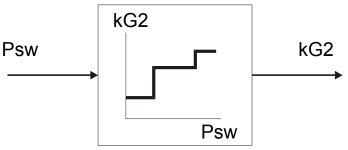

Fig. 9. Gain adaptation vs. swing amplitude.

The total gain is the product of the different gain factors

$$k_G = k_{G1} \times k_{G2} \tag{4}$$

Sometimes it is adequate to adjust the phase shift from *90°*. This may e.g. be the case when SVC is used to provide damping. It may even be desirable to adapt the phase shift in real-time with respect to the actual power flow in the line. This may be easily be implemented in the Phasor-POD concept by a simple scheduling of $\beta$ versus any relevant parameter.

In the damping control signal in (2) the limitations related to the maximum capability of the main circuit have not been considered. Its phase information therefore is unaffected by such constraints.

The permitted operating range of a TCSC for power oscillation damping is depicted in figure 10.

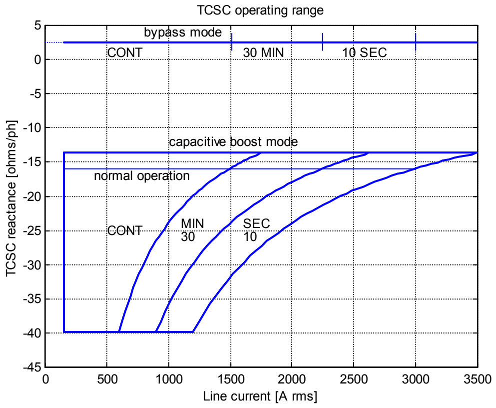

Fig. 10. Typical operating range diagram for a TCSC designed for POD.

The reactance of the TCSC can be continuously varied on the capacitive side from the natural (negative) reactance of the capacitor bank to a minimum reactance at maximum permitted thyristor boost. This limitation depends on the line current amplitude in order to limit the maximum capacitor voltage. It is advantageous to operate the TCSC with low boost factor in steady-state conditions in order to minimise the losses and the harmonic distortion of the inserted voltage. Therefore the dynamical reactance change in the inductive direction, which may be brought about by boost factor adjustment, is small. The TCSC however offers the possibility of turning on the thyristors continuously to temporarily bypass the capacitor bank. The TCSC, i.e. the capacitor bank and the inductor in parallel, then inserts a low inductive reactance in the line. This bypass mode can be used when big changes in the inductive direction are requested by the control. An adequate principle is to utilise the bypass mode whenever the reactance control signal exceeds the midpoint in the non-controllable reactance gap between the bypass and capacitive boost mode. Figure 11 shows the result of this principle in the case when the oscillation amplitude decreases. It can be seen that this principle generates a reactance variation which retains the phase of the control signal. On the capacitive side the control signal will be limited at the maximum permissible boost level.

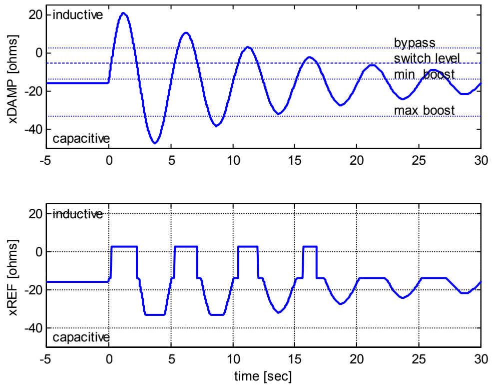

Fig. 11. Limitation of control signal for TCSC.

