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Improvement of Transmission Capacity by FACTS devices in Central East Europe power system

Michal Kolcun*. Zsolt Čonka*, Ľubomír Beňa*, Martin Kanálik*,Dušan Medveď*

** Department of Electric Power Engineering, Technical University of Košice, Košice, Slovakia*
(e-mail: michal.kolcun@tuke.sk, zsolt.conka@tuke.sk, lubomir.bena@tuke.sk, martin.kanalik@tuke.sk,
dusan.medved@tuke.sk)

Abstract: The increased demand for power transfer in combination with environmental and economic issues which set constraints to building new lines, force the implementation of new technologies into the existing system in order to improve its power capability. This paper investigates the use of specific FACTS devices and WAMS systems to maximize total transfer capability generally defined as the maximum power transfer transaction in Central-East-Europe power system. Optimal allocation and control of these devices will be very important for TSO or other power market regulators. Effectiveness, optimal allocation and utilization of phasor measurement units (PMUs) for different types of FACTS devices designed for power flow control and increasing transfer capacity were investigated. Paper also compares the economic aspects of these devices.

Keywords: WAMS, FACTS, power flow, transfer capacity, PMU

1. INTRODUCTION

By liberalization of the electricity market we have gained new opportunities and possibilities for electricity market participants. On the other hand, liberalization also causes considerable problems for operators of transmission system operators (TSO). Unsolved problem of our time is the constantly increasing number of unpredictable renewable energy in northern Europe and insufficient power generation in south. Due to unplanned power flow, the security criterion N-1 is unfulfilled cause of overloading of interconnecting transmission lines. This facts brings operation of existing transmission systems closer to their physical limits.

One of the opportunities for solving this problems was building of new power transmission lines or effectiveness utilization of existing transmission system capacity by utilization of specialized systems such as flexible alternating current (AC) transmission systems (FACTS). This special devices can perfectly control the power flow across transmission lines and helps operators to maintaining stable operation of power systems. In combination with sophisticated WAMS systems it can solve this problem.

Transmission system operators of each power systems talk about the need of increase of the reliability and safety of the power system. Transmission system operators sometimes have to manage the power system to its safety operational limits. Moreover, in some cases, it may also occur a large area outages (Black out), that have negative consequences for society as a whole. Due to the facts, the monitoring of power systems are made through a SCADA (Supervisory Control and Data Acquisition) systems and EMS (Energy Management Systems), which do not work in real time and thus the results are not applicable for fast transient processes occurring in the system. Moreover, both these control schemes are not time synchronized.

2. WIDE-AREA MONITORING SYSTEM

First PMU (GPS based) was invented in 1988. Synchrophasor technology has developed for the last few years. During this time, it was designed and implemented by advice promising new concepts, such as the wide-area measurement / monitoring system (WAMS). It brings huge potential for the modernization of the management, operation, supervision and protection of energy systems.

WAMS (Wide Area Monitoring System) systems is synchronous measurements of phasors and mainly used in the transmission lines.

Furthermore the surface monitoring and visualization of the network in real time or consequential off-line analysis of the operating situations These subsystems are used also for monitoring of system stability, operational management of the network and early warning systems. Application of WAMS systems can also be found in distribution networks, for example in the management of distributed energy resources. Synchronous measurement error generally decreases in subsequent calculations and control systems, resulting in an improvement of dispatching management network.

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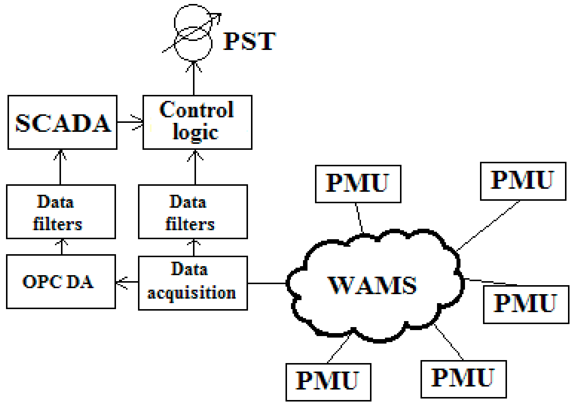

Fig. 1. PST control scheme with WAMS

Use of PMU for data acquisition for regulation of FACTS devices can bring new possibilities for further development of the network control. Measurement of phasors at different part of the power system, can be used for optimization of power flow, minimize power loses or to maximize transmission capacity between various TSO. Example of utilization of WAMS for control of phase shift transformer is shown on Fig 2.

