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Damping of Power-System Oscillations with the Application of a GUPFC

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***Abstract*—FACTS devices might be successfully applied in power-system dynamics; however, appropriate control is a precondition for this. Some attempts were already made in searching of proper control strategies, but mainly according to local parameters and only for simple FACTS devices with only one controllable parameter. In this paper we present a control strategy for a GUPFC with multiple controllable parameters that is based on the energy function of a whole electric-power system and thus considers global parameters. The basis for the implementation of such a strategy that is proposed in this paper is to know the energy function of a power system that includes GUPFCs. Already-known energy functions that proved to be suitable for an electric-power system do not include such a device. Therefore, in this paper an energy function that considers the GUPFC's action in the form of a supplement to the already-known structure-preserving energy functions was constructed. The application of proposed control strategy was used in numerical example of damping of power-system oscillations after the fault clearing. The results show that the magnitudes of the GUPFC's series-injected voltages remain set to their maximum values and that only the angles of these voltages change, similar to the "bang-bang" control strategies proposed for some other FACTS devices.**

***Index Terms*-- FACTS devices, GUPFC, Lyapunov energy function, power system control, power system dynamic stability.**

I. Introduction

THIS paper presents the way how to control one of the FACTS devices with multiple controllable parameters, i.e., a generalized unified power-flow controller (GUPFC), for improvement of power-system dynamics. Primarily, FACTS devices are used for the increase and control of power-flow in steady-state operation modes. Due to their rapid response, FACTS devices might be able to play an important role in transient- and oscillatory-stability improvement. However, the open question remains how to control such a complex device in order to achieve the best results. In this paper we try to answer a part of this question by applying the energy-function approach.

An energy function based on a structure-preserving frame has been constructed for the power-system with a GUPFC. Based on this newly developed energy function the control strategy has been proposed. In addition the energy function can also be applied in any other energy-function-based calculations, e.g., transient-stability assessment using the Lyapunov direct method.

Using the above Lyapunov energy function the system can be illustrated with a mechanical analogy as a ball rolling on a potential energy surface, as in [1]. This visualization is presented in Fig. 1. The potential energy of a given post-fault system depends on the machine angles. In the case of a two-machine system the potential energy can be presented as a surface on a three-dimensional chart, where the x and y axes represent the angle of each machine (i.e., δ_1 and δ_2 according to Fig. 1). The potential-energy surface has a local minimum at the stable equilibrium point, which corresponds to the machine angles during the post-fault steady-state operation. Around this stable equilibrium point the potential-energy surface forms a bowl-shaped area, which is the area of stable system operation.

The kinetic energy of the system is equated to the kinetic energy of a ball that rolls along the potential-energy surface according to the generator swing trajectory. In steady-state operation the ball stands still at the stable equilibrium point. However, when the fault occurs, the ball is pushed toward the edge of the bowl-shaped area of the potential-energy surface until the fault is cleared. Depending on the total of the kinetic and potential energies of the ball at the time of fault clearing, the ball can either escape from the bowl over the saddle (i.e., an unstable case) or it can continue to oscillate within the bowl (i.e., a stable case).

To assess the stability of the system the kinetic energy is compared with the potential energy at the border of the stable area.

