Paper

Analytical and Experimental Study of a Rotary Phase Shifter for Power System Applications

Member Marta Molinas (Tokyo Institute of Technology)
Student member Hirokazu Nakamura (Tokyo Institute of Technology)
Student member Akihiro Koyanagi (Tokyo Institute of Technology)
Member Ryuichi Shimada (Tokyo Institute of Technology)

Abstract – A Rotary Phase Shifter (RPS) is proposed to maintain power schedule across tie-lines in interconnected power systems. Power flow can vary widely from the scheduled power due to the unbalance between generation and load that causes frequency fluctuations in interconnected power systems. The Rotary Phase Shifter which is basically a wound rotor induction machine can be placed between two interconnected power systems to control the power flowing from a non-utility-owned generation (NUG) to a large utility. The primary objective would be to maintain the power schedule across the interconnection by controlling the torque on the rotary phase shifter. A model of the RPS and a control strategy for it are presented. Experimental studies on a reduced scale two-area power system show that following a local disturbance, the rotary phase shifter allows the desired setting of tie-line flows regardless of load conditions and the system as a whole operates in an optimal fashion.

Keywords: Rotary phase shifter, Wound-rotor induction machine, Tie-line power flow control, Non-utility generation.

I. INTRODUCTION

High demand for electric power and growing environmental concerns are forcing power systems to expand through new tie-line interconnections with the participation of new type of utilities, moving towards a deregulated energy market. Operation of these interconnected systems represents a serious challenge in the sense that frequency and tie-line flows must be tightly maintained on schedule, not only to meet load growth and increased power transfers, but also because electrical loads themselves are changing. Since not all customers require the same quality of power, not all types of utilities have the same level of frequency control and, when they get interconnected, undesired flows are generated. In a centralized control structure, when frequency variations arise, governor control, automatic generation control (AGC), and the inertia of generators themselves [1,2] are controlling most of these variations. Governor control would be effective enough provided all machines are equipped with it, but very often control is installed on only a few machines. AGC performance has been deteriorating over recent years [3]. It is feasible and effective only under certain assumptions that are not likely to be satisfied in a deregulated industry. New modes of energy management, such as open access and the emergence of NUG in the system, as well as demand side management of large industrial loads, require unconventional control solutions. Instead of a control structure fully concentrated on the generation side, new control structures in a truly distributed manner are required. It is also necessary to allow for a new type of control to accommodate non-uniform power quality required at particular levels of the grid.

With the emergence of power deregulation in Japan, a new problem is being posed to power system engineers if NUG with insufficient ability of frequency control are to be incorporated into the Japanese power grid. Fluctuation of frequency will generate undesired power flows and in order to maintain a tie-line power schedule in a complex grid, direct control of power flow will be required [4, 5].

At present, power electronics options such as unified power flow controllers (UPFC) and static phase shifters (SPS), that would provide the desired control, are being extensively researched [6]. However, these devices will respond more appropriately in centralized control structures. No real case application of these devices exists so far, though the need for a power flow controller is imminent in the new deregulated scenario. This represents a serious technological challenge in the present environment of power systems. In facing this challenge, we propose the rotary phase shifter (RPS), which is a novel, non-conventional, non-power electronics phase shifter, to cope with the control of tie line flows of NUGs and power buyers. Previous works [7,8] state the basis for the proposal of this new power flow control approach. This type of phase shifter will allow NUGs to exert tight control over their power sale to other utilities. For this reason, it represents a solution within reach to the problem of tie-line fluctuations that they will eventually face in future. Additionally, power lines will benefit from the absence of harmonics with improved power quality.

The feasibility of the RPS is analytically and experimentally investigated in a reduced scale, interconnected power system. A wound rotor induction machine is used as RPS and a control strategy is designed for it. The performance of the RPS is tested in a two-area power system model with the RPS located on the tie-line. Experimental results show that the RPS is capable of maintaining the scheduled tie-line power.