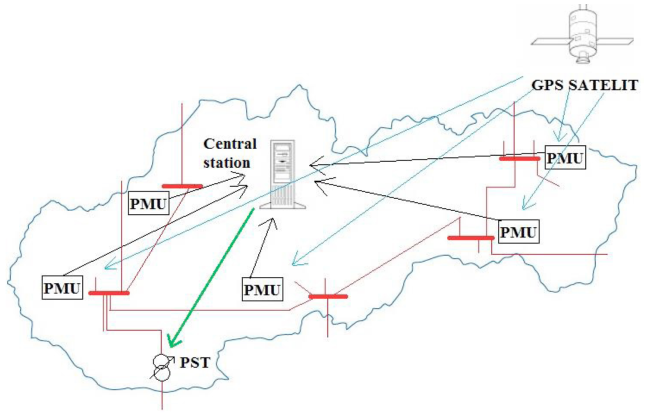

Fig. 2. Slovak power system with PMUs and PST.

3. PHASE SHIFT TRANSFORMER

Phase shift transformer is mainly used for active power flow control at the interface between two large independent power systems.

Phase-shifting transformers are mainly used to control the active power flow in related networks or to control the active power flow at the profiles between two large and independently controlled power systems.

PST transformer principle is based on the use of adjustable angle ratio of the transformer. Winding of the serial unit is connected directly into HV level (e.g. 400 kV), in which the phase angle is controlled. It means, that the overall voltage is consists of primary voltage and phase shifted (additional) voltage. Regulating transformer with tap changer is supplied from serial unit (Fig. 3).

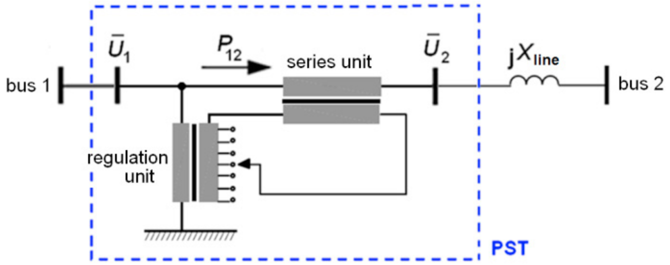

Fig. 3. Simplified scheme of PST

Key parameters for any transmission line, determine the line impedance, power flow: phase angle between the starting and receiving nodes and terminal bus voltages. U_1 and U_2 are magnitudes of the bus voltages at both ends of the line with the angle $\delta = \delta_1 - \delta_2$ among them. The impedance of the line is marked as X_{12}. In this case, the expression for active power flow across transmission line is: (1)

$$P_{12} = \frac{U_1 \cdot U_2}{X_{12}} \cdot \sin\left(\delta_1 - \delta_2\right) \qquad (1)$$

If the PST is inserted in to outgoing feeder, the transferred power flow by transmission line is given:

$$P_{12} = P_{12} \pm \Delta P = \frac{U_1 \cdot U_2}{X_{line} + \Delta X} \cdot \sin\left(\delta_1 - \delta_2 + \Delta\delta\right) \qquad (2)$$

where:

ΔP – additional power flow due to PST regulation,
ΔX – additional reactance in PST outgoing feeder,
$\Delta\vartheta$ – angle between primary and secondary voltage of PST.

In case, when the phase shift between primary and secondary winding equals zero ($\Delta\delta = 0°$), the power flow across the line with PST is limited only by its own reactance ΔX .

