Multi-Line Power Flow Control: An Evaluation of the GIPFC (Generalized Interline Power Flow Controller)

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Abstract -- The GIPFC (Generalized Interline Power Flow Controller) is one of the newest devices within the FACTS technology. By utilizing this device, an enhanced controllability over independent transmission systems or those lines whose sending-end are connected to a common bus, can be obtained. The performance of a GIPFC controlling two balanced independent AC systems, is in this paper analyzed and evaluated. Nonetheless, this study can well be extended to systems having more than two transmission systems. The model and the analysis developed are based on the *d-q* orthogonal coordinates, which showed to be a quite an appropriate and easy method for assessing the GIPFC response towards the system's operation. However, to observe its dynamic behavior and simultaneously validate the previous steady-state analysis, a 12-pulse VSI-based GIPFC model was also built in the ATP program. The results obtained validated the GIPFC model initially presented.

Keywords -- GIPFC, IPFC, Power Flow Control, UPFC, VSI.

I. Introduction

OVER the last years, the incorporation of power electronics into the power grid has grown significantly. Among the various benefits brought by the FACTS (Flexible AC Transmission Systems) controllers, it can be highlighted: the increased transmission capacity through real and reactive power flow control, voltage stabilization and power system oscillation suppression, among others. Though, obtaining such benefits demand also extensive research and development efforts. Recent efforts, for instance, with the UPFC (Unified Power Flow Controller) technology, have resulted in the field verification at relatively high voltages [16], [18]. Most of today's power systems are seeking new and efficient forms of controlling power as investment in transmission facilities has declined steadily over the last 25 years or so, while demand keeps growing continuously.

The GIPFC's forerunner device is the UPFC. So far, various analyses regarding the UPFC response and performance towards the power flow control and terminal voltage support, have been carried out, namely [6]-[14]. As an extended version of the UPFC, the GIPFC appears as an excellent solution for the control of multi-line systems, but it also presents its own complexities while operating under certain dynamic conditions (e.g. system oscillation, stability analysis, etc). The GIPFC (Fig. 1) also allows to simultaneously and independently inject over each compensated line, a controllable series voltage and so enable to control the transferred power in also each line. Despite the existence of some references on this device and on the IPFC [1]-[6], [15] its control versatility comes also accompanied with a certain degree of complexity in its structure, control system as well as the possible side effects whilst interacting with the network. Hence, the importance of the analysis discussed in this paper. Along the text, and where applicable, comparative comments regarding the GIPFC and the IPFC, will be presented.

The GIPFC steady-state operation also requires that the sum of the active power, exchanged by the total number of converters, be zero. Under certain conditions such as when no voltage support in the substation bus is required, the shunt converter can be dispensed with and the GIPFC (now an IPFC scheme), will be basically constituted by SSSCs connected to each other through a common DC capacitor. In this case, the real power required for varying the angular position of the series voltages, will have to be supplied from one of the AC systems.

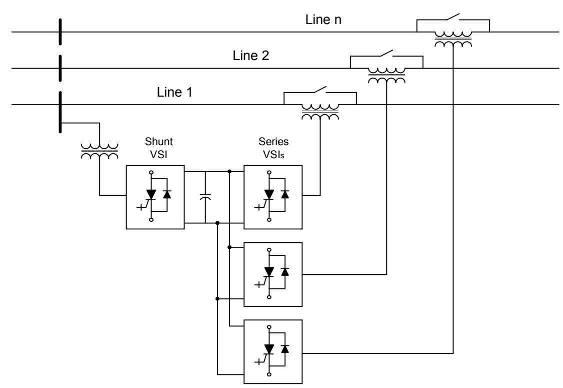

Fig. 1 GIPFC basic configuration for multi-line power flow control

In the GIPFC configuration, the series voltage injected onto each line can be controlled in both its magnitude ($0 \leq V_{pq\_n} \leq V_{pq\_n}^{max}$) and phase angle ($0 \leq \theta_{pq\_n} \leq 360°$), thus it can be decomposed into a quadrature and an in-phase voltage component. Recall that, quadrature voltage injection, with respect to the line current, has predominant effect on the real power flow. In-phase voltage injection has predominant effect on the line's reactive power flow and it is associated to the real power exchange between the converters.

The subscript n, in these voltage and angle ranges, refers to any of the series converters present in the whole system.

II. GIPFC / IPFC Model and Analysis

The analysis developed in this section considers a GIPFC connected to two balanced independent AC systems (Fig. 2). If

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buses V_{11} and V_{21} would be merged having more than two compensated lines, the scheme would reflect the case of a multi-line substation from which power is dispatched to different receiving-ends.