II. THE ROTARY PHASE SHIFTER

A model for the RPS is developed in order to analyze and understand its behavior under any operating condition. The fundamental equations of a polyphase induction machine of wound rotor type and two external voltage sources at its terminals is used. To study the most general case, the shaft is assumed to be rotating at a speed $\dot{\theta}_m = \omega_m$. The general equation of the RPS arranged in matrix form is:

$$\begin{bmatrix} v_s \\ v_r \end{bmatrix} = \begin{bmatrix} (R_s + pL_{ss}) & pM \\ (p - j\dot{\theta}_m)M & R_r + (p - j\dot{\theta}_m)L_{rr} \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix} \quad (1)$$

v_s , v_r, i_s , i_r, are instantaneous values of voltages and currents of stator and rotor windings. In (1) all currents and voltages are referred to a reference frame fixed on the stator, for which the following transformation was used for rotor quantities:

$$\begin{bmatrix} v_r \\ i_r \end{bmatrix} = e^{j\dot{\theta}_m t} \cdot \begin{bmatrix} v_r{}^r \\ i_r{}^r \end{bmatrix} \quad (2)$$

$\dot{\theta}_m = \dot{\theta}_s - \dot{\theta}_r$; $\dot{\theta}_s$ is the rotating speed of the stator voltage phasor; $\dot{\theta}_r$ is the rotating speed of the rotor voltage phasor. In (2) the vector on the right hand side contains rotor voltage and current on the rotor reference frame. By multiplying (1) by the current vector, the total distribution of power is obtained:

$$P_s + P_r = [i_s \;\; i_r] \cdot \begin{bmatrix} v_s \\ v_r \end{bmatrix} \quad (3)$$

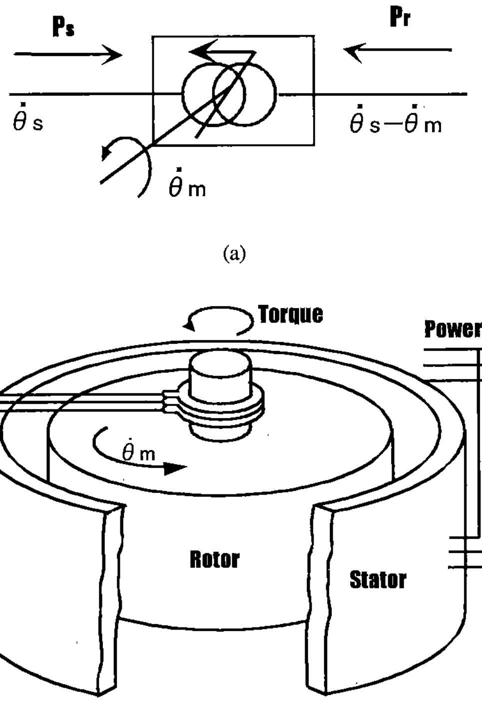
In (3), neglecting the total ohmic losses and knowing that the change of the magnetic field energy is zero in one cycle, the power-torque relations are:

$$\left.\begin{aligned} P_s + P_r &= \dot{\theta}_m \cdot T_e \\ P_s &= \dot{\theta}_s \cdot T_e \\ P_r &= (\dot{\theta}_m - \dot{\theta}_s) \cdot T_e \end{aligned}\right\} \quad (4)$$

where P_s is the power at the stator side, P_r the power at the rotor side, and T_e the electromagnetic torque. The balance of power expressed by the set equation (4) is schematically indicated in Fig. 1 (a). The sketch of Fig. 1 (b) gives an overview of what is schematically represented in Fig. 1 (a). It is important to note that if stator and rotor are fed respectively at angular frequencies ω_s and ω_r, each part produces a travelling wave of m.m.f. around the gap. Interaction of these two travelling waves produces pulsating torque at all speeds ω_m, except that for which $\omega_m + \omega_r = \omega_s$, because only when stator and rotor m.m.f. rotate in synchronism a unidirectional torque can be established. From (4) it is clear that if the electromagnetic torque T_e is zero, both P_s and P_r will be zero, and therefore no power can flow through the RPS. In order to enable transfer and control of power through the RPS at zero or constant speed, it will be necessary to externally apply a mechanical torque on the shaft of the RPS. This is explained by the dynamic equation of the RPS,