Without PST, the loading angle is $5° - 10°$. The maximum regulation range of Phase shift transformer is $\Delta\vartheta = 30° - 40°$.

Control angle of phase shift transformer has a significant impact on the power flow across transmission line. Function $\sin\left(\delta_1 - \delta_2 + \Delta\delta\right)$ can be considered as linear in operation area. Hence, the regulation angle $\Delta\delta$ is proportional to tap setting, the resulting flow of active power influenced by regulation of taps will be in proportion with tap setting of PST.

Impact of PST on power flow can be simply demonstrated on a power flow analysis in simply case of parallel lines according to the following figure.

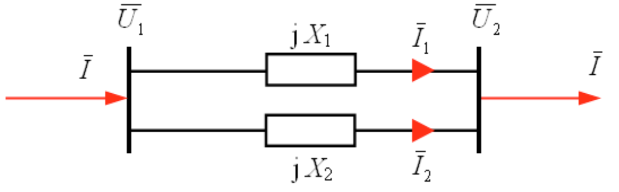

Fig. 4. Network with parallel lines

The current in node 2 is divided according to the proportion of impedances of parallel lines as follows:

$$X_1 \cdot \bar{I}_1 = X_2 \cdot \bar{I}_2 \Rightarrow \frac{\bar{I}_1}{\bar{I}_2} = \frac{X_2}{X_1}$$

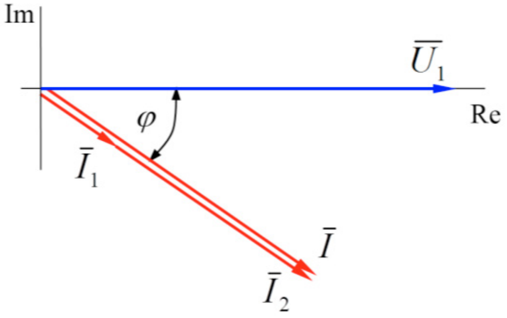

Fig. 5. Phasor diagram of voltage and currents (without PST)

This distribution depends on reactance of each lines, which may be in some cases undesirable (e.g. overloading of one line). If the resistance and line shunt admittance are neglected, then currents $\bar{I}_1$ and $\bar{I}_2$ have the same phase shift (Fig. 5).

The current distribution among lines can be caused by connection of PST to the network, according to Fig. 6.

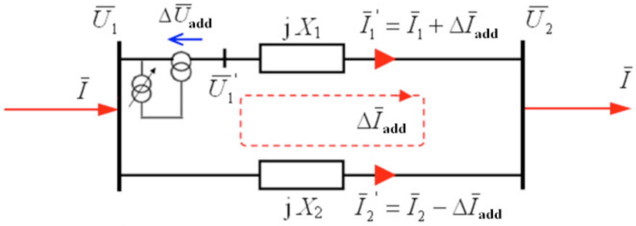

Fig. 6. Network with PST

Voltage difference, $\Delta\bar{U}_{add} = \bar{U}_1' - \bar{U}_1$, called additional voltage, will cause circulating current

$$\Delta\bar{I}_{add} = \frac{\bar{U}_1' - \bar{U}_1}{\mathrm{j}(X_1 + X_2)} = -\mathrm{j}\frac{\Delta\bar{U}_{add}}{X_1 + X_2},$$

which is added to the initial current.

Consequently currents in the two parallel lines are

$I_1' = I_1 + \Delta\bar{I}_{add}$; $I_2' = I_2 - \Delta\bar{I}_{add}$

If difference between primary voltage angle and additional voltage equals zero ($\alpha = 0°$), then there is a direct axis regulation. Because only network reactances are considered, additional current is delayed by 90° of additional voltage and has inductive character (Fig. 7). From the above it is clear, that it is possible to influence mainly active power flow (the reactive part of currents is changing I_1, I_2).