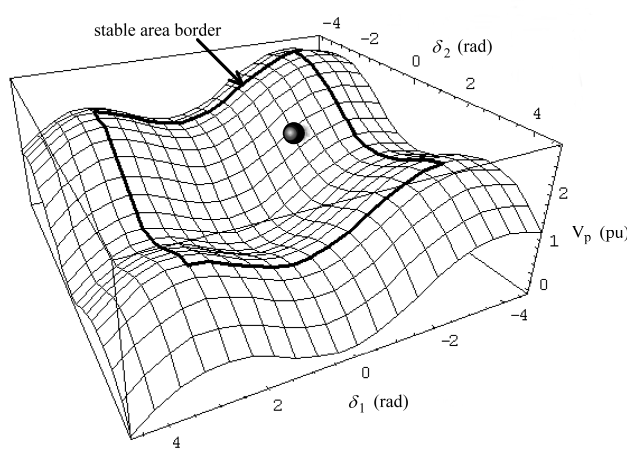

Fig. 1. A ball on a potential-energy surface

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According to the proposed control strategy the GUPFC's controllable parameters should be set so that the values of the time derivative of the potential part of the structure-preserving energy function (SPEF) for the power system with a GUPFC are as big as possible. They are calculated numerically for each of the chosen time intervals. Similar approaches have been used for various FACTS devices, but they all consider only the part of the SPEF that is related to the FACTS device, i.e., the control Lyapunov functions. Consequently, these control strategies consider only local parameters or global parameters that are reduced to a single-machine equivalent. Although such locally optimal control strategies are easy to apply and give satisfactory results, they do not give the answer to or an insight into the problem of the maximum possible effect of a FACTS device on the system's dynamic behavior (e.g., transient-stability improvement, oscillation damping). On the contrary, the proposed control strategy considers all the parts of the SPEF and thus uses global parameters (angles of all machines and phasors of voltages of all nodes should be known) that give a globally optimum control in the Lyapunov sense. This kind of control strategy can either be used as a reference for locally optimal control (in order to get an answer as to how effective is locally optimal control in the global sense) or, e.g., neural-network controllers could be trained. Global network parameters can be obtained with Phasor Measurement Units (PMU) based on Global Positioning System (GPS) synchronization using ground-based communications with an expected time delay of less than 30 ms for a typical data-transmission distance up to 2000 km. This fact opens up the possibility to also apply the presented control strategy for real-time control-parameter setting.

The paper is organized as follows: In the next section the operating characteristics of a GUPFC that are relevant for the construction of the energy function are presented. Then the construction of the energy function and the control strategy based on this energy function are presented. Next section presents numerical examples of the application of the proposed control strategy and the last section draws the conclusions.

II. Operating Characteristics of the GUPFC

In this section we describe operating characteristics of the GUPFC. It is described in more details in [2]-[6]. In addition to series branches it has at least one parallel branch. The operation of a GUPFC is much like the operation of a UPFC, because the parallel branch can compensate for the active power injected in the series branches. The model of a GUPFC is presented in Fig. 2.

Each of the series branches can be represented as a series branch of a stand-alone UPFC. In this case the GUPFC's parallel branch is the sum of the parallel branches of all the stand-alone UPFCs. For readers' convenience we will describe briefly the basic features of a single GUPFC branch with belonging part of the parallel GUPFC's branch that can be equated to a stand-alone UPFC. A more detailed description can be found in, e.g., [7] or [8].

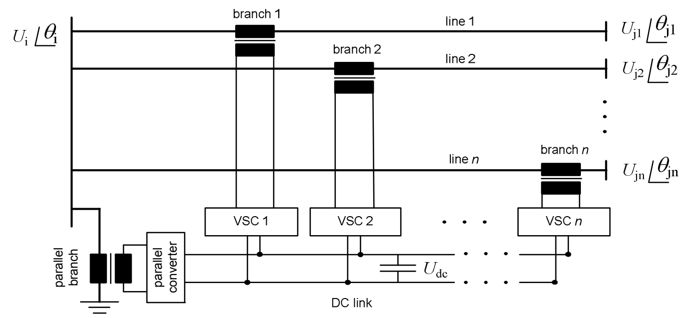

Fig. 2. Model of a GUPFC with *n* series branches and one parallel branch

In a lossless system a single GUPFC branch can be represented by a series-connected reactive voltage source with an accompanied transformer reactance X_{TRS} and a shunt-connected current source. The basic model of a device placed in a system between buses *i* and *j* and a phasor diagram is presented in Fig. 3 (a–b).