For ease of analysis, the equivalent sending and receiving-end sources in both systems were regarded as stiff AC sources (infinite buses). Also, it is assumed that Systems 1 and 2 have identical line parameters, although in practice they would usually be different.

Under the IPFC configuration (P_{sh}=0, Q_{sh}=0), System 2 will be termed as secondary system, as it will have to provide the series real power demanded by the primary system. This is, for the case of a classical IPFC scheme, the real power exchange of converter 2 is pre-defined (i.e. there exists a constraint for line 2) and therefore, only its series reactive compensation can utterly be utilized to control the power flow in this line.

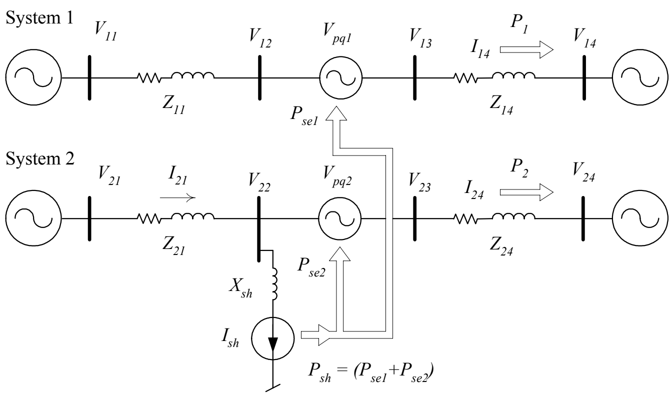


Fig. 2 Elementary GIPFC scheme used in the analysis

The GIPFC model developed in this section is based on the *d-q* orthogonal co-ordinates [14], which proved to be suitable for the steady-state analysis, as it facilitated the control of the quadrature and direct magnitudes of the ideal sources representing the converters. Each converter in the analyzed system was regarded as a shunt or series source operating with fundamental frequency and characterized by ideal sinusoidal waveforms [12], [13].

The steady-state power equality between the shunt and series inverters was strictly applied to the model. Thus, it can be established that:

$$P_{sh} = \sum_{i=1}^{m} P_{se\_i} \tag{1}$$

In (1), m stands for the total number of series converters. In our case m=2, therefore,

$$P_{sh} = V_{22d} I_{shd} + V_{22q} I_{shq} \tag{2}$$

$$P_{se1} = V_{p1} I_{14d} + V_{q1} I_{14q} \tag{3}$$

$$P_{se2} = V_{p2} I_{24d} + V_{q2} I_{24q} \tag{4}$$

The reactive power injected (absorbed) by the shunt converter can be expressed as,

$$Q_{sh} = V_{22d} I_{shq} - V_{22q} I_{shd} \tag{5}$$

From the circuit considered (Fig. 2), it can also be established the following relation:

$$V_{22(d,q)} + V_{pq2} = Z_{24} I_{24(d,q)} + V_{24(d,q)} \tag{6}$$

similarly for System 1,

$$V_{12(d,q)} + V_{pq1} = Z_{14} I_{14(d,q)} + V_{14(d,q)} \tag{7}$$

The V_p component in eqs. (6) and (7), corresponds to the direct axis component of the series voltages. Regarding the shunt current, which is defined as $I_{sh} = \sqrt{I_{shd}^{\,2} + I_{shq}^{\,2}}$ whose angle is given by $\theta_{sh} = tan^{-1}\left(I_{shq}/I_{shd}\right)$, then, it can be written (8) at bus V_{22},

$$I_{sh(d,q)} = I_{21(d,q)} - I_{24(d,q)} \tag{8}$$

So as to resolve the above expressions we also need two more additional expressions, thus,

$$V_{21(d,q)} - V_{24(d,q)} + V_{pq2} = Z_{21} I_{21(d,q)} + Z_{24} I_{24(d,q)} \tag{9}$$

$$V_{11(d,q)} - V_{14(d,q)} + V_{pq1} = (Z_{11} + Z_{14}) I_{14(d,q)} \tag{10}$$

Manipulating the above expressions, it will be obtained a set of 10 equations (some of them non-linear) that can be solved using any iterative method. Once computed the unknown variables (i.e. the *d-q* components of V_{12}, V_{22}, I_{sh}, I_{14}, I_{24}), the power flow in the receiving-end of Systems 1 and 2, with or without the series and shunt compensation effect, can be calculated through (11).

