AGC and FACTS Stabilization Device Coordination in Interconnected Power System Control

D.D. Rasolomampionona *

Abstracts -- FACTS device like TCPAR can be used to regulate the power flow in the tie-lines of interconnected power system. When TCPAR is equipped with power regulator and frequency-based stabiliser it can also significantly influence the power flow in the transient states occurring after power disturbances. In the case of simple interconnected power system, consisting of two power systems the control of TCPAR can force a good damping of both power swings and oscillations of local frequency. In the case of larger interconnected power system consisting of more than two power systems the influence of the control of TCPAR on damping can be more complicated. Strong damping of local frequency oscillations and power swings in one tie-line may cause larger oscillations in remote tie-lines and other systems. Hence using devices like TCPAR as a tool for damping of power swings and frequency oscillations in a large interconnected power system must be justified by detailed analysis of power system dynamics.

**Index Terms**-- flexible AC transmission systems, power system stability, Automatic Generation Control

**I. INTRODUCTION**

Worldwide transmission systems are undergoing continuous changes and restructuring. They are becoming more heavily loaded and are being operated in ways not originally envisioned. Transmission systems must be flexible to react to more diverse generation and load patterns. In addition, the economical utilization of transmission system assets is of vital importance to enable utilities in industrialized countries to remain competitive and to survive. In developing countries, the optimized use of transmission systems investments is also important to support industry, create employment and utilize efficiently scarce economic resources. Classical automatic generation and power control should be modified in result of deregulation of electric power energy sector and introduction of market mechanism in power trade. The restructuring of management and propriety in the power system sector should be accompanied at least by a partly decentralized power system control.

Flexible AC Transmission Systems (FACTS) is a technology that responds to these needs. It significantly alters the way transmission systems are developed and controlled together with improvements in asset utilization, system flexibility and system performance. They are used for the dynamic control of voltage, impedance and phase angle of high voltage AC transmission lines. According to several specialists FACTS devices can be used as tools in control decentralisation. Those devices are used in transmission line voltage and power regulation [2]. Their role in regulation processes of interconnected power systems is not fully analysed yet.

Introduction of far-reaching changes in power system control is a problem requiring a very careful analysis. There are some circumstances, making admit to a certain apprehension that a full control decentralisation can endanger the power system security. Any change in power system control, among others the use of FACTS devices in transmission network should be preceded by adequate wide studies. Producers and numerous adherents of FACTS systems demonstrate that FACTS devices like TCPAR or UPFC can participate in power system control in a perfect manner, both in steady-state and in transient states for power post-disturbance swing damping. There is a very few information about the influence of the use of these devices on far lower steady-state phenomena accompanying the power and frequency regulation after a long-term imbalance of tie-line interchange power. In this paper some results of a research financed by the Polish SCSR (State Committee for Scientific Research) are presented. The problem concerning the coordination of the FACTS devices like TCPAR, used for tie-line power control in interconnected power systems equipped with an AGC system is presented in this paper.

**II. AN INTERCONNECTED POWER SYSTEM COMPOSED OF TWO SUBSYSTEMS**

In interconnected power systems automatic generation control is implemented in such a way that each area, or subsystem, has its own central regulator. As shown in Figure 1, the power system is in equilibrium if, for each area, the total power generation $P_T$ the total power demand $P_L$ and the net tie-line interchange power $P_{tie}$ satisfy the condition:

$$P_T - (P_L + P_{tie}) = 0 \quad (1)$$

The objectives of each area regulator is to maintain frequency at the scheduled level (frequency control) and to maintain net load.
tie-line interchanges from the given area at the scheduled values (tie-line control).

![Fig. 1. Power balance of a control area](image)

The regulation is executed by changing the power output of the turbines in the area through varying $P_{ref}$ in their governing systems. Figure 2 shows a functional diagram of the central regulator. Frequency is measured in the local low voltage network and compared with the reference frequency to produce a signal that is proportional to the frequency deviation $\Delta f$. The information on power flows in the tie-lines is sent via telecommunication lines to the central controller which compares it with the reference value in order to produce a signal proportional to the tie-line interchange error $\Delta P_{tie}$.