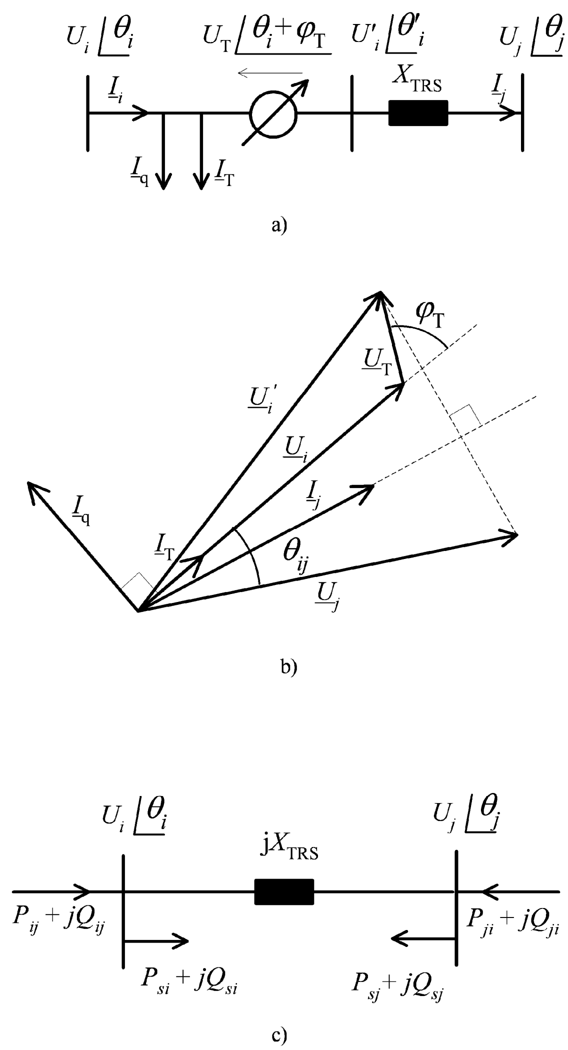

Fig. 3. a) Basic model of the single GUPFC branch.
b) Phasor diagram.
c) GUPFC injection model for a single branch.

Current $\underline{I}_{\mathrm{T}}$ is in phase with $\underline{U}_i$ and represents the active power exchange between the parallel and series GUPFC branches. This power is equal to the active power injection of the series branch. The current $\underline{I}_{\mathrm{q}}$ represents the reactive parallel branch current that is independent of the voltage magnitude U_i for the largest part of the operating area. The controllable parameters are U_{T}, φ_{T} and I_{q}, whereas I_{T} depends on the active power injected in the series branch. U_{T} represents the magnitude of the injected voltage $\underline{U}_{\mathrm{T}}$, while φ_{T} represents the angle of the injected voltage $\underline{U}_{\mathrm{T}}$ according to the bus voltage $\underline{U}_i$.

The injection model for one branch of a GUPFC is presented in [9]. It is the same as a general SSSC injection model. We now reproduce these equations and add the shunt-connected current source to obtain a complete GUPFC injection model for a single branch.

$$P_{si} = \frac{U_i U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \sin\left(\varphi_{\mathrm{T}}\right) + U_i \cdot I_{\mathrm{T}} \tag{1}$$

$$P_{sj} = -\frac{U_j U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \sin\left(\theta_{ij} + \varphi_{\mathrm{T}}\right) \tag{2}$$

$$Q_{si} = \frac{U_i \cdot U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \cos\left(\varphi_{\mathrm{T}}\right) + U_i \cdot I_{\mathrm{q}} \tag{3}$$

$$Q_{sj} = -\frac{U_j \cdot U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \cos\left(\theta_{ij} + \varphi_{\mathrm{T}}\right) \tag{4}$$

where $\theta_{ij} = \theta_i - \theta_j$ according to Fig. 3.