$$S_1 = \left(P_1 + jQ_1\right) = V_{14} I_{14}^{\,*} \tag{11a}$$

$$S_2 = \left(P_2 + jQ_2\right) = V_{24} I_{24}^{\,*} \tag{11b}$$

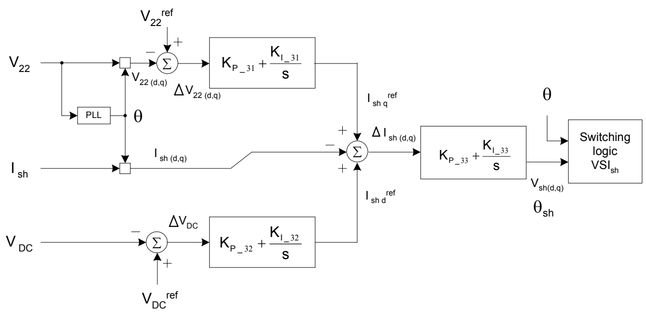
The model above developed is also valid for the case of a classical IPFC configuration. As in this case, the shunt VSI will no longer be present in the secondary system, some of the variables in the above equations will have to be zeroed (i.e. I_{shd}=0, I_{shq}=0 and Q_{sh}=0), thus, leaving only one variable (V_{q2}) in System 2 to be independently controlled.

Note that, under the IPFC configuration System 1 will have two independently controlled variables (i.e. V_{pq1}, θ_{pq1}). Conversely, System 2, which will have to provide the series real power demanded by System 1, will only have one variable (V_{q2}) to be independently controlled. Of course, the primary inverter will have priority over the secondary inverter in achieving its set-point requirements.

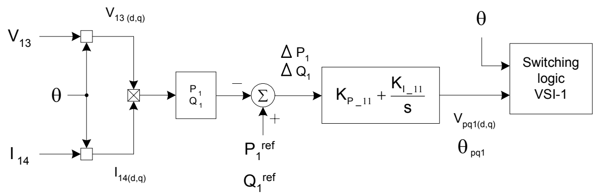
III. GIPFC OVERALL CONTROL SYSTEM

The control system of the GIPFC analyzed here, upon which was also built the ATP program to simulate the system shown in Fig. 7, uses PI (Proportional-Integral) controllers. The output of the AC voltage controller relating V_{22} (Fig. 3a) is the quadrature component of I_{sh} , and the output of the DC voltage controller is the in-phase component of I_{sh}. The *d,q* components of V_{sh} and its phase angle (θ_{sh}), obtained from the shunt current controller, are then used in the shunt converter switching logic.

Through the series converters (VSI-1, VSI-2), it can be controlled either the power flow [17] or the series voltage injected [7]. In the series control system used, the ΔP and ΔQ errors are utilized by the PI controllers to compute the V_q and V_d components of the series voltage (Fig. 3b) and its series angle, which will then be used in the series converter switching logic. The control diagram of the GIPFC secondary system (System 2) will essentially be similar to that illustrated in Fig. 3(b).



(a)



(b)

Fig. 3 Control block diagrams of the: (a) shunt converter in System 2, (b) series converter in System 1

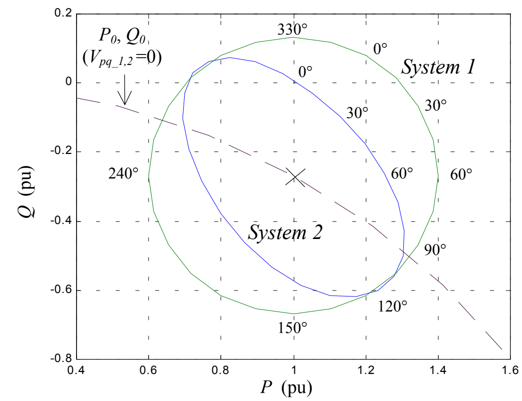
Despite each series converter (Fig. 3b) seems to have no link with the control diagram of the shunt VSI shown in Fig. 3(a), they will actually be related through the parameters of eq. (2), since the active power $P_{sh} \cong P_{DC}$. Also, they will be subjected to variations occurring in the DC voltage. Neither unbalanced system conditions nor systems with high harmonic content can be accurately studied using the models developed, as they are based on balanced system conditions and sinusoidal (or quasi sinusoidal) voltage and current waveforms. Researches concerning the mentioned aspects are currently underway.

