A SOFTWARE TOOL FOR PRESENTING FACTS DEVICES IN AN ELECTRIC POWER SYSTEM

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POVZETEK

*Vpliv naprav FACTS (Flexible AC Transmission System) na elektroenergetski sitem (EES) je odvisen od mnogo parametrov, posledično je ta vpliv težko prikazati jasno in hkrati vsestransko. Zaradi tega smo razvili računalniški program, ki omogoča grafični prikaz delovne in jalove moči ter fazorjev napetosti in tokov v longitudinalnem EES, ki lahko vsebuje različne naprave FACTS. Program omogoča enostavno spreminjanje parametrov naprav FACTS in parametrov EES, medtem ko se grafi sproti osvežujejo. Program je brezplačno dostopen na spletu (*http://lpee.fe.uni-*lj.si/index.php?option=com_content&view=category* *&layout=blog&id=42&Itemid=29*). Za demonstracijo uporabe programa smo v članku prikazali primerjavo med dvema podobnima—vendar z upoštevanjem določenih parametrov zelo različnima—napravama FACTS. Z uporabo programa lahko uporabnik dobi nov vpogled v način delovanja in vplivanja naprav FACTS na EES. Program prikazuje tudi številčne vrednosti delovne in jalove moči ter vrednosti napetosti in tokov, zato ga lahko uporabimo tudi za hitro oceno verodostojnosti rezultatov drugih—bolj detajlnih— izračunov.*

ABSTRACT

*The effects of Flexible AC Transmission System (FACTS) devices on an electric-power system (EPS) depend on many parameters. As a result, an easily understood and at the same time comprehensive explanation of these effects can be a difficult task. For this reason we have developed a computer program that can graphically represent the active and the reactive power and the phasors of the voltages and currents in a longitudinal EPS incorporating various FACTS devices. The design of the program makes it easy to change the parameters of the FACTS devices and the parameters of the EPS while the charts are simultaneously refreshed. The program is available, free of charge, on the web (*http://lpee.fe.uni-lj.si/index.php?option=com_content&view=category&layout=blog&id=42 *&Itemid=29*). To demonstrate the applicability of the program, a comparison between two similar—but when considering certain parameters, very different—FACTS devices has been performed. Using this program a user can gain a new insight into the effect of FACTS devices on an EPS, i.e., by changing the EPS's parameters and the parameter of a FACTS device, and by observing the changes in the power flow and the movement of the phasors of the voltages and currents. As the numerical results are also available "on-line", the program can be used as a simple control of plausibility of the results for other—more detailed— calculations.*

1.   INTRODUCTION

From the EPS's point of view, the consideration of FACTS devices is usually focused on the problem of controlling the power flows and voltages in an electrical network using these devices. However, a detailed presentation of the structure and internal operation of FACTS devices is beyond the scope of this research. Instead, the emphasis is on the effect of FACTS devices on the EPS, i.e., what we can achieve by using various FACTS devices. For this purpose, mathematical models of FACTS devices have been developed, e.g., [1]-[6].

In order to demonstrate the effect of FACTS devices on an EPS, diagrams that show the dependence of the active power and the reactive power on the transmission angle, i.e., the so-called $P\text{-}\delta$ and $Q\text{-}\delta$ diagrams, are normally used in combination with a presentation of the phasors for voltage and current of the two-machine EPS. Explaining the effect of a FACTS device is usually limited to a static representation of these phasors, and with some additional input the change of a certain phasor can be presented under conditions for which the other parameters stay unchanged (a situation that is, in general, unrealistic). The parameters of the EPS and the parameters of the FACTS devices normally interact with each other, e.g., a change in the angle of the series-injected voltage of a FACTS device usually causes a change in the magnitudes and angles of voltages at other nodes. However, it has been pointed out that applying basic equations and a few pictures is not the best way to introduce the subject, and that some kind of feeling for the effect of FACTS devices for the circumstances in an EPS is required. Therefore, a computer program has been developed that enables a presentation of the relations in a two-machine EPS that includes various FACTS devices and that enables any parameter to be changed on-line. In this way it is possible to visualize the effect of FACTS devices on the $P\text{-}\delta$ and $Q\text{-}\delta$ characteristics and especially on the relationship between the FACTS parameters and the EPS. As the numerical results are also available on-line, the program can be used as a simple control of plausibility of the results for other—more detailed— calculations. This program, which has been given the name "FACTS-schoolroom", is freely available and can be obtained from the website of the Laboratory of Electric Power Supply   (http://lpee.fe.uni-lj.si/index.php?option=com_content&view=category&layout= blog&id=42&Itemid=29), which is part of the Faculty of Electrical Engineering at the University of Ljubljana.