Furthermore, we replace the GUPFC's shunt-connected injection of active power with the injection of active power in the series branch. This active power is equal to the real part of the scalar product of the series-injected voltage $\underline{U}_{\mathrm{T}}$ and the conjugated value of the current $\underline{I}_j$.

$$U_i \cdot I_{\mathrm{T}} = \mathrm{Re}\left[\underline{U}_{\mathrm{T}} \cdot \underline{I}_j^{*}\right] \tag{5}$$

The current $\underline{I}_j$ can be assigned as:

$$\underline{I}_j = \left(\frac{\underline{U}'_i - \underline{U}_j}{\mathrm{j}X_{\mathrm{TRS}}}\right) \tag{6}$$

Expressing the magnitude and the argument of the voltage $\underline{U}_i$' as:

$$\left|\underline{U}'_i\right| = \sqrt{\left(U_i + U_{\mathrm{T}} \cdot \cos\left(\varphi_{\mathrm{T}}\right)\right)^2 + \left(U_{\mathrm{T}} \cdot \sin\left(\varphi_{\mathrm{T}}\right)\right)^2} \tag{7}$$

$$\arg\left(\underline{U}'_i\right) = \theta_i + \arctan\left(\frac{U_{\mathrm{T}} \cdot \sin\left(\varphi_{\mathrm{T}}\right)}{U_i + U_{\mathrm{T}} \cdot \sin\left(\varphi_{\mathrm{T}}\right)}\right) \tag{8}$$

after a few algebraic calculations we can rewrite the active power as:

$$\underline{U}_i \cdot \underline{I}_{\mathrm{T}} = \frac{U_j U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \sin\left(\theta_{ij} + \varphi_{\mathrm{T}}\right) - \frac{U_i U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \sin\left(\varphi_{\mathrm{T}}\right) \tag{9}$$

and consequently express the real power injection as:

$$P_{si} = \frac{U_j U_{\mathrm{T}}}{X_{\mathrm{TRS}}} \sin\left(\theta_{ij} + \varphi_{\mathrm{T}}\right) = -P_{sj} \tag{10}$$

The above equations describe an analytical method for confirming the real power balance of a GUPFC ($P_{si} = -P_{sj}$).

The injection model formally corresponds to the model derived in [10], where the magnitude of the series-injected voltage U_{T} is denoted as $r \cdot U_i$. This is correct in the case of a phase-shifting transformer, where its series-injected voltage magnitude is in proportion to the bus voltage magnitude U_i, and, consequently, the controlled parameter is r. In the case of a UPFC such a formulation is not appropriate, because the magnitude of the series-injected voltage U_{T} does not depend on the magnitude of the bus voltage U_i, and, consequently, the controlled parameter cannot be r but the magnitude U_{T} itself.

III. Construction of an Energy Function

In [11] the energy function for a UPFC was constructed. According to [11] and the equality of a single GUPFC branch to a stand-alone UPFC the energy function of the w-th GUPFC's series branch can be denoted as:

$$V_{\mathrm{GUPFC}w} = \frac{U_{\mathrm{T}w}}{X_{\mathrm{TRS}w}}\left(U_i \cdot \cos\left(\varphi_{\mathrm{T}w}\right) - U_{jw} \cdot \cos\left(\theta_{ijw} + \varphi_{\mathrm{T}w}\right)\right) \tag{11}$$

where $\theta_{ijw} = \theta_i - \theta_{jw}$ according to Fig. 2
$U_{\mathrm{T}w}$ is the magnitude of the series injected voltage,
$\varphi_{\mathrm{T}w}$ is the angle of the series injected voltage,
$X_{\mathrm{TRS}w}$ is the reactance of the series transformer,
U_i and U_{jw} are the voltages according to Fig. 2.