$$T_m - T_e = J \cdot \ddot{\theta}_m + D \cdot \dot{\theta}_m \quad (5)$$

In accordance with (5), if the mechanical torque T_m is zero and the speed is constant, then T_e is also zero and as dictated by (4), power cannot flow through the RPS. The behavior of the machine can be analyzed for different values of the inertia constant J and the damping coefficient D. Depending on the values of these parameters, a frequency difference between stator and rotor voltage supplies, will affect differently the dynamic performance of the machine. If J is small, the rotor will more easily rotate at the frequency difference, thus tending to an equilibrium point. However, if J is large, it will take longer to the rotor to react and a situation of instability may arise.



(a)

(b)

Fig. 1—The Rotary Phase Shifter
(a) Power balance, (b) Sketch of the RPS

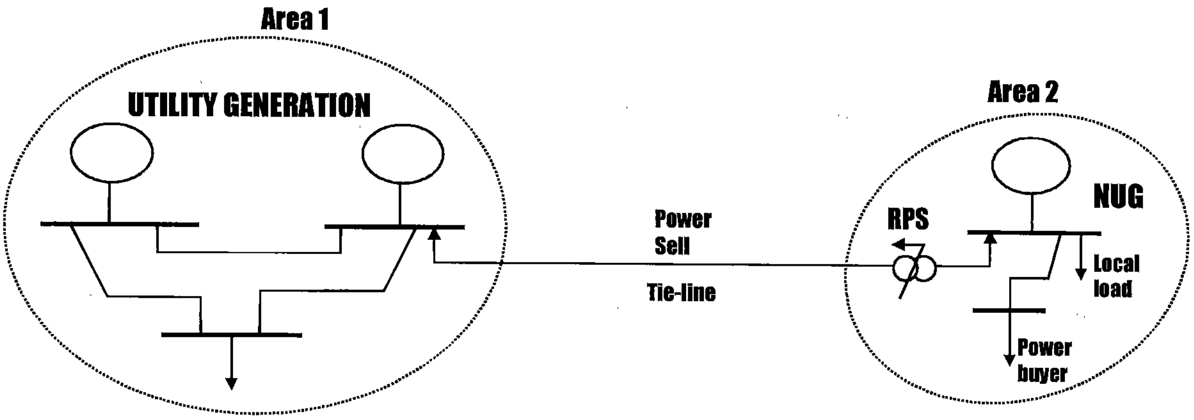


Fig. 2—Schematic representation of the system

In the limit, when the rotor is fixed and no control is applied, large circulation of power may occur. As for the damping torque, the absence of it will tend to amplify a momentary divergence from synchronism, giving rise to instability. From the model and assumptions made, the basic control strategy is designed. For that purpose, a particular case-study is analyzed in the following section.

III. TIE-LINE POWER FLOW CONTROL

The system studied consists of two electric power areas connected by a tie-line. A single equivalent machine is used to represent each area, the one of larger capacity represents a large utility generation and the smaller one is a NUG with local load and power buyers. Through the tie-line, power is transferred from the NUG to the large utility. The rotary phase shifter is placed on the tie-line at the sending end of the NUG and considered as a local compensating device. Governor and AVR control actions are not considered in order to focus on the effect of the RPS alone. This system is shown schematically in Fig. 2.

A. Statement of the problem

When local or remote load fluctuations occur, the NUG will have its frequency affected by the load fluctuation. In order to ensure that power buyers get the scheduled power regardless of the local frequency value of the NUG, a decentralized and preferably direct power flow controller will be necessary.