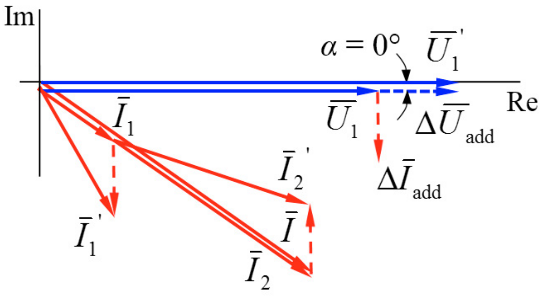

Fig. 7. Phasor diagram of voltage and currents for direct axis voltage regulation

If additional voltage is in upright to basic voltage ($\alpha = 90°$), it is called quadrature voltage control. Because only network reactance's are considered, additional current is delayed by 90° of additional voltage and has active character.

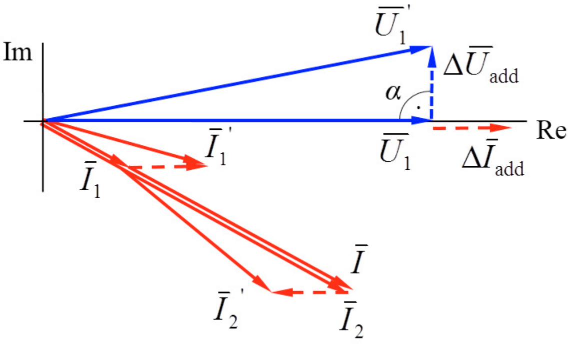

Fig. 8. Phasor diagram of voltage and currents for quadrature voltage regulation

Resulting distribution of currents shows the phasor diagram, Fig. 8. It is clear, that quadrature voltage regulation influences flows of active power (regulation is changing real component of currents I_1, I_2).

Phase shift transformer for power flow control is one of the solutions to increase transfer capacity of interconnections between neighbours TSO.

4. TRANSFER CAPACITY CALCULATION

Maximum feasible power exchange, which can be transmitted between two meshed power systems reliably and without disturbances of the system stability criterion is represented by Total Transfer Capacity (TTC). To determine how much electricity can be transmitted by interconnecting lines there are necessary essential tasks as: modelling and simulation of the effects of energy exchanges between the two interconnected electricity networks. This is achieved by a suitable simulation model. Based on the expected net configuration, cross-border trade scenarios of consumption and production of electricity, generated energy is pushed between the two systems to activate other cross-border flows, by increasing production in one system and reducing production in the second power system.

Electricity consumption in both systems remains unchanged. The profile charged to until they reach the safety limits [3], [4], [7], [9].

The resulting TTC value represents the maximum expected amount of power flow that can be safety transferred through the interconnection between this two systems.

NTC is given by the following equation:

$$\mathrm{NTC} = \mathrm{TTC} - \mathrm{TRM} \qquad (3)$$

Transmission reliability margin (TRM) covers the inaccuracy of estimated power flow at cross-border interconnection due to uncertain information's from market players and unexpected real time events. Information from the merchants is imperfect when transmission capacity must be notified. This comes in addition to the precariousness on some power system parameters, as well as the uncertainty of tie-line flows due to unexpected real time events, which are always possible. In this article we consider the value of TRM at 200 MW

Fig. 9. PST placements in Slovak power system

Calculation of maximal transfer capacity between Slovakia - Hungary and Slovakia - Czech Republic was provided by simulation program. In the simulation program there was constructed model of Central East Europe power system, with all lines, transformers, generators and with other necessary elements of power system. Total transfer capacity calculation was realised by maintaining of N-1 safety criterion in whole power system. For maximize the power flow between Slovakia and Hungary there was decreased the power generation in south part of CEE power system (Romania, Croatia) and increasing power generation in the north part of power system (North Germany, North Poland).

The simulation below contains

The simulation below consist of four variants of TTC calculation on Slovakia - Czech Republic interconnection and three variants of Slovakia - Hungary interconnection.