The GUPFC's parallel branch may provide the reactive current I_{q} in addition to the active-power compensation for the series branches. Like the UPFC presented in [11] the energy function for this reactive current can be denoted as:

$$V_{\mathrm{GUPFCq}} = U_i \cdot I_{\mathrm{q}} \tag{12}$$

For a GUPFC consisting of n-series branches and one parallel branch the energy function can be denoted as the sum of the energy functions of all the series branches (11) plus the energy function for a parallel branch (12):

$$V_{\mathrm{GUPFC}} = \sum_{w=1}^{n}\left[\frac{U_{\mathrm{T}w}}{X_{\mathrm{TRS}w}}\left(U_i \cdot \cos\left(\varphi_{\mathrm{T}w}\right) - U_{jw} \cdot \cos\left(\theta_{ijw} + \varphi_{\mathrm{T}w}\right)\right)\right] + I_{\mathrm{q}} \cdot U_i \tag{13}$$

Because the obtained energy function (13) was constructed for a system with a preserved structure, it acts like an extension to any SPEF, e.g., the energy function for the electric-power system (without FACTS devices) that was constructed in [12].

The SPEF of the N-bus and m-generators power system presented in [12] is denoted as:

$$V\left(\tilde{\omega},\tilde{\phi},U\right)=V_{\mathrm{k}}\left(\tilde{\omega}\right)+V_{\mathrm{p1}}\left(\tilde{\phi},U\right)+V_{\mathrm{p2}}\left(\tilde{\phi}\right)+K \tag{14}$$

where $\tilde{\phi}=\left[\tilde{\delta}^{\mathrm{T}},\tilde{\theta}^{\mathrm{T}}\right]^{\mathrm{T}}$,

δ is a vector consisting of m rotor angles,
θ is a vector consisting of N bus voltage angles,
ω is a vector consisting of m rotor velocities,
U is a vector consisting of N bus voltage magnitudes

The tilde denotes the values in the center-of-angle (COA). K is an arbitrary constant, usually chosen so that it places the origin of (14) at zero. V_{k} is the kinetic energy. The rest of the SPEF (14) is the potential energy,

The newly developed energy function for a GUPFC (13) acts like an extension to any structure-preserving energy function, e.g., (14). The energy function for the power system with a GUPFC is therefore:

$$V\left(\tilde{\omega},\tilde{\phi},U\right)=V_{\mathrm{k}}\left(\tilde{\omega}\right)+V_{\mathrm{p1}}\left(\tilde{\phi},U\right)+V_{\mathrm{p2}}\left(\tilde{\phi}\right)+V_{\mathrm{GUPFC}}\left(\tilde{\phi}\right)+K \tag{15}$$

Obviously, the energy function V_{GUPFC} can be extended to deal with any number of GUPFCs installed in the system.

IV. Control Strategy Based on an Energy Function

The presented optimal control strategy is not based on a feed-back control for the control parameters, which is the traditional way of applying Lyapunov theory, but it is based on numerical calculations of the time derivative of the energy function (15) for a system with a GUPFC. The optimal GUPFC control parameters are obtained by repetition of the time-domain simulation within short time intervals.

It was established in the past [7], [9] that a UPFC has to inject the maximum U_{T} and I_{q} in order to achieve the maximum transient-stability improvement. So only angles of series-injected voltages should be controlled in the case of a GUPFC. The main idea about defining the proper voltage angles is that within each interval Δt, where voltage angles are constant, we are searching for such angles that give a maximum change in the potential energy of the system according to the energy function (15). This principle is presented in Fig. 4 in the form of a flow chart. A step-by-step description follows:

1. The time-domain simulation for the period of the short circuit is performed in order to obtain the rotor angles and speeds at the moment of fault clearing.
2. Setting the initial constant values for the GUPFC's controllable parameters.
3. Time-domain simulation of the post-fault system for the period of the time interval Δt. The values of the energy function at the beginning and at the end of the interval Δt are calculated.
4. If all relevant values, i.e., the values that might be optimal, of the GUPFC's controllable parameters were applied in step 3, go to step 6, otherwise another set of the GUPFC's controllable parameters is determined in step 5. It was established that the optimal parameters do not change rapidly and, consequently, the relevant set of values of the controllable parameters do not need to be for all possible values, but can be limited to the region of optimal values from the previous time interval Δt.
5. New constant values of the GUPFC's controllable parameters are set.
6. Optimal GUPFC's controllable parameters are determined according to the values of the potential part of the energy function at the beginning and at the end of time interval Δt. These values of the energy function were obtained for various values of the controllable parameters in step 3. The controllable parameters that give the biggest increase (or the smallest decrease) in the potential part of the energy function are determined as the optimal parameters.