To show that the RPS can perform this function, we have analyzed the following situation. In the system of Fig. 2, frequency at Area 1 is supposed to be tightly maintained at rated value; Area 2 sells power to Area 1 through the tie-line (0.3 p.u., Base: 1kVA, 200 V); the local frequency at Area 2 is sensitive to load fluctuations, and when load changes from 0 to 0.3 p.u. it generates a frequency variation that will affect the power flow from this area in the absence of control. When frequency is lower than rated the NUG units are decelerating and less power will be transferred through the tie-line. When frequency is higher than rated, the NUG units are accelerating and more than the scheduled power will flow on the tie-line. This is expressed by the following equation:

$$\Delta\omega_2 = \frac{4\cdot\int \Delta P dt}{GD_2^2\cdot\omega_2} \qquad (6)$$

where

ΔP: power output variation of Area 2 [kW] ;

GD_2 : equivalent flywheel effect of Area 2 [Kg.m^2]

ω_2: rated frequency of Area 2 [rad/s]

$\Delta\ \omega_2$: frequency variation of Area 2 [rad/s]

If the purpose is to maintain the tie-line transfer unaltered, $\Delta P = 0$, then it will be necessary to maintain constant the torque exerted on the RPS to the value corresponding to the desired tie-line transfer. This value is determined by (4). With the RPS at the sending end of the NUG the tie-line transfer can then be maintained as scheduled regardless of local and/or remote load conditions in the interconnected system. In this way, the RPS serves as a decentralized power flow controller and also frees neighbor utilities and power buyers from the problem of frequency fluctuations in local and remote parts of the power grid. The next section briefly explains the control strategy designed for the RPS to perform its control action.

B. Control strategy

The primary objective of the control system is to maintain or change a power schedule according to a control signal. The set (4) implies that in order to maintain or change the scheduled power, the electromagnetic torque produced by the power flowing through the tie-line must equal the mechanical torque externally exerted on the RPS at any moment. The control strategy is based on this concept. In order to test the time response characteristics of the RPS for a given operating condition, a step signal of power is given to it through the control system. Fig. 3 shows a schematic control configuration, in which F_1 is a PI controller, F_2 a feed-forward controller, P_e actual power flow, P_e^* the command signal or scheduled power. The idea of using a feed-forward controller is to minimize the transient error, but since it is open-loop control it will not cancel the effects of disturbances under normal operating conditions.

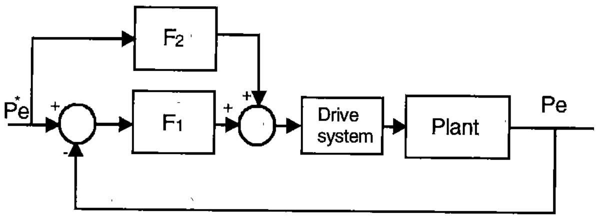


Fig. 3—Block diagram of control system

It is, therefore necessary to include a feedback loop as shown in Fig. 3. Since the equations that govern the system are non-linear, simulations were carried out to test the control performance. The PI controller transfer function is,

$$F_1(S) = K_p\left(1+\frac{K_i}{K_pS}\right) \tag{7}$$

where K_i and K_p are the control gains that are determined for the stable condition of the system by trial and error after several simulations ($K_i = 0.01$, $K_p = 0.01$).

Fig. 4 shows the time responses of the RPS to the step command of power. Power is quickly adjusted to the step signal in a settling time of 3 seconds, as shown in Fig. 4 (a). The transients of control and electromagnetic torque are shown in Fig. 4 (b). For the same settling time, both are adjusted to the same value as it would be expected from (5). The control configuration presented in this paper can also be used for other control purposes. For instance, Area 2 might represent a power system with generating units that are weak with respect to frequency variations, such as nuclear generating units or steam turbines. In these cases the RPS can prevent them from step-outs by reducing their power share to the minimum [9].