## V. FREQUENCY CORRECTION

The Phasor-POD extracts a phasor that represents power swings with the expected oscillation frequency all the time. In steady-state the extracted phasor is null. The search frequency has been determined from measurements or calculations. A phase error is obtained for power oscillations with frequencies that deviate from the search frequency. It is natural that small variations of the oscillation frequency occur due to varying network conditions, loads etc. However, once a power oscillation arise the frequency error can be observed in the Phasor Estimator as a rotation of the estimated phasor. It is rather simple to arrange a frequency adjusting mechanism based on the requirement that the phasor estimate shall have a constant argument in the rotating co-ordinate system. Simulations has shown that it is advantageous to delay the release the frequency adjustment to about one cycle after the onset of a power oscillation. Figure 12 depicts the frequency correction system in block form.

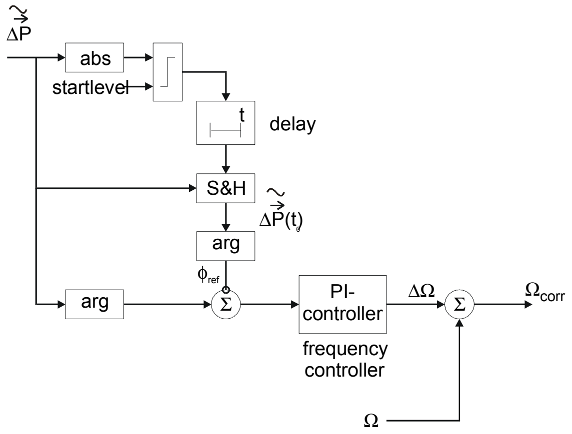

Fig. 12. Frequency correction system

The frequency correction adjusts the Phasor Estimator frequency between certain rather narrow limits close to the expected oscillation frequency. If the frequency correction reaches the limit and remains there for a considerable time the POD function will be disabled. The reason for doing so is to prevent the TCSC from interacting with oscillations that emerge from other sources than the oscillations for which the TCSC was intended.

## VI. NORTH-SOUTH INTERCONNECTION

The North-South Interconnection in Brazil was commissioned in the beginning of 1999 [4]. The 1000 km long transmission line is provided with two TCSCs, one in each end. A series of test were conducted in order to prove the effectiveness of the TCSC. A 375 MW hydro generator was tripped when the network was intentionally weakened. The results of two such tests are shown in figure 13.

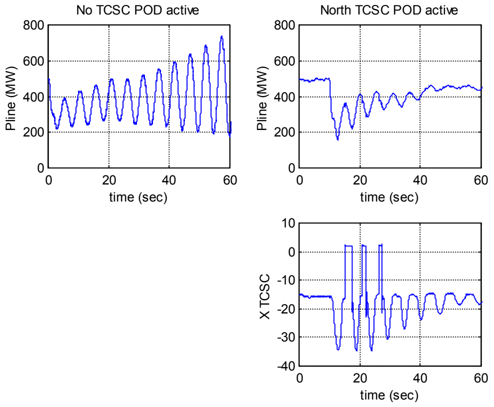

Fig.. 13: Test record of POD using TCSC.

The upper diagram shows the power in the line and the lower diagram shows the reactance inserted by the TCSC. Two cases are recorded in figure 13. The left-most curve shows the power oscillation when no POD was active and the right-most curve when the north POD (using Phasor-POD control) was active. The registrations show that the system without the POD is unstable, while the single TCSC is able to successfully keep the system in synchronism during the disturbance.

## VII. CONCLUSIONS

It has been shown in the paper that the Phasor-POD concept is very useful for controlling FACTS damping devices like TCSC. Specifically it appears to be useful for adapting complex gain/phase scheduling.

## VIII. REFERENCES

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## APPENDIX A: DERIVATION OF A PHASOR ESTIMATION ALGORITHM

First rewrite equation (1) as

$$\begin{aligned} P_{av} &= p(t) - \mathrm{Re}\left(\Delta\vec{P} e^{j\Omega t}\right) \\ \Delta\vec{P} &= e^{-j\Omega t}\left[2\left(p(t) - P_{av}\right) - \Delta\vec{P}^{*} e^{-j\Omega t}\right] \end{aligned} \tag{A1}$$