IV. Results

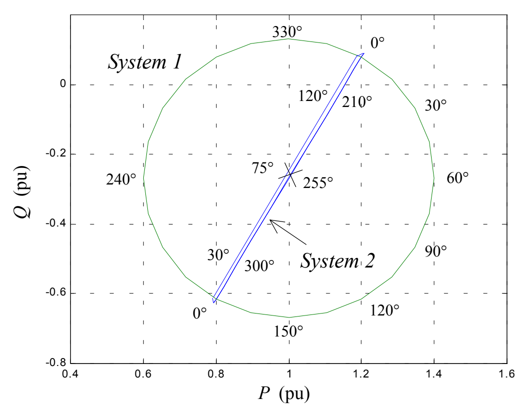
The results in the *P*-*Q* plane shown in Fig. 4 were obtained using the mathematical model developed in Section II, for which, both series angles were simultaneously varied from 0 through 2π (Fig. 4a). The region inside the circle and the ellipse correspond to the controlled area provided by the series converters 1 and 2, respectively. Note the pattern of the response corresponding to System 2 (Fig. 4a), on account of the constraint referred in Section II. For this condition, no shunt reactive power (Q_{sh}=0) was applied to bus V_{22} (System 2). During the uncompensated condition, the receiving-end active and reactive power were equal to $P^{(0)}{}_1=P^{(0)}{}_2$=1.0 pu and $Q^{(0)}{}_1=Q^{(0)}{}_2$=-0.2679 pu, respectively.

In case the shunt VSI be connected to another line, the compensated systems considered would ideally present a circular controlled region as each of them will not affect the other's voltage or power characteristic. A similar result will be obtained when $(Z_{11}=Z_{21}) \cong 0$, as in this case, voltage V_{12} & V_{22} will be replaced by V_{11} & V_{21} (stiff sources).

Fig 4(b), shows the power flow control behavior of System 1 and its effect upon System 2 (uncompensated) in a classical IPFC configuration. Note that, as V_{pq1} approaches to the quadrature position with respect to its line current (in our case θ_{pq1}=75°, 225°), both P_2 and Q_2 on System 2, return to the uncompensated condition (i.e. P_0 & Q_0). This being due to the less (eventually null) demand in the exchanged power (P_{se1}, P_{se2}) between the seriesly connected VSIs.



(a)



(b)

Fig. 4 *P*-*Q* plane at the receiving-end of Systems 1 & 2 for simultaneous compensation: (a) GIPFC, (b) IPFC configuration

In other words, while the power flow in System 1 (P_1) can be set to operate in an uncompensated mode, $P_1^{(o)}$, with solely System 2 being compensated through V_{pq2} (GIPFC case), the opposite operative condition (i.e. System 1 being compensated and System 2 kept unaltered) will present a drawback. That is, it is not possible to maintain unaltered the power flow over System 2, $P_2^{(o)}$, when solely System 1 is being compensated. Despite the voltage V_{pq2}=0, the bus voltage (V_{22}) and consequently the power flow (P_2), will vary.

In the IPFC configuration such an effect over the uncompensated System 2 becomes obvious, unless V_{pq1} is set to operate in quadrature with the line current, I_{14}. Although, this variation will be proportional to the level of compensation applied to System 1 (i.e. high values of V_{pq1} will cause relatively significant variations over System 2). This fact shows the slight degradation that System 2 experiences, on account of helping to control the power flow in System 1 (Fig. 5). Evidently, the referred effect may become less significant when, say, a high power line provides the real power required by a low capacity line in order to improve its power transmission [1]. In this way, the former will become only slightly affected in its own transmission features.

A similar result to that shown in Fig 5 was obtained for the GIPFC configuration, though in this case, the line voltage can be supported through the shunt VSI. The line voltage support over V_{22} and the shunt converter's output waveform obtained through the model presented in Section II and in the ATP program can be observed in Fig. 6 and Fig. 10, respectively.