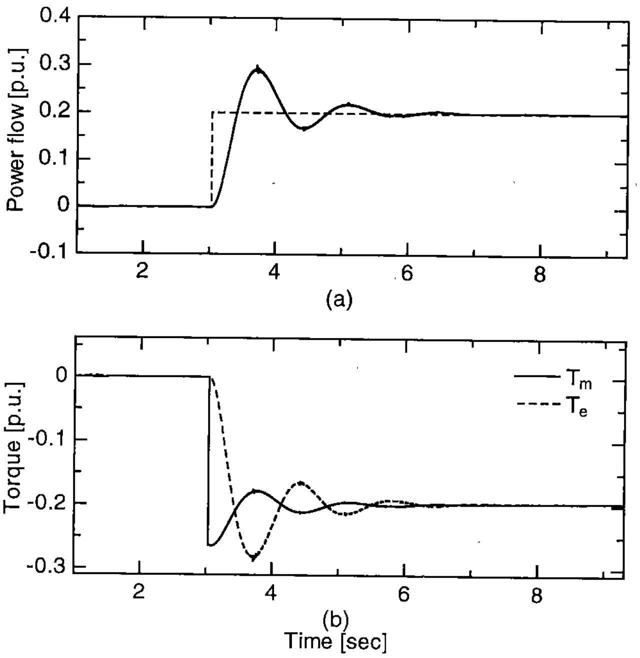


Fig. 4—Time responses of control system

IV. EXPERIMENTAL CONFIGURATION

The experimental set-up of the two-area interconnected system of Fig. 2 is schematically described in Fig. 5. The utility line represents Area 1, the synchronous generator (SG) represents Area 2, a wound rotor induction machine is used as RPS. An overview of the machine used as the experimental RPS is shown in Fig. 6. A bank of lamps with its on-off switching mechanism is used to generate the load fluctuation P_L (from 0 to 0.2 p.u.). Two inverters, A and B are used for control purposes. Inverter A is used to control the torque on the shaft of the RPS, inverter B to drive the synchronous machine. Initially, the power sell from Area 2 to Area 1 is 0.3 p.u.. The switching signal is given to operate the lamp bank according to the following sequence:

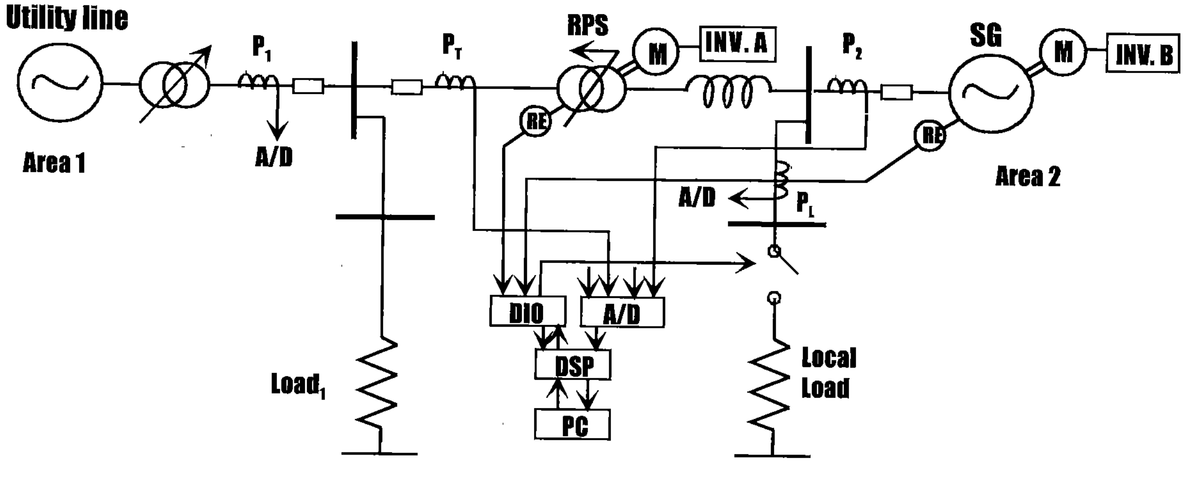


Fig. 5—Experimental configuration

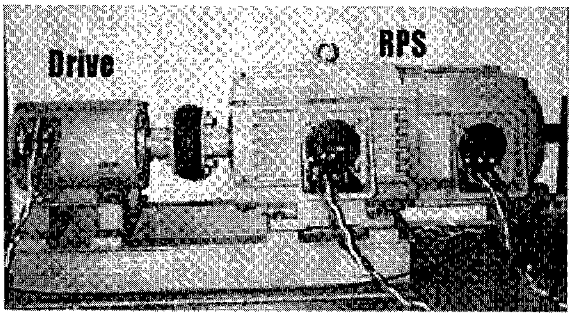


Fig. 6—Overview of the experimental RPS

$0 < t < 5\ s\ldots\ldots.P_L = 0,$

$5\ s < t < 10\ s\ldots.. P_L = 0.2$ p.u.,

$10\ s < t < 15\ s\ldots.P_L = 0,$

The data acquisition system is composed of a rotary encoder (RE) to detect the frequency of SG, an A/D converter, Digital Signal Processor (DSP) and Digital Input Output (DIO). The mechanical power on the RPS was maintained constant in order to ensure that the tie-line power flow $P_T = 0.3$ p.u. be unchanged. In the initial condition, $P_L = 0$; and $P_T = 0.3$ p.u.. Control is exerted by adjusting the input signal of the inverter used to generate the torque on the RPS shaft. The control operates under the principle of keeping the power sale constant regardless of load conditions. When $P_L = 0$, the control input is such that $P_T = 0.3$ p.u., and when $P_L = 0.2$ p.u., P_T should be maintained constant.

Table 1. – Ratings of experimental devices

Synchronous Generator (Area 2)	Power rating: 1.0kVA Rated speed: 1500 rpm AC Voltage: 200V Current: 2.88 A
Utility Line (Area 1)	AC Voltage: 200V Current: >50 A
Induction Machine (RPS)	Wound rotor type Power rating: 1.0kVA AC Voltage: 200V Current: 4.8 A No. of poles: 6
Inverters	Power rating: 6.5kVA Frequency range: 0.2-400Hz Current: 17 A
Drives	Squirrel Cage type Power rating: 1.5kVA AC Voltage: 200V Current: 6.8 A No. of poles: 4
Local load P_L	Lamp set: 0.2 kW Switching sequence: 5 s.
Load$_1$	Lamp set: 0.5 kW

V. EXPERIMENTAL RESULTS

The effect of the rotary phase shifter is evaluated observing the power flow through the tie-line before and after the local load variation at Area 2. For the load variation observed in Fig.7, the electrical output power of Area 1 is shown in Fig.8, and it is seen that it is not affected by the load variation at Area 2 when the control is applied. For this case, the frequency of Area 2 is shown in Fig. 9(a)-Control. However, when the RPS control is disabled (fixed rotor), the load increase is entirely supplied by Area 1. As a consequence, the frequency of Area 2 does not fluctuate as it is observed in Fig. 9 (a)-No Control. The speed of the RPS is shown in the same figure, and it corresponds to the difference of frequency between Area 1 and Area 2 (0.7 Hz) in the Control case when the load P_L is not applied. Rating of experimental devices are given in Table I.

After the application of local load at Area 2 ($t = 5$ s.), the output power at Area 2 remains constant without control of the RPS. When control is applied it increases in the amount of the load increase in order to supply for its own load, as it is observed in Fig. 9 (b). The power through the RPS is maintained constant regardless of the local load fluctuation as predicted by the equations presented in a previous section. This result can be observed in Fig. 9 (c). The torque on the RPS was maintained at the value corresponding to the desired tie-line flow (0.3 p.u.). When the RPS is not applied (fixed rotor) the power flow on the tie-line changes as it is shown by the dashed line in Fig. 9 (c). The control exerted on the RPS has permitted to maintain constant tie-line transfer when the local load at Area 2 increased. It is important to note that the RPS also serves as a de-coupling device between two