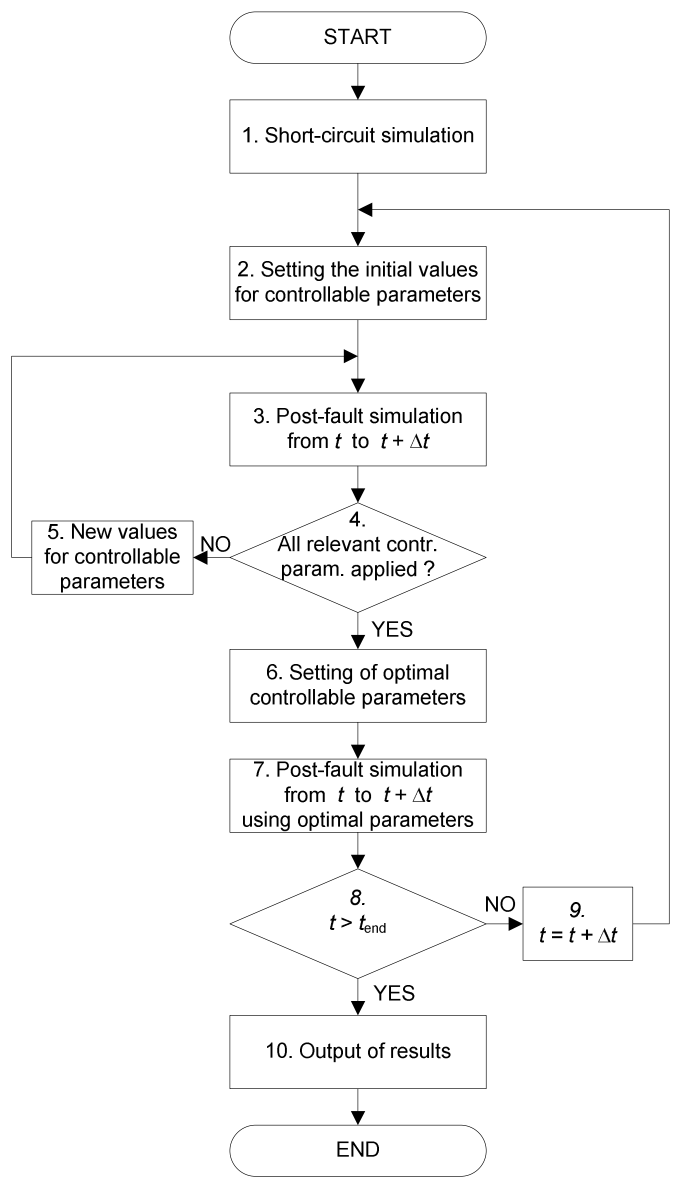

Fig. 4. Flow chart of a control strategy

7. Time-domain simulation of the post-fault system for the period of time interval Δt with optimal GUPFC's controllable parameters applied. This step is the same as step 3, except that optimal controllable parameters are applied.
8. If the time t_{end} is reached, then go to step 10, otherwise go to step 9. The time t_{end} is the total time of the post-fault period, i.e., around 1 s for the first-swing and about 10 s for subsequent oscillations.
9. Go to the next time interval Δt and continue from step 2. The rotor angles at the beginning of the next interval are determined as the rotor angles at the end of the current interval obtained in step 7.

V. Numerical Examples of the Application of the Proposed Control Strategy

The proposed control strategy was applied to a GUPFC in order to damp oscillations after the fault. The test system was an IEEE 9-bus 3-machine system with a GUPFC, which is presented in Fig. 5. The fault is a three-phase short-circuit near bus 7.