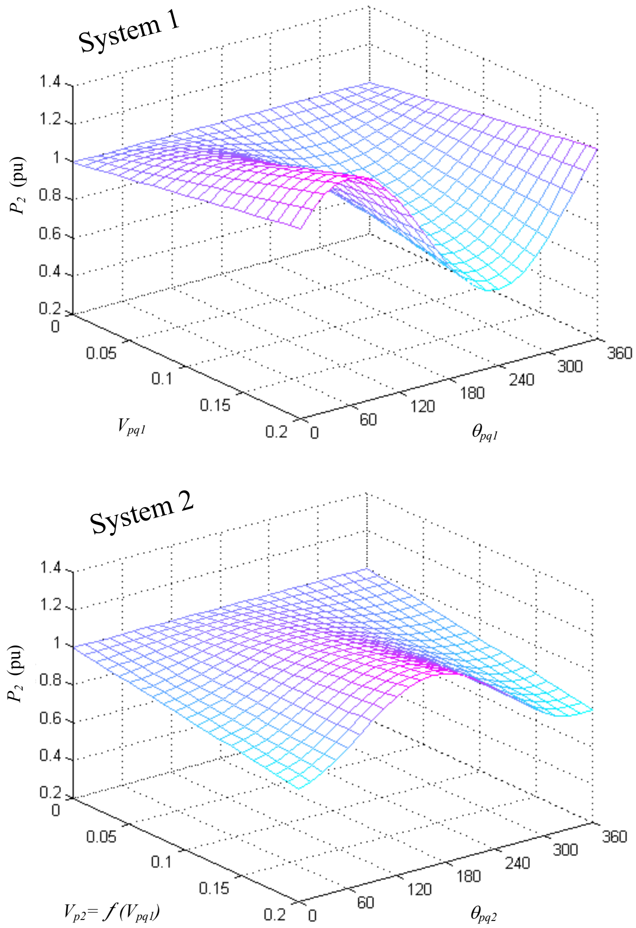


Fig. 5 Power flow control on System 1 (V_{pq1}=0→0.2 pu) and its effect over System 2 (uncompensated) in the IPFC configuration

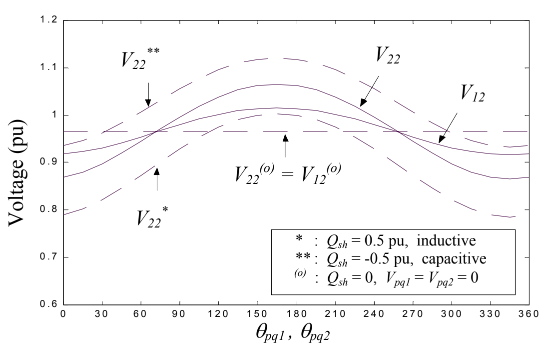


Fig. 6 Voltage variation of buses V_{12} and V_{22}

While the bus voltage V_{22} in the GIPFC case (dashed lines) can be decreased through the injection of an inductive shunt reactive power (V_{22}^{*}) or boosted through the injection of a capacitive shunt reactive power (V_{22}^{**}), the bus voltage variation in System 1 (V_{12}) depends only on the series voltageV_{pq1} (Fig. 6). The uncontrolled line voltage pattern (continuous line) also applies for the IPFC case, as it has been specified with the same line parameters as the GIPFC case.

On the other hand, the results shown in Figs. 8, 9 and 10, have been obtained using the GIPFC scheme depicted in Fig. 7. A number of tree (two series and one shunt) 12-pulse three-level VSI-based converters using the phase-shift control technique, were implemented in the ATP program. The series converters were connected to two independent AC systems which were assumed to operate at a rated voltage of 230 kV. The shunt converter's apparent power was rated to ±200 MVA, a fair amount to fulfil the real power demand from both series VSIs and to compensate, through its shunt reactive power, the terminal voltage (V_{22}).

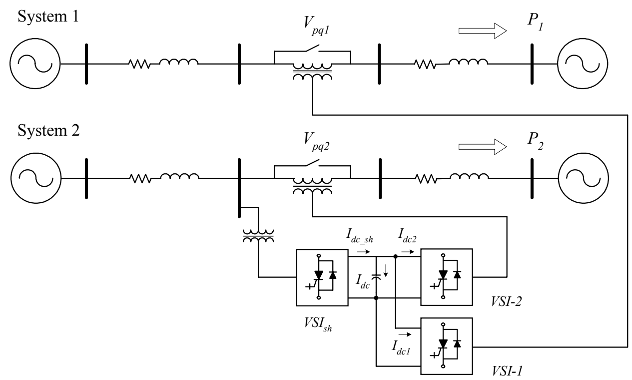


Fig. 7 GIPFC scheme implemented in ATP

The control sequence of the power flow over Systems 1 & 2 (Fig. 8a) can be summed up as follows: due to system requirements, at t=0.1 sec. P_2 is reduced whereas P_1, is increased. Subsequently, the power flow reduction effect of P_2 is cancelled out (t=0.2 sec) whereas P_1, on account of an hypothetical greater demand, is increased even more. The final control action occurs at t=0.3 sec. when P_2 is, due to a system requirement too, once again forced to reduce its transmitted power.