![Fig. 2. Functional diagram of a central regulator](image)

In the past the central control of frequency and power interchanges was implemented using large analogue controllers but this has now been replaced by a central computer. In normal operating conditions this computer also performs security assessment analysis and economic dispatch, i.e. allocation of the generated power among the power plants in a way that minimises the production cost. Should an emergency occur the computer may change the allocation of power in order to prevent system blackout. A detailed description of these facilities is beyond the scope of this paper. The $\Delta P_{ref}$ signals, resulting from the frequency and tie-line control, and the $P_{tie}$ signals, resulting from the economic dispatch or emergency control, are transmitted to the power plants using the same telecommunication links.

The frequency regulation process can be approximately analysed using a simplified mathematical model, which considers the dynamics of rotors, turbines and their respective prime movers [1], [4]. Having regard to this fact and the derived equations, after introducing the following symbols:

$$G_T(s), \ G_{RT}(s), \ G_{Rf}(s)$$

which are, respectively: the equivalent transfer functions of turbines, prime movers, secondary controllers (frequency controllers), the derivation of the appropriate relations and performance of the adequate transformations lead to the following block diagram:

![Fig. 3. Power system frequency control block diagram](image)

Maintaining a primary regulation margin at the set level is a centrally co-ordinated service provided by transmission system operator (TSO). The primary control goal is to automatically increase/decrease the power of primary control ranked sources within a few seconds (in the scope of set control margin) in order to balance frequency deviations. The primary control has a proportional character and contributes to maintaining a balance between generation and consumption using a turbine power or speed regulator. The right part of Fig. 3 represents the power system with its turbines and prime mover control (primary regulation). The amplification of the feed-back loop is indicated by the symbol $R$. The left part is the frequency control (secondary regulation). The secondary control goal is to maintain frequency at the nominal (required) value and balance with the interconnected systems at the required value. Secondary control must be harmonised with primary control. Primary control possibilities are preferred to frequency deviations, and secondary control is applied when a frequency deviation persists or in case of a deviation from the agreed balance.

The relation between the tie-line power $\Delta P_{tie}$ and frequency deviation $\Delta f$ in the interconnected subsystems can be determined using the model described in [1], [4]. Tie-line power flow deviations depend on the terminal line voltage angle and are strictly linked to frequency deviations,

![Fig. 4. Power balance in two interconnected systems](image)

Interconnection may necessitate reinforcement of existing networks for stability or other reliability considerations. The reinforcement may be assisted by the deployment of Flexible AC Transmission System (FACTS) devices and computer-controlled energy management system (EMS). Flexible AC Transmission System technologies are aimed to install power electronic devices at the proper places of the existing AC
systems to improve their steady-state and dynamic behavior and keep preset power transfer. Generally, the objectives of FACTS technology are to enhance system controllability and to increase power transfer limit. Detailed simulation of possible steady state, dynamic state and transient state operation must be studied based the proposed interconnection schemes, taking applications of various FACTS devices into account.

A. The mathematical model

The power system model including the TCPAR model can be obtained from the incremental matrix equation of active power including the TCPAR equation. The obtained equivalent system is presented in Fig. 6.

The TCPAR device can be replaced by an equivalent reactance [5] and a transformation ration $\eta = \beta + j \gamma$. The direct component $\beta$ of this ratio influences the voltage level control and the reactive power flow. Similarly the quadrature component $\gamma$ influences the voltage angle control and the active power flow. The TCPAR device is much simpler than UPFC device and controls the quadrature component $\gamma$ only.