In the following sections the FACTS-schoolroom program is first described and then the use of the program is presented with the example of comparing two similar—but considering certain parameters, very different—FACTS devices.

2.   ABOUT THE FACTS-SCHOOLROOM PROGRAM

From the programming point of view, the FACTS-schoolroom program is not a very complicated program; it is a single "exe" file and requires no installation. However, it effectively shows the parameters of the EPS, i.e., it visualizes the active and the reactive power flow and the phasors of voltages and currents. Fig. 1 shows the main form of the program.

The EPS considered in the program is a longitudinally formed two-machine EPS. The FACTS devices included in the program are a Static Synchronous Series Compensator (SSSC), a Controllable Series Compensator (CSC), two kinds of Phase Shifting Transformers (PSTs), (i.e., two commonly used types: a Phase Angle Regulator (PAR) and a Quadrature Boosting Transformer (QBT)), a Static Var Compensator (SVC), a STATic COMpensator (STATCOM), a Unified Power Flow Controller (UPFC) and a UPFC in a more detailed EPS representation that also includes parallel susceptances and series resistances.

The inclusion of a FACTS device in the EPS is represented by the scheme in the middle of the main window. The parameters of the EPS and the parameters of the FACTS device can be quickly set using sliders or by a numerical entry in the edit boxes at the top of the main window. The parameters of the EPS are graphically presented in two charts. The chart on the left presents the dependence of the active and reactive powers on the selected parameter.
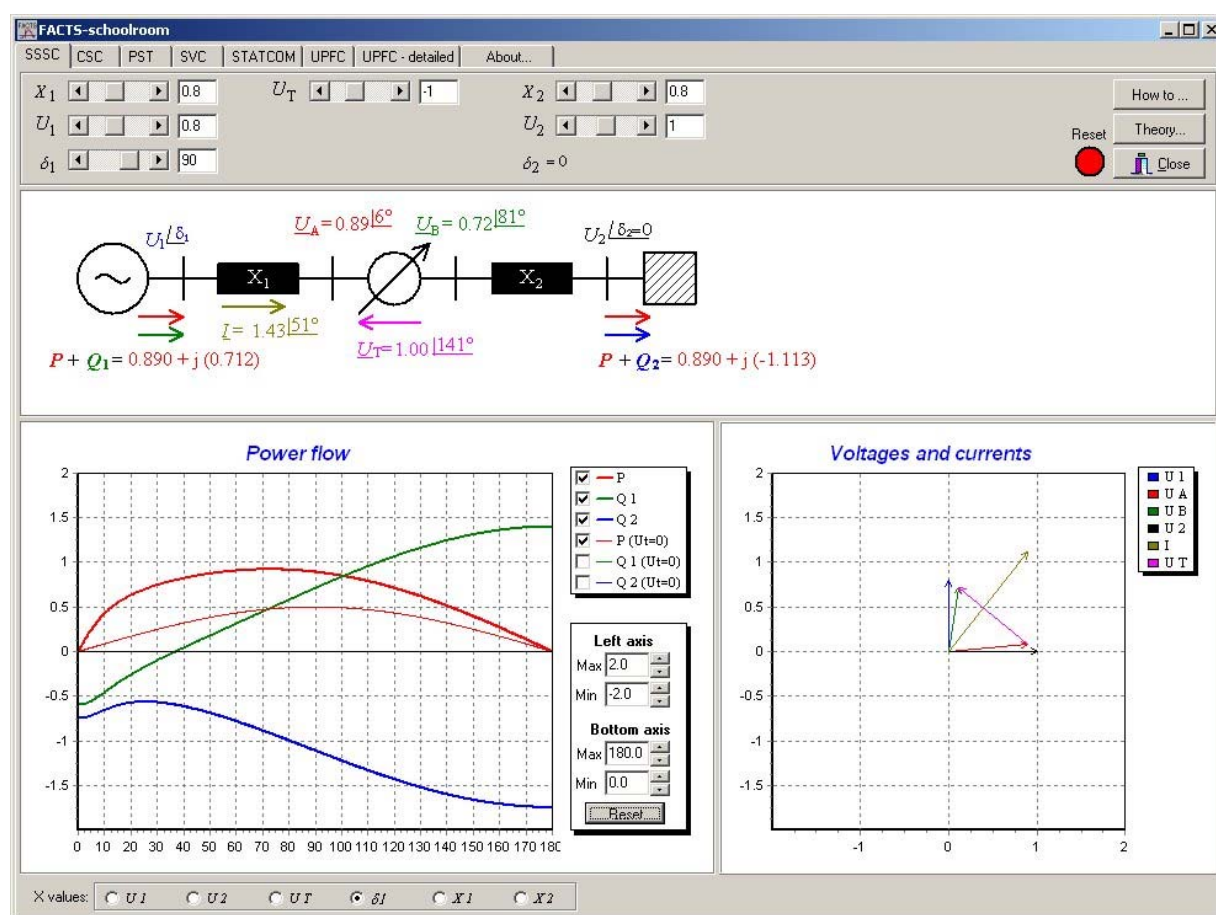