4.1 Variant SK-HU I.

Table 1 below shows the results of calculations for the basic engagement network. The basic model does not include PST transformer. Calculations were made of regard to compliance with the security criteria N-1 and respecting the maximum possible overload capacity of devices. For maximize the power flow between Slovakia and Hungary there was decreased the power generation in Croatia and Romania and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 448 (VE Gabčíkovo - Györ) when line V449 (Levice - Göd) was switched off.

Table 1. Transfer capacity for variant SK-HU I.

Branch	**Line loads [MW]**	**TTC [MW]**	**NTC [MW]**	**Limit element (N-1)**
448 (Gabčíkovo-Györ)	1077,2	1928,4	1728,4	448 (449)
449 (Levice-Göd)	851,2			

4.2 Variant SK-HU II.

Table 2 below shows the results of calculations for the basic engagement network. In this variant has been installed PST on line V 449 (Levice - Göd). Calculations were made of regard to compliance with the security criteria N-1 and respecting the maximum possible overload capacity of devices. For maximize the power flow between Slovakia and Hungary there was decreased the power generation in Croatia and Romania and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 490 (EMO - Levice) when line V491 (EMO - Levice) was switched off.

Table 2. Transfer capacity for variant SK-HU II.

Branch	**Line loads [MW]**	**TTC [MW]**	**NTC [MW**	**Limit element (N-1)**
448 (Gabčíkovo-Györ)	1085,8	2382,8	2182,8	490 (491)
449 (Levice-Göd)	1296,9			

4.3 Variant SK-HU III.

Table 3 below shows the results of calculations for the basic engagement network. In this variant has been installed PST on line V 448 (VE Gabčíkovo - Györ). Calculations were made of regard to compliance with the security criteria N-1 and respecting the maximum possible overload capacity of devices. For maximize the power flow between Slovakia and

Hungary there was decreased the power generation in Croatia and Romania and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 440 (Lemešany - Mukačevo) when line V449 (Levice - Göd) was switched off.

Table 3. Transfer capacity for variant SK-HU III.

Branch	Line loads [MW]	TTC [MW]	NTC [MW]	Limit element (N-1)
448 (Gabčíkovo-Györ)	1317,8	2512	2312	440 (449)
449 (Levice-Göd)	1194,2			

4.4 Variant SK-CZ I.

Table 4 below shows the results of calculations for the basic engagement network. The basic model does not include PST transformer. For maximize the power flow between Slovak and Czech republic there was decreased the power generation in Hungary and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 270 (Liskovec – P. Bystrica), when line V 404 (Nošovice – Varín) was turned off.

Table 4. Transfer capacity for variant SK-CZ I.

Branch	Line loads [MW]	TTC [MW]	NTC [MW]	Limit element (N-1)
404 (Nošovice – Varín)	-889	2545,7	2345,7	270 (404)
424 (Sokolnice – Križovany)	-532,2			
497 (Sokolnice – Stupava)	-910,1			
280 (Sokolnice – Senica)	-101,2			
270 (Liskovec – P. Bystrica)	-113,4			

4.5 Variant SK-CZ II.

Table 5 below shows the results of calculations for the basic engagement network. In this variant has been installed PST on line V 404 (Varín - Nošovice). For maximize the power flow between Slovak and Czech republic there was decreased the power generation in Hungary and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 280 (Senica - Sokolnice) when line V497 (Stupava - Sokolnice) was switched off.

Table 5. Transfer capacity for variant SK-CZ II.

Branch	Line loads [MW]	TTC [MW]	NTC [MW]	Limit element (N-1)
404 (Nošovice – Varín)	-1340,2	2677,5	2477,5	280 (497)
424 (Sokolnice – Križovany)	-336,9			
497 (Sokolnice – Stupava)	-661,3			
280 (Sokolnice – Senica)	-242			
270 (Liskovec – P. Bystrica)	-97,1			

4.6 Variant SK-CZ III.

Table 6 below shows the results of calculations for the basic engagement network. In this variant has been installed PST on line V 424 (Križovany - Sokolnice). For maximize the power flow between Slovak and Czech republic there was decreased the power generation in Hungary and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 270 (P. Bystrica - Lískovec) when line V404 (Varín - Nošovice) was switched off.