Due to the assumptions made the right-hand-sides of the equations in (A1) are constants or slowly varying functions of time. Therefore we obtain estimates $\tilde{P}_{av}, \Delta\tilde{\vec{P}}$ of the constants by applying low-pass filters to the right-hand-sides of the equations. Then the following algorithm is obtained

$$\begin{aligned} \tilde{P}_{av} &= H_{LP,av}\left\{p(t) - \mathrm{Re}\left(\Delta\tilde{\vec{P}} e^{j\Omega t}\right)\right\} \\ \Delta\tilde{\vec{P}} &= H_{LP,ph}\left\{e^{-j\Omega t}\left[2\left(p(t) - \tilde{P}_{av}\right) - \Delta\tilde{\vec{P}}^{*} e^{-j\Omega t}\right]\right\} \end{aligned} \tag{A2}$$

where $H_{LP,av}, H_{LP,ph}$ are operators representing low-pass filters. Typically first or second order filters with a cut-off frequency at about 0.2-0.5 times Ω would be used.

## APPENDIX B: TRANSFER FUNCTION FROM MEASURED POWER TO DAMPING SIGNAL

Assume that the input signal is sinusoidal

$$p(t) = \mathrm{Re}\left\{A e^{j\omega t}\right\} = \mathrm{Re}\left\{\left(A e^{j(\omega-\Omega)t}\right) e^{j\Omega t}\right\} \tag{B1}$$

where *A* is a complex constant. The steady-state solution to (A2) then has the form

$$\begin{aligned} \tilde{P}_{av} &= B_0 e^{j\omega t} \\ \Delta\tilde{\vec{P}} &= C_1 e^{j(\omega-\Omega)t} + C_2^{*} e^{-j(\omega+\Omega)t} \end{aligned} \tag{B2}$$

where $B_0$, $C_1$ and $C_2$ are determined from the linear system

$$\begin{pmatrix} 1 & h_0 & h_0 \\ h_1 & 1 & h_1 \\ h_2 & h_2 & 1 \end{pmatrix}\begin{pmatrix} B_0 \\ C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} h_0 \\ h_1 \\ h_2 \end{pmatrix} A \tag{B3}$$

and

$$\begin{aligned} h_0 &= H_{LP,av}(j\omega) \\ h_1 &= H_{LP,ph}\left(j(\omega-\Omega)\right) \\ h_2 &= H_{LP,ph}\left(j(\omega+\Omega)\right) \end{aligned} \tag{B4}$$

The transfer function from the input signal to the damping signal *D* output representing the average power is obtained as

$$\begin{aligned} D(t) &= \mathrm{Re}\left\{k_G e^{j\beta} \Delta\vec{P} e^{j\Omega t}\right\} = \\ &= \mathrm{Re}\left\{k_G\left(e^{j\beta} C_1 + e^{-j\beta} C_2\right) e^{j\omega t}\right\} \end{aligned} \tag{B5}$$

A comparison with (B1) yields

$$G_D = \frac{D}{p} = k_G\left(e^{j\beta} C_1 + e^{-j\beta} C_2\right) \tag{B6}$$

## XI. BIOGRAPHIES

Lennart Ängquist was born in Växjö, Sweden, in 1946. He graduated (M.Sc.) from Lund Institute of Technology in 1968. He has been employed by ABB (formerly ASEA) in various technical departments. He was working with industrial and traction motor drives 1974-1987. Thereafter he has been working with FACTS applications in electrical power systems.

Carlos Gama was born in Minas Gerais, Brazil, in 1959. He graduated in Electrical Engineering from Federal University of Rio de Janeiro in 1982 and got his Master Degree (M.Sc.) from Federal University of Santa Catarina. He has already worked for manufacturer, utilities as well as a consultant in power systems analysis, control and design. His has been working with studies, design and implementation of DC links and FACTS devices in Brazil over the last 15 years. He is now working for ONS (Brazilian ISO) and is a regular member of CIGRÉ –SC14.