Fig. 1. Main window of the FACTS-schoolroom program

In order to present the effect of the FACTS device and for the user's convenience, the active and reactive powers for the case of an inactive FACTS device are represented by a thin line. The chart on the right-hand side presents the phasors of the voltage and current that depend on the parameters set at the top of the main window.

The effects of the FACTS devices on the EPS is determined by applying equations as described in the program according to [1] and [4]–[6]. To view these descriptions, the button "Theory…" should be clicked on. Each of the devices is described in a separate tab-sheet.

The form of the charts can be edited with a comprehensive editor that can be opened with a double-click on the chart. The mouse button can be used to zoom and pan, as described in the window that is opened by clicking on the button "How to…" on the right-hand side of the main window. Additionally, the minimum and maximum values of the vertical and horizontal axes can be quickly set by the editor at the bottom-right-hand side of the power-flow chart. It should be noted that special attention has been paid to the graphical presentation. The users should have the feeling that they are playing with the FACTS devices and the EPS, and they should have fun doing so. Therefore, for the presentation of the chart a comprehensive chart component has been used that makes it possible to present data in almost every possible way (however, most of them are unusable for our purposes), as such an approach is usually attractive, especially for the students as the potential users of the program.

Probably, the most important feature of the program is that it makes it easy to change the parameters of a FACTS device and the parameters of an EPS, while the charts are simultaneously refreshed. In the literature, in contrast, the power-flow characteristics and phasor diagrams are usually shown for various values of a single parameter of the FACTS device. In a paper it is not possible in practice to show clearly a power-flow diagram or a phasor diagram that considers the various parameters of an EPS and the various parameters of a FACTS device. However, using the FACTS-schoolroom program, by changing the EPS's parameters and a parameter of a FACTS device, together with the observation of the changes in the power-flow chart and the movement of phasors in the voltages-and-currents chart, a new insight is provided into the interrelation of the EPS's voltages and currents and consequently into the power flow through the EPS.

As the most common representation of the effects of FACTS devices on power flow is via the transmission characteristics, i.e., $P\text{-}\delta$ diagrams, this is the default selection in the FACTS-schoolroom program. However, with the program the dependence of the power flow on the other parameters can also be observed, i.e., the dependence of the active and reactive power on the voltage magnitudes, the series impedances and on the parameters of a FACTS device can be presented by selecting the proper radio-button at the bottom of the window.

3.   EXAMPLE OF THE USE OF THE PROGRAM FOR EXPLAINING THE DIFFERENCE BETWEEN THE IMPACT OF A CSC AND A SSSC ON THE EPS

Dynamic simulations have shown that under particular conditions the rated power of a SSSC can be much lower than the rated power of a CSC when achieving the same effect on the damping of oscillations [7]. However, there seems to be something wrong, especially when considering (as most people do) the SSSC as a kind of series compensation. Even the phasor diagram of the CSC is identical to the SSSC's diagram. To explain and analyze the behavior of both FACTS devices, the CSC and SSSC are positioned inside a two-machine test

system. The theoretical background is explained and then the behavior of the SSSC in the area of small transmission angles is presented, using figures and the FACTS-schoolroom program.