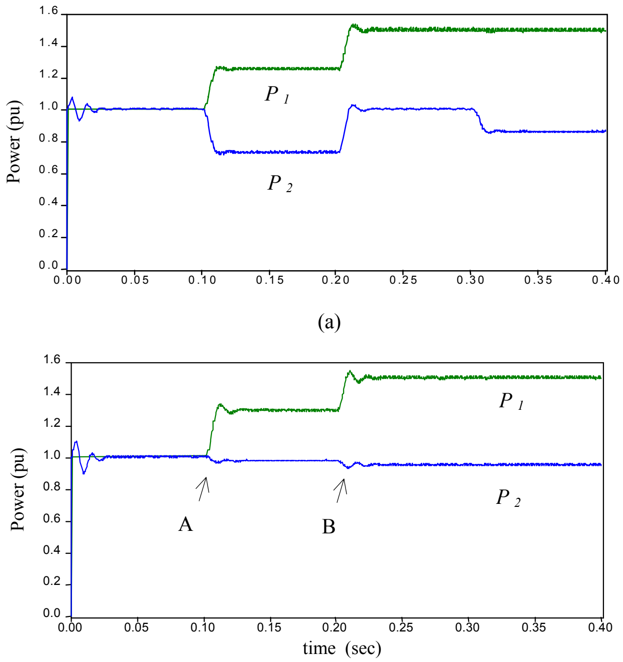
In Fig. 8(b), it is shown the effect of System 1 over System 2 when only the former is compensated. Observe the small power flow reduction occurring in System 2 (points A & B) on account of helping to increase the power flow on System 1.

The amplitude variation of each series voltage injected (V_{pq1}, V_{pq2}), characterizing the effect of the power flow behavior shown in Fig. 8(a), can be observed in Fig. 9.

The GIPFC implemented in the two-independent AC systems provided to each line a high degree of controllability, as the transmitted power can be almost instantaneously reduced or increased according to the operative requirements of the system as a whole.

DC-Link Control

In this last part of the paper, a brief analysis on the DC link behavior, will be developed. The steady-state input and output power in the DC link, assuming the VSIs as ideal converters, can be written as (see Fig. 7):



(a)

(b)

Fig. 8 Power flow control over Lines 1 & 2 (GIPFC): (a) Simultaneous compensation of P_1 & P_2 (b) Compensation of only Line 1

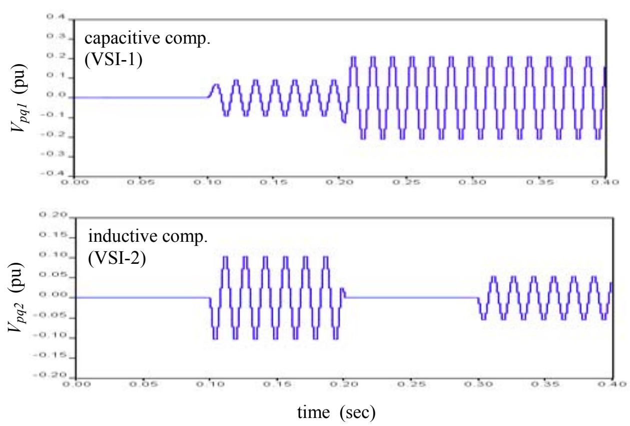


Fig. 9 Series voltages (V_{pq1}, V_{pq2}) injected to Systems 1 & 2 characterizing the power flow control shown in Fig. 8(a)

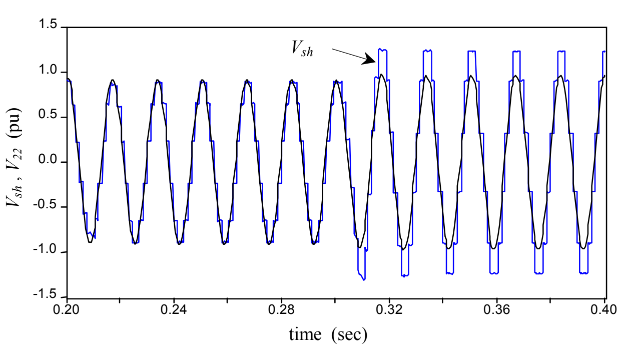


Fig. 10 Output waveform of the shunt converter's voltage (V_{sh}) and the line voltage (V_{22})