The value of the energy function was calculated according to (15), which includes the proposed energy function (13) for a GUPFC. The GUPFC's parameters that were controlled are U_{T1}, U_{T2}, φ_{T1} and φ_{T2}. As expected, according to the proposed control strategy, voltages U_{T1} and U_{T2} are always set to a constant, i.e. their maximum, value. The only controllable parameters that change are angles φ_{T1} and φ_{T2}.

The oscillations of the generator rotor angles δ_1, δ_2 and δ_3 are presented in Fig. 6. The origin of the time axis is the time of the fault clearing. The oscillations with the active GUPFC are presented in black, while the oscillation with the inactive GUPFC is in gray.

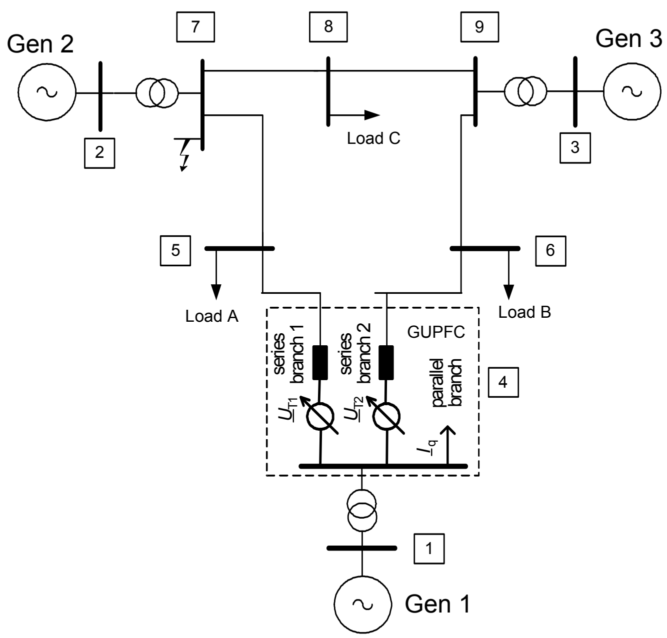

Fig. 5. An IEEE 9-bus test system with a GUPFC

It is clear that by applying the proposed control strategy the oscillations of the rotor angles can be successfully damped. After 2 seconds the oscillations are almost damped. Angles of series-injected voltages φ_{T1} and φ_{T2} for the period of oscillation damping are presented in Fig. 7.

The results show that for the damping of oscillations angles of the series-injected voltages change a few times by 180°, thus demonstrating the similarity with the bang-bang control strategies proposed for some other FACTS devices [13].

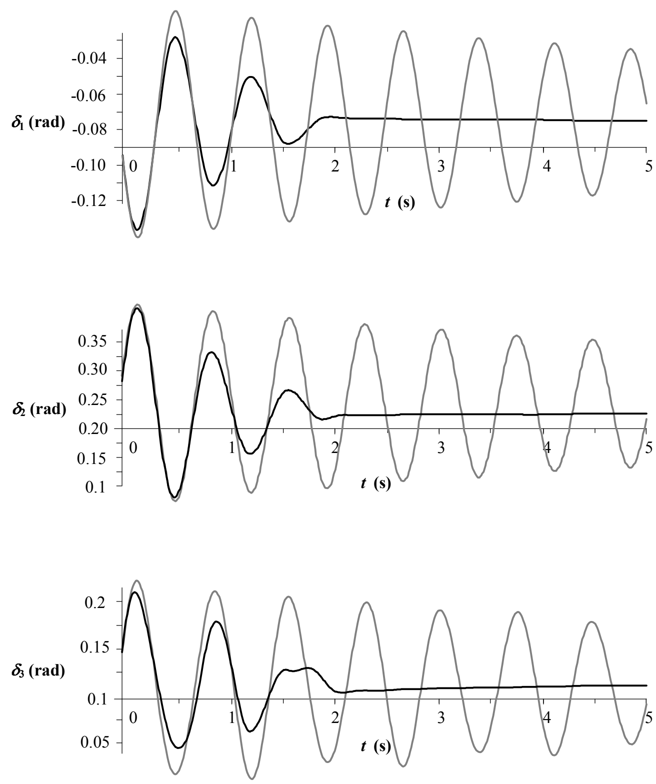

Fig. 6. Generator rotor angles δ_1, δ_2 and δ_3 with active (black) and inactive (grey) GUPFC after the fault is cleared.