The CSC and SSSC are respectively represented by a controllable capacitance (Fig. 2a) and reactive voltage source (fig. 2b), the phase of which is shifted by 90° with respect to the line current. The corresponding vector diagram is shown in Fig. 2c. The same representation and vector diagram in the voltages-and-currents chart is shown in the FACTS-schoolroom program.
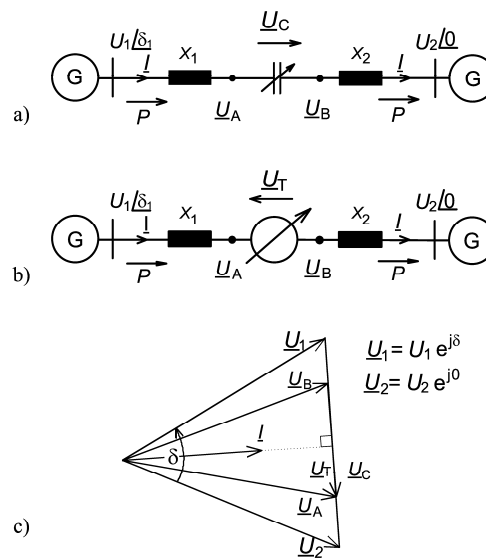

Fig. 2. a) Representation of a system with a CSC
b) Representation of a system with a SSSC
c) Phasor diagram (U_T<0)

It is clear that there is no difference between the CSC and the SSSC. However, if the operating characteristics and limitations are taken into consideration, the effects of the CSC and SSSC on the power flow are very different. In the CSC's case the system impedance is simply reduced by the CSC's compensation ratio K [1], and the transmission characteristic can be expressed as:

$$P = \frac{U_1 U_2}{(X_1 + X_2) \cdot (1 - K)} \sin(\delta) \qquad (1)$$

The magnitude of the injected voltage U_T is the SSSC's controllable parameter. Inside the SSSC's operating area it is independent of line current's magnitude. Considering [1] and [7], the analytical expression for the transmitted active power as a real function of the system parameters and the controllable SSSC parameter U_T can be expressed as:

$$P = \frac{U_1 U_2 \sin(\delta_1)}{X_1 + X_2}\left(1 - \frac{U_T}{\sqrt{U_1{}^2 + U_2{}^2 - 2U_1 U_2 \cos(\delta_1)}}\right) \qquad (2)$$

The parameter U_T in fact represents the magnitude of the U_T phasor, but it can also be negative. This U_T sign change means turning the $\underline{U}_T$ phasor by 180°. A similar description for both of the FACTS devices and the above equations can be found in the FACTS-schoolroom program by clicking on the button "Theory…".

The effect of the CSC and SSSC on the transmission characteristic can be visualized as a function of the ratio $P_1/$Pmax (Pmax being the maximum of the basic characteristic U^2/X sin(δ); U=1 P.U.) vs. the transmission angle δ. To present this function in the paper, the parameters of an EPS should be selected according to the specifics that need to be pointed out. In the presented case the relationship between the voltage magnitudes U_2 and U_T are important in order to show that it is possible to reverse the line's power flow. The function of the ratio $P_1/$Pmax is presented for the CSC and SSSC in Fig. 3a and 3b, respectively.
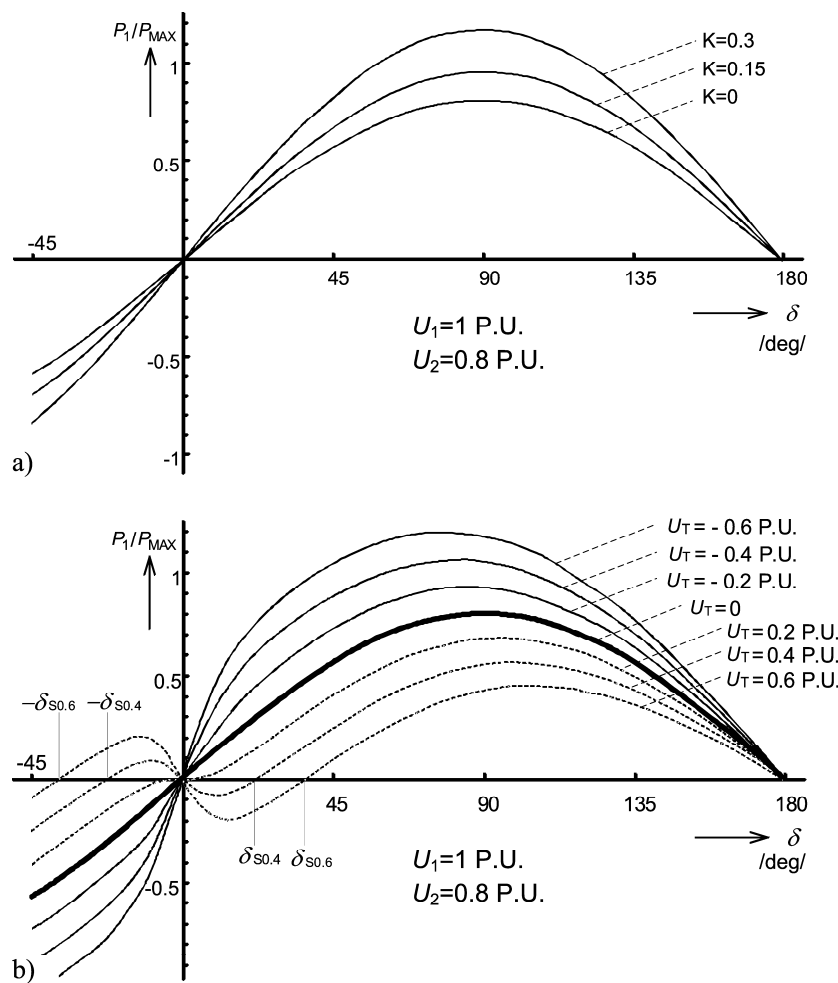