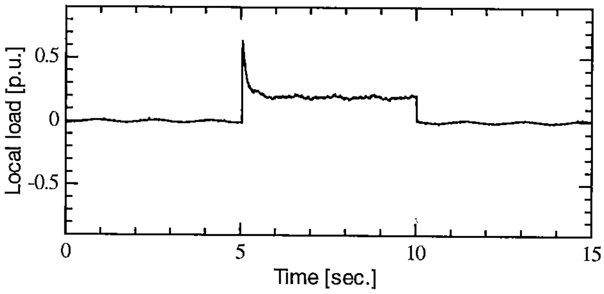


Fig. 7—Local load variation P_L

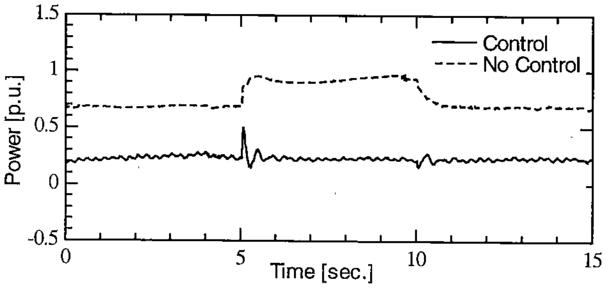
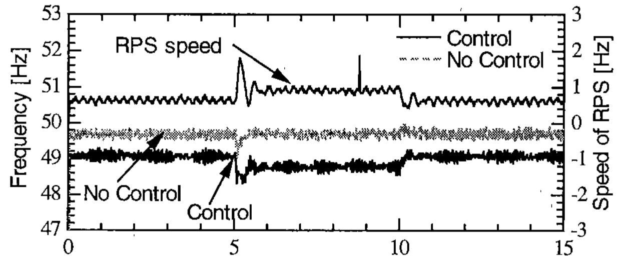
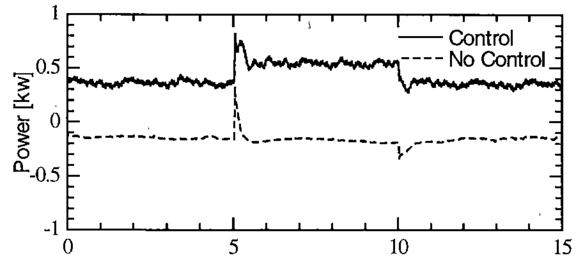


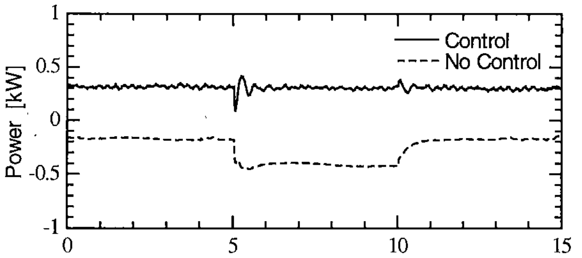
Fig. 8—Area 1 output power P_1



(a) Frequency of Area 2 and RPS



(b) Area 2 output power P_2



(c) RPS power P_T

Fig. 9—Experimental results: Area 2

systems with different frequencies, acting as a synchronizing mechanism. If the two areas were linked together without the RPS, any frequency deviation at Area 1 (or Area 2) will generate undesirable power flows on the tie-line tending always to synchronize both systems. This can greatly affect power transactions in an energy market moving towards deregulation.

Though a simple situation was chosen to experimentally demonstrate the capability of the RPS, it is clear from the results observed that the RPS can successfully perform as a tie-line power flow controller by controlling the mechanical torque on its shaft.

VI. CONCLUSIONS

This paper proposed the use of a rotary phase shifter to control tie-line power transfer from NUGs to large utilities or power buyers connected to the power grid. Experimental results indicate that the RPS has high potential for power flow control by controlling the mechanical torque on its shaft. It is important to note the double function the RPS is performing:

1) de-coupling two systems with different frequencies: it can be used to provide synchronizing torque in power systems.
2) maintaining the tie-line flows to scheduled values regardless of load conditions.

With fast response, step-outs of generators can be prevented. The use of an RPS in actual cases will have an additional obvious advantage: the sinusoidal current waves in both, primary and secondary will provide a substantially improved and cleaner line with regards to harmonics, without additional cost compared to the power electronics devices. Regarding the transmission angle, the effective control range is expanded to 360° . The RPS will face the problem of maintenance, and in other aspects, such as short circuit conditions, it will behave like a conventional transformer. The relative size of the drive will be in the order of 0.1 % of the power controlled. Finally, given the fact that the RPS is not a new technology but a retro-fit of a very mature one, the technical feasibility is an obvious advantage we would like to stress. If the appropriate control system is designed and a practical version of the machine could be devised, it will prove to have considerable industrial significance. In a preliminary design of the RPS, the predicted efficiency is of 98%. The next step of this investigation will be focused on design considerations of an RPS for real applications.