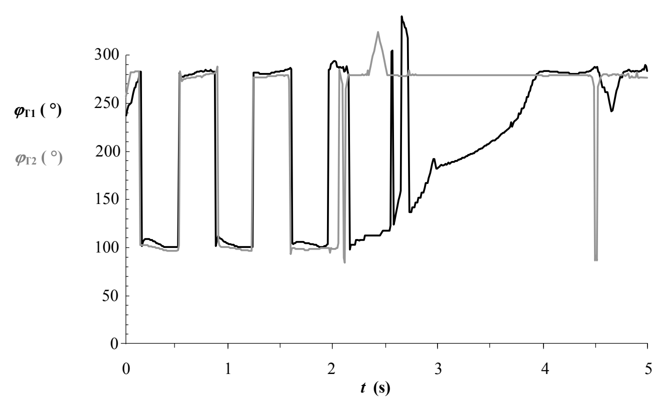

Fig. 7. Angles φ_{T1} and φ_{T2} for the period of oscillation damping.

VI. Conclusions

The proposed control strategy for a GUPFC is based on its energy function. For this reason, we first constructed the energy function for a GUPFC that can also be applied in any other energy-function based calculations, e.g., for a transient-stability assessment using direct methods.

The principle of the proposed control strategy is based on a numerical search for the maximum of the time derivative of the potential part of the energy function for an electric-power system comprising GUPFCs. To follow this principle, the GUPFC is controlled in the form of sectional-constant controllable parameters. The control strategy for the GUPFC control parameters' setting was demonstrated on the example of the damping of oscillations. The results show that the magnitudes of the GUPFC's series-injected voltages and the magnitude of parallel current should be set to the maximum values and that only the angle of series-injected voltages changes a few times by 180^{o}, thus demonstrating a similarity with the bang-bang control strategies proposed for some other FACTS devices. As can be seen from the results, a GUPFC could be an effective device for transient-stability improvement and oscillation damping; however, appropriate control is a precondition for this.

The energy function applied presents the energy of the whole system and therefore the control strategy gives the global optimum in the Lyapunov sense. Therefore, it can serve as a reference for any control strategy based on local parameters or it can be used for, e.g., the learning of neural-network controllers.

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VIII. Biographies

Valentin Azbe received his B.Sc., M.Sc. and Dr.Sc degrees from The University of Ljubljana, Slovenia, in 1996, 2003, and 2005, respectively. After receiving his diploma he worked with IBE, consulting engineers, Slovenia, as a project manager in the Department for Overhead-Lines design. In 2000 he joined the Department of Power Systems and Devices at the Faculty of Electrical Engineering, The University of Ljubljana, where he has since worked as a junior researcher. In 2005 he became a Teaching Assistant. His areas of interest include system analysis, FACTS devices, power-system protection and DC power-system analysis.

Rafael Mihalic received the Dipl. Eng., M.Sc. and Dr.Sc. degrees from The University of Ljubljana, Ljubljana, Slovenia, in 1986, 1989, and 1993, respectively.

He became a Teaching Assistant in the Department of Power Systems and Devices, Faculty for Electrical and Computer Engineering, The University of Ljubljana, in 1986. Between 1988 and 1991, he was a member of the Siemens Power Transmission and Distribution Group, Erlangen, Germany. Since 2005 he has been a Professor at the University of Ljubljana. His areas of interest include system analysis and FACTS devices. Prof. Mihalic is a member of Cigre (Paris, France).