Fig. 3. a) CSC Transmission characteristics
b) SSSC Transmission characteristics

In the presented case U_1 equals 1 P.U., and U_2 equals 0.8 P.U. Because the CSC is in fact a controllable impedance, the CSC only reduces the equivalent system reactance for the compensation degree K, and the basic transmission characteristic (K=0) is multiplied by the factor 1/(1-K). Comparing the characteristics 3a and 3b it can be concluded that the SSSC is more efficient than the CSC in the area of small transmission angles (short lines or a low power-flow level). It can also be concluded that in contrast to the CSC, with the SSSC it is possible to reverse the line power flow.

The presented SSSC behavior can also be explained by studying the phasor diagrams. To present this behavior in the classical way, i.e., using static charts on paper, the phasors of the voltages and currents can be presented as in Fig. 4. If the phasor difference between U_1 and U_2 is changed (in the figure in steps of 10° from 45° to -45°), then the peak of the system-reactance-voltage-drop phasor ΔU ($\Delta U = U_1 + U_T - U_2$) draws a trajectory, as shown in Fig. 4. The magnitude of the test-system current I is in direct proportion to ΔU, its phase lagging by 90°. The real component of the current I is directly proportional to the transmitted active power. The numbered points on the current trajectory correspond to the numbered positions of the U_1 phasor.
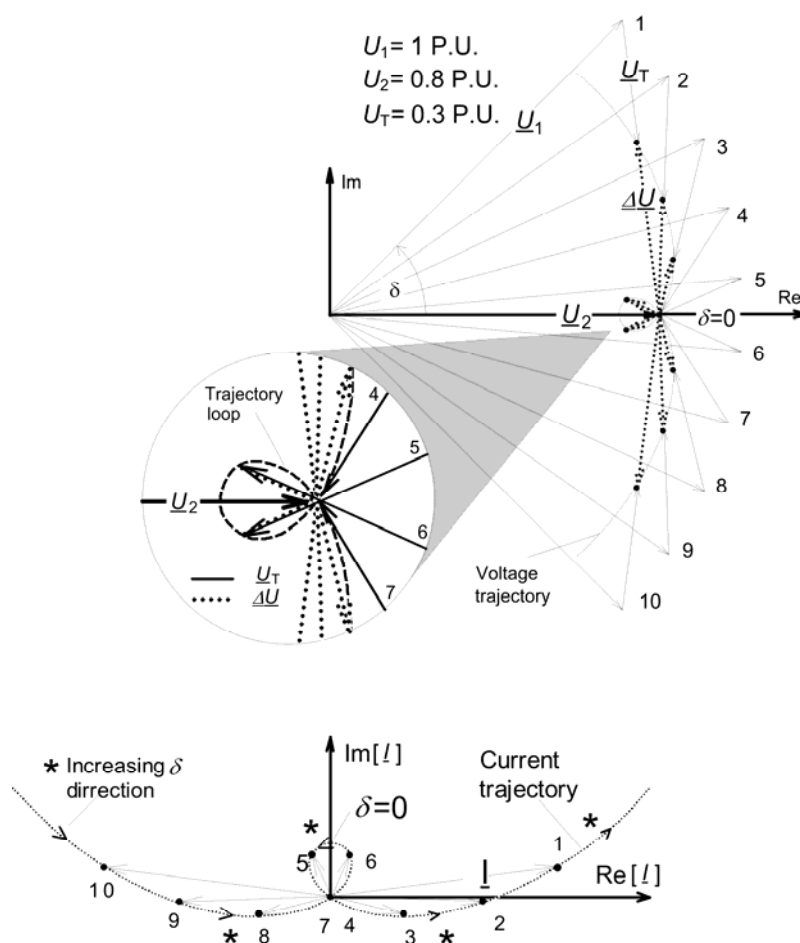