(Manuscript received Feb. 2, 2000 and revised June 14, 2000)

REFERENCES

[1] L.Gyugyi, “Power Electronics in Electric Utilities: Static Var Compensators,” *Proc. of IEEE, Special Issue on Power Electronics*, April 1988, pp.483-494.

[2] P.M. Anderson, A.A. Fouad, Power System Control and Stability, IEEE Press, NJ, 1993.

[3] Marija D. Illic, Shell Liu, Hierarchical Power Systems Control Its Value in a Changing Industry, Springer –Verlag London Limited, 1996, pp. 55.

[4] J.G.Kappenman, D.L.Van House,"Static Phase Shifter Applications and Concepts for the Minnesota-Ontario Interconnection," *FACTS Applications*, 1993, pp. 12-18.

[5] I.Ngamroo, Y.Mitani, K.Tsuji, "LFC and Stabilization of Multi-Area interconnected Power System by Descentralized Control of a SMES and Solid-State Phase Shifters," IEEE Catalogue, No.:98EX137, 1998, pp. 85-90.

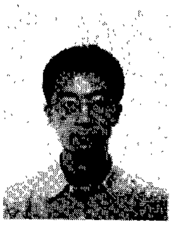
[6] Y. Mitani, T. Uranaka, K. Tsuji, "Power System Stabilization by Superconducting Magnetic Energy Storage with Solid-State Phase Shifter," *IEEE Trans. on Power Systems*, vol. 10, No. 3, August 1995, pp. 1614-1619.

[7] H. Chikaraishi, M. Arimitsu, Y. Wang, S. Uemura, R. Shimada, “Fast Response Power Stabilizer Using the AC-Excited Flywheel Generator, “ *IEEJ Trans. On Industry Applications*, vol. 113-D, No. 11, 1993, pp. 1254-1261. (in Japanese)

[8] M.Molinas, H.Nakamura, A.Koyanagi, R.Shimada, “Analytical and Experimental Study on the Application of a Rotary Phase Shifter to Power Systems” *IEEJ Proc. of the Meeting on Power System Technology*, pp. 87-92, 1999.

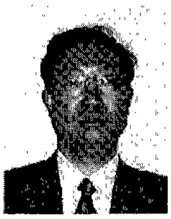
[9] J.Kobuchi, M.Molinas, S.Syofyan, R.Shimada, "Power System Transient Stability Enhancement with Inductive Frequency Converter," *Industry Application IEEJ Anual Meeting*, March 1998, vol. 5, pp. 1-2 (in Japanese).

Marta Molinas (Member) received the Diploma in Electro-mechanical Engineering from the National University of Asuncion, Paraguay in 1992; her Master of engineering from Ryukyu University, Japan, in 1997. She is now pursuing her Doctor degree at the Research Laboratory for Nuclear Reactors of Tokyo Institute of Technology. Her field of interests includes Power Systems Control and Electrical Machines.



Hirokazu Nakamura (Student member) He was born in Japan on May 15, 1976. In 1997 he graduated from the Kushiro National College of Technology. He received his B.S. degree in electrical engineering from Tokyo Institute of Technology in 1999. Since April 1999 he has been a graduate student at the Research Laboratory for Nuclear Reactors of Tokyo Institute of Technology. His research is focused on Power Flow Control.

Akihiro Koyanagi (Student member) He was born in Japan on October 19, 1977. He received his B.S. degree in electrical engineering from Tokyo Institute of Technology in 2000. Since then, he has been a graduate student at the Research Laboratory for Nuclear Reactors of Tokyo Institute of Technology. His research is focused on the hardware aspects of rotating machines.



Ryuichi Shimada (Member) He was born in Japan on January 31, 1948. He received his D.Eng. from Tokyo Institute of Technology in 1975 and then joined the Japan Atomic Energy Research Institute. Since 1988 he has been with Tokyo Institute of Technology where he is currently a Professor at the Research Laboratory for Nuclear Reactors. He is engaged in the research of Nuclear Fusion, Plasma Control and Energy Systems.