$$P_{se} = \sum_{i=1}^{2} P_{se\_i} = V_{dc}(I_{dc1} + I_{dc2}) \tag{13a}$$

$$P_{sh} = V_{dc} I_{dc\_sh} \tag{13b}$$

The transient-state of the DC link voltage can be expressed as:

$$C\frac{dv_{dc}}{dt} = i_{dc} \tag{14}$$

$$C\frac{dv_{dc}}{dt} = i_{dc\_sh} - (i_{dc1} + i_{dc2}) \tag{15}$$

As during steady-state V_{dc} should theoretically remain constant, then it follows that $C\frac{dv_{dc}}{dt} = 0$, therefore, eq. (15) can be written as:

$$I_{dc\_sh} = (I_{dc1} + I_{dc2}) \tag{16}$$

If, conversely, the DC voltage varies the DC link currents (I_{dc1}, I_{dc2}, I_{dc_sh}) will also do so, thus, establishing an energy exchange between the DC capacitor and the AC system.

Fig. 11, shows the steady-state and dynamic behavior of the DC link voltage obtained in ATP. Note the almost constant pattern of the DC voltage (V_{dc}≅1.45 pu), which agrees with the above analysis.

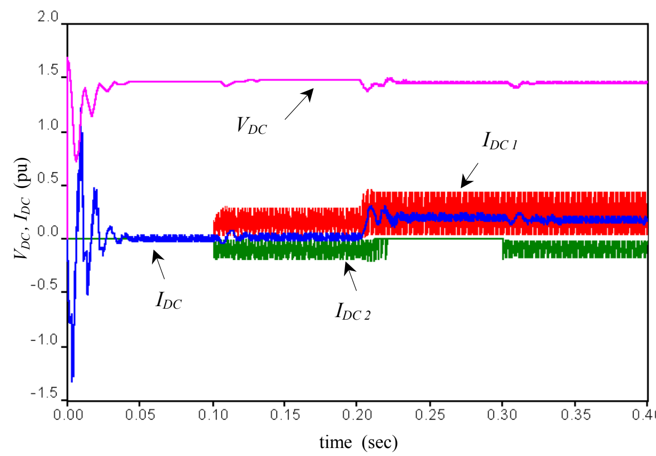


Fig. 11 DC circuit parameters' response characterizing the power flow control shown in Fig. 8(a)

Evidently, the use of a higher pulse number in the VSIs will contribute to the obtention of nearly sinusoidal output waveforms and thus, reduce the small ripple observed in the results of Figs. 8 and 11, as it was verified in [19].

V. Conclusions

The steady-state conditions of an elementary GIPFC linking two independent AC systems, was in this paper initially modeled and analyzed. The referred analysis was based upon the GIPFC shunt and series real power balance, when the converters' losses are neglected. The model developed can also be adapted, by doing some minor changes, to the case of an IPFC device. The simulations performed showed the GIPFC and IPFC capabilities and advantages for controlling simultaneously both active and reactive power flow. The *d-q* orthogonal coordinates used in the analysis allowed to evaluate, in a comprehensive way, different operation modes of the GIPFC.

To examine the dynamic response and validate the model initially developed, a GIPFC scheme comprising one shunt and two seriesly connected converters, based upon a 12-pulse VSI-based scheme, was also built in the ATP program. The simulations performed coordinated with the GIPFC model presented in Section II and showed the attributes of this device when controlling the power flow over multi-line systems.

VI. References

[1] L. Gyugyi, K. K. Sen, C. D. Schauder, “Interline Power Flow Controller Concept: A New Approach to Power Flow Management in Transmission Systems,” *IEEE Transactions on Power Delivery*, vol. 14, No. 3, 1998, pp. 1115-1123.

[2] C. Jianhong; T.T. Lie; D.M. Vilathgamuwa; “Basic Control of Interline Power Flow Controller,” in *Proc. IEEE Power Engineering Society, Winter Meeting 2002*, vol. 1, 2002, pp. 521-525.

[3] V. Diez-Valencia, U.D. Annakkage, A.M. Gole, P. Demchenko, D. Jacobson, “Interline Power Flow Controller (IPFC) Steady State Operation,” in *Proc. Canadian Conference on Electrical and Computer Engineering, IEEE CCECE 2002*, vol. 1, 2002, pp. 280-284.

[4] R. Strzelecki, G. Benysek, Z. Fedyczak, J. Bojarski, “Interline Power Flow Controller-Probabilistic Approach,” in *Proc. IEEE 33rd Annual Power Electronics Specialists Conference, PESC 2002*, vol. 2, 2002, pp. 1037-1042.