Fig. 4. Current and voltage trajectory

As shown above, the trajectory builds a loop, and while the system's operating point is on this loop, the power is flowing in a reverse direction. It is also shown that the loop appears only if the magnitude of $\underline{U}_T$ is higher than the difference between the magnitudes of $\underline{U}_1$ and $\underline{U}_2$. Based on this, a reverse power flow in the presented case can only be achieved if the magnitude of $\underline{U}_T$ is higher than 0.2 P.U. Also as shown above, points "4" and "7" on the trajectory represent the operating point in which the voltage difference between $\underline{U}_1$ and $\underline{U}_2$ is fully compensated by the SSSC. In this point the current equals 0 and its phase is changed by 180° (i.e., from inductive to capacitive), while the transmission characteristic crosses the "0" axis. The form of the transmission characteristics in the vicinity of the $\delta_1{=}0$ point can also be explained by Fig. 4. The smaller is the difference in magnitude between $\underline{U}_1$ and $\underline{U}_2$ the faster is the $\underline{\Delta U}$ phase change and thus the greater is the gradient $dP/d\delta$. If $|\underline{U}_1| \approx |\underline{U}_2|$ then the phase change is very fast and therefore the step change of the transmission characteristic occurs near the $\delta_1{=}0$ point.

Using the FACTS-schoolroom program a new insight into the behavior of a SSSC can be achieved, while the movements of the phasors are observed. In addition to Fig. 4, the phasors $\underline{U}_A$ and $\underline{U}_B$ are also shown on the voltages-and-currents diagram on the bottom-right-hand side of the main form and the voltage $\underline{U}_T$ is placed between the peaks of these two phasors. The amplitude U_T of the series injected voltage of a SSSC should be set to a value higher than 0.2 P.U. so as to achieve a reverse power flow in the vicinity of the $\delta_1{=}0$ point. By slowly changing the angle δ_1 of the generator (using the slider in the top-left-hand corner of the main form), the trajectory of the phasors presented in Fig. 4 can be observed. It can be seen that when the phasor $\underline{U}_T$ becomes greater than the difference between the phasors $\underline{U}_1$ and $\underline{U}_2$, the phasor of the line current $\underline{I}$ reverses the direction. The phenomenon of achieving a reverse power flow in the vicinity of the $\delta_1{=}0$ point depends on the parameters of the EPS and the SSSC that can be changed in the FACTS-schoolroom program. By changing these parameters, similar power-reversing trajectories of the phasor $\underline{I}$ can be achieved, e.g., by changing the phasors $\underline{U}_1$ and $\underline{U}_2$ in the area of the small angles δ_1. To see the dependence of the power-flow direction on, e.g., the voltages $\underline{U}_1$ and $\underline{U}_2$, the X-axis of the power-flow chart can be set to present the magnitude of the phasor $\underline{U}_2$, as shown in Fig. 5. By changing the magnitude of the phasor $\underline{U}_1$ it can be seen that the reverse power flow has its maximum at the point where the magnitudes of the phasors $\underline{U}_1$ and $\underline{U}_2$ are equal.