Using the node potential method in the power system in Fig. 2, it can be demonstrated (more detailed in [6]) that the interchange tie-line active power is given by the following expression:

$$ P_{\text{tie}} = b \sin \delta - \gamma b \cos \delta, \quad b = \frac{|E_A| |E_B|}{X_S} \tag{2} $$

where $\gamma$ is the TCPAR quadrature component, $E_A, E_B, X_S$ are the equivalent emfs of both of the subsystems and the equivalent reactance of the whole transmission system (the TCPAR device reactance included), respectively. The emfs’ arguments are $\delta_A, \delta_B$ respectively. In the expression (2) the angle $\delta = (\delta_A - \delta_B)$.

The pre-fault values of the variables at the steady-state are marked by a “hat” (‘’*) inserted on the top of the appropriate symbol. They are, respectively $\hat{P}_{\text{tie}}, \hat{\delta}, \hat{\gamma}$. Differentiating the expression (1) in the neighbourhood of the given values yields:

$$ \Delta P_{\text{tie}} = \frac{\partial P_{\text{tie}}}{\partial \delta} \Delta \delta + \frac{\partial P_{\text{tie}}}{\partial \gamma} \Delta \gamma \tag{3} $$

After some simple mathematical transformation the following expression is obtained

$$ \Delta P_{\text{tie}} = \left(1 + \gamma^2 \right) \hat{P}_{\text{tie}} + \gamma \hat{P}_{\text{tie}} \Delta \delta - \hat{H}_{\text{tie}} \Delta \gamma \tag{4} $$

where

$$ \hat{H}_{\text{tie}} = \frac{\partial P_{\text{tie}}}{\partial \delta} \bigg|_{\delta=\delta', \gamma=0} = b \cos \hat{\delta} \tag{5} $$

The model corresponding to the expression (4) is shown in Fig. 7.

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**Fig. 5.** Block diagram of frequency regulation in a two-area power system composed of subsystem A and B

**Fig. 6.** Illustration of the interconnection of two power system areas, with a TCPAR device installed on the tie-line
B. An example of simulation results

For the simulation analysis an interconnected power system composed of two systems, of which the installed active power are far different one from another is used. Generation, demand and interchange line powers are shown in Fig. 4. the symbol \( T_m \) is the mechanical time constant of the generating unit equivalent circuit, \( S_{2W} \) is the short-circuit power (which is needed for computing the equivalent reactance). Typical parameters of reheat steam-turbine have been considered for the model. Detailed information about power system data are in [6]. The system A is much smaller than system B, nonetheless in the analysed case it exports an amount of active power of 500MW from the system A. The tie-line voltage is 400kV.

![Fig. 7. Interchange tie-line model with TCPAR device](image)

The simulation analysis has been performed using several models of control units with different input signals. Their results are presented in [6]. It results from the analysis that, from the damping of power and frequency swings point of view, the best performance has been obtained when using a power regulator with a frequency-based PSS (Fig.9).

A power imbalance in the system A or B has been simulated in form of a power step change in the SUM node, between the block diagram of governor-turbine and the equivalent transfer function of the power system. A few examples of some simulation results are depicted in Fig. 6-8. The power unbalance step change was \( \Delta P_0^A = 200 \text{ MW} \). The thin solid line time responses represent signals obtained for the model without TCPAR device. Bolder signals corresponds to signals obtained when using the power control system with a frequency-based PSS (Fig. 9). It could be observed (Fig.10-12) that the TCPAR introduced a full damping of inter-area swings and power and frequency signals, resulting from the AGC action are almost aperiodical. This example shows an excellent coordinated operation TCPAR control system and AGC in damping power system oscillations occurring during transient state.
control parameters : \( K_p = 0.002, \ T_p = 5 \text{s}, \ K_T = 2000, \ T_T = 1 \text{s}, \ K_F = 1, \ \gamma_{\text{MAX}} = +0.2, \ \gamma_{\text{MIN}} = -0.2 \)

The attention should be paid to the interconnected system, on which the TCPAR installed on the tie-line is not able to control the power flow between subsystem A and B because the transformation ratio change \( \gamma \) results only in changes of \( E_A, E_B \) voltage angles. The situation is totally different for an interconnected power system composed of more than two subsystem, which results in more than one inter-tie lines. The TCPAR device installed in one (or more) tie-lines can change the loads of different lines through change in load flow between subsystems. However it has no influence in the total power balance of each subsystem.