[5] N.G. Hingorani, L. Gyugyi, “*Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems,”* IEEE Press, N.Y., 2000.

[6] Y.H. Song, A.T. Johns, “*Flexible AC Transmission Systems – FACTS,”* IEE Press, London, UK, 1999.

[7] K.K. Sen, E.J. Stacey, “UPFC-Unified Power Flow Controller: Theory, Modeling and Applications,” *IEEE Transactions on Power Delivery*, vol. 13, No. 4, 1998, 1953-60.

[8] Z. Huang, et al., “Application of Unified Power Flow Controller in Interconnected Power Systems –Modeling, Interface, Control Strategy and Study Case,” *IEEE Transactions on Power Systems*, vol. 15, No. 2, 2000, 817-824.

[9] J. Bian, D.G. Ramey, R.J. Nelson, A. Edris, “A Study of Equipment Sizes and Constraints for a Unified Power Flow Controller (UPFC),” in *Proc. IEEE/PES-1996 Transmission and Distribution Conference*, L.A.-California, 1996, pp. 332-338.

[10] H. Fugita, Y. Watanabe, H. Akagi, “Control and Analysis of a Unified Power Flow Controller,” *IEEE Transactions on Power Electronics*, vol. 14, No. 6, 1999, pp. 1021-1027.

[11] J.G. Douglas, G.T. Heydt, “Power Flow Control and Power Flow Studies for Systems with FACTS Devices,” *IEEE Transactions on Power Systems*, vol. 13, No. 1, 1998, pp. 60-65.

[12] E. Uzunovic, C. Cañizares, J. Reeve, “Fundamental Frequency Model of Unified Power Flow Controller,” in *Proc. North American Power Symposium – NAPS 1998*, Cleveland, Ohio, 1998, 294-299.

[13] Keri A.F.J., Lombard X., et al., “Unified Power Flow Controller (UPFC): Modeling and Analysis,” *IEEE Transactions on Power Delivery*, vol. 14, No. 2, 1999, pp. 648-654.

[14] R.L. Vasquez-Arnez, L.C. Zanetta Jr., “Unified Power Flow Controller (UPFC): its Versatility in Handling Power Flow and Interaction with the Network,” in *Proc. IEEE/PES Transmission & Distribution Conference 2002, Asia Pacific*, Yokohama, Japan, 2002, vol. 2, pp. 1338-1343.

[15] B. Fardanesh, B. Shperling, E. Uzunovic, S. Zelingher, “Multi-converter FACTS Devices: the Generalized Unified Power Flow Controller (GUPFC),” in *Proc. IEEE Power Engineering Society Summer Meeting, 2000*, vol. 2, 16-20 July 2000, pp. 1020 - 1025.

[16] C. Schauder, E. Stacey, M. Lund, L. Gyugyi, L. Kovalsky, A. Keri, A. Mehraban, A. Edris, “AEP UPFC Project: Installation, Commissioning and Operation of the ±160 MVA STATCOM (Phase I),”, *IEEE Transactions on Power Delivery*, vol. 13, No.4, Oct. 1998, pp. 1530-35.

[17] A. Tang, S. Cheng “Study of the Impacts of UPFC upon Dynamic Power Quality”, *Journal of Electrical and Electronics Engineering*, Istanbul University, vol. 5, No. 1, 2005, pp. 1315-1321.

[18] X. Wei, J.H. Chow, B. Fardanesh, Abdel-Aty Edris “A Dispatch Strategy for an Interline Power Flow Controller Operating at Rated Capacity”, in *Proc. PSCE 2004 – Power Systems Conference & Exposition*, IEEE PES, New York, Oct. 10-13, 2004.

[19] R.L.V. Arnez, L.C. Zanetta Jr., “48-Pulse Based SSSC (Static Synchronous Series Compensator) an Evaluation of its Performance,” in *Proc. WSEAS International Conferences on: System Science, Applied Mathematics & Computer Science and Power Engineering Systems 2002*, Rio de Janeiro, Brazil, Oct. 21-24, 2002.

VII. Biographies

Luiz Cera Zanetta Jr. received his B.Sc. degree in 1974, the M.Sc. in 1984 and the Ph.D. degree in 1989 all from the University of São Paulo, Brazil. From 1975 until 1989, he joined the power systems group at Themag Engineering Ltd. which developed power systems studies for most of the Brazilian utilities. He currently is an associate professor in the same institution, working on the field of electrical system dynamics, electromagnetic transients and FACTS.

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