4.   CONCLUSION

This paper presents a novel approach to understanding of FACTS devices. A computer program called FACTS-schoolroom, which can be downloaded from our website, was developed to present the effects of FACTS devices on an EPS. The program calculates and presents the power-flow diagram and a diagram of the phasors of voltage and current, while the parameters of the EPS and the parameters of the FACTS device are being changed. The use of the program is presented for an example of comparing CSC and SSSC characteristics

in the area of small transmission angles, where reversible power flow can be achieved with an SSSC. The visualization of the parameters of the EPS enables an easier and deeper insight into the impact of FACTS devices on an EPS, and this is the key element in understanding FACTS devices.
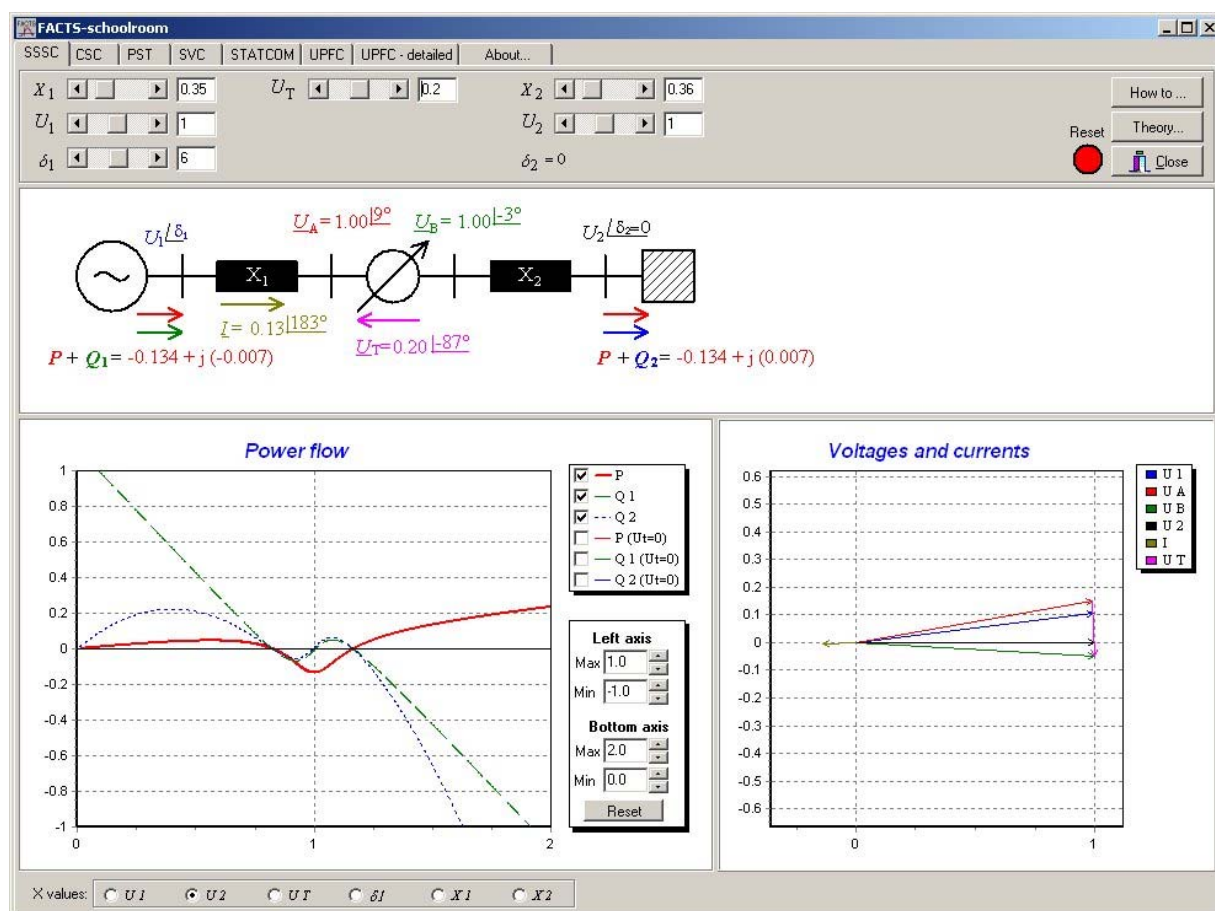

Fig. 5. The dependence of power flow on the magnitude of the voltage $\underline{U_2}$

5.   LITERATURE

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