III. SIMULATION RESULTS FOR AN INTERCONNECTED POWER SYSTEM COMPOSED OF THREE SUBSYSTEMS

Basic data of the three systems are presented in Fig. 13. The block diagram of this system is built in the same way as for the two subsystem model presented on Fig. 5, but based on three subsystems with three different AGC control systems and three tie-lines. A full presentation of the block diagram can be found in [6]. Like for the two subsystem case simulation results have also shown that the best influence on transient time responses has been obtained when the TCP was equipped with a power control system with a frequency-based PSS (Fig. 9).

![Figure 12](image_url)  
**Fig. 12.** Time response of tie-line power after a power imbalance occurs in the subsystem A

During simulation analysis it has been assumed that only one TCPAR device has been installed in the tie-line between the subsystems A and B. For instantaneous powers of different subsystems equal to power reference values this TCPAR can have an influence upon the loads of the tie-lines A-B and A-C to balance the total power flowing in those tie-lines. In other words, the TCPAR can unburden the line A-B at the cost of line A-C and vice-versa.

During steady-state the influence of TCPAR device depends on the system, at which the power imbalance has occurred.

If the disturbance in power imbalance occurs in the subsystem A, instantaneous local frequency deviations of system A results in very efficient response of the TCPAR regulator and a very strong damping of power and frequency swings. This phenomenon is illustrated in Fig. 14, in which it can be observed that frequency oscillations of all three subsystems are lower after the TCPAR device has been installed. Also inter-area power swings have been damped in such a way that power time responses do not contain typical inter-area oscillations but low aperiodical power deviations forced by AGC of different subsystems (Fig. 15-16).

![Figure 13](image_url)  
**Fig. 13.** Basic data of the interconnected power system composed of three subsystems

If the disturbance in power imbalance occurs in the subsystem B, power control system with a frequency-based PSS makes the subsystem A local frequency oscillations strongly damped. However this situation has no significant influence on subsystem B and C local frequency oscillation.
subsystem A local frequency oscillation damping has a unwanted back effect consisting on stronger power deviation in other tie-lines, in particular line A-C and B-C.

The same situation takes place when the disturbance in power imbalance occurs in subsystem C. Power control system with a frequency-based PSS damps only subsystem A local frequency oscillations, but has no significant influence on subsystem B and A local frequency oscillation. Quite strong power swings, comparable to those of system without TCPAR occurs in all tie-lines.

Control parameters $K_p = 0.002$, $T_p = 5s$, $K_f = 2000$, $T_f = 1s$, $K_F = 1$, $\gamma_{MAX} = +0.2$, $\gamma_{MIN} = -0.2$

IV. CONCLUSIONS

The strongest effect of TCPAR action on frequency and power swing damping is obtained when using power control system with a frequency-based PSS. When a simulation analysis of a simple interconnected power system composed with two subsystems has been performed, a very good damping of frequency and power swings has been observed. Unfortunately less optimistic observations results from the analysis of the interconnected system composed with three (or more) subsystems. In this case only the damping of system frequency, of which the frequency is the input of the frequency-based PSS. However the TCPAR action can enforce the tie-line interchange power, in particular in tie-lines located relatively far away from the TCPAR device. For these reasons the use of TCPAR based on power control system with a frequency-based PSS in very large interconnected power systems requires more carefulness and performance of more detailed analysis of the power system

V. REFERENCES

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VI. BIOGRAPHY

Desire Dauphin Rasolomampionona was born in 1963 in Madagascar. He received his MSc (1988) and PhD (1994) in Electrical Engineering from Warsaw University of Technology. He joined the Warsaw University of Technology faculty in 1994 at the Power System Protection Division, Institute of Power Engineering. His research interests include protection and control of power system and computer networking.