Table 6. Transfer capacity for variant SK-CZ III.

Branch	Line loads [MW]	TTC [MW]	NTC [MW]	Limit element (N-1)
404 (Nošovice – Varín)	-586,8	2738,5	2538,5	270 (404)
424 (Sokolnice – Križovany)	-1336,3			
497 (Sokolnice – Stupava)	-492,1			
280 (Sokolnice – Senica)	-172,2			
270 (Liskovec – P. Bystrica)	-151,1			

4.7 Variant SK-CZ IV.

Table 7 below shows the results of calculations for the basic engagement network. In this variant has been installed PST on line V 497 (Sokolnice – Stupava). For maximize the power flow between Slovak and Czech republic there was decreased the power generation in Hungary and increasing power generation in the north part of power system (North Germany, North Poland). Increasing the power flow has been stopped, once the N-1 criterion is not met. The limit element for this case was the line V 270 (P. Bystrica - Lískovec) when line V404 (Varín - Nošovice) was switched off.

Table 7. Transfer capacity for variant SK-CZ IV.

Branch	Line loads [MW]	TTC [MW]	NTC [MW	Limit element (N-1)
404 (Nošovice – Varín)	-682	2741,9	2541,9	270 (404)
424 (Sokolnice – Križovany)	-352,2			
497 (Sokolnice – Stupava)	-1335,1			
280 (Sokolnice – Senica)	-217,4			
270 (Liskovec – P. Bystrica)	-155,2			

5. ECONOMIC ASPECTS

On the final price of PST have the greatest impact, two main parameters of the transformer - Rated power [MVA] and control capability of PST (regulatory angle of PST). These two characteristics of the transformer, especially for large transmitted power is significant for economical solution. The investment for PST transformer with the same parameters according to experience, reaching about 160% of the standard transformer price, there can therefore be considered with a value of € 19,000 to 1 MVA of installed capacity. For presupposition maximal current limitation 2000 A corresponds circa 1400 MW PST transformer. Install of PST requires the construction of specialized fields in substations. Field for PST must be equipped compared to standard outlets (eg. for line or transformer) - a measure, protected and especially on a full field equipment by-pass (In contrast with conventional fields are fields with PST featured by 2 or 3 circuit breaker and with an appropriate number of isolators). Price of one average field in substation of 400 kV is approximately 3.0 million €. Price of field with PST is approximately 4.5 million €.

5. CONCLUSIONS

The results of the simulations suggest new possibilities for increasing the transmission capacity between transmission systems using a PMU and WAMS systems. Properly designed control system PST transformers using time-synchronized measured data from the PMU can increase the transmission capacity of existing lines. Finding a suitable location for both PST transformer and PMU devices, we can increase transmission capacity and also the efficiency and usability of these devices.

The results show that the most suitable location of a phase shift transformer. The best place for installing a PST transformer on cross-border connection between Slovakia and Czech Republic is on line V 497 (Sokolnice – Stupava). Total transfer capacity with PST installed on line V 497 (Sokolnice – Stupava) was 2727,1 MW. The total transfer capacity with PST installed on line 424 (Sokolnice – Križovany) was 2698,4 MW, and the TTC with phase shift transformer on line 404 (Nošovice – Varín) was 2681,4 MW.

The most suitable location installing a phase shift transformer on inter-connection between Slovakia and Hungary was on line 448 (Gabčíkovo-Györ). The value of total transfer capacity with a phase shift transformer installed on line 448 (Gabčíkovo-Györ) was 2511 MW. The total transfer capacity with PST installed on line 449 (Levice-Göd) was 2394 MW.

The most suitable place for installation of PMU measurement units in Slovak power system is Lemešany, Križovany, Sučany, Levice and Stupava power stations.

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