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A Robust Control Strategy for UPFC to Improve Transient Stability Using Fuzzy Bang-Bang Control

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Abstract: Unified Power Flow Controller (UPFC) has been widely used to enhance damping of power swings. The control strategy adopted to mitigate power system oscillations in an effective and robust manner is the key issue. Various control methods used to improve the transient stability based on optimal parameters, state variables and injection model were studied. A scheme based on fuzzy bang-bang control is proposed for UPFC in this paper. Using Fuzzy Logic Control (FLC) based on bang-bang control; the UPFC will contribute to the damping of power swings without deteriorating the effect of the other Power Oscillation Damping (POD) devices. The damping effect is robust with respect to loading condition, fault location and network structure. Furthermore, the control inputs are based on rotor-angle signals that are estimated from voltage and power measurements. The FLC design is based on Lyapunov function analysis and is simulated on a single generator power system model. Numerical simulations show that the performance of controller is effective for both single-phase and three-phase fault. This single generator approach can be extended to multi-generator systems.

Key words: Bang-bang control, fuzzy logic control, local rotor angle estimation, robustness, transient stability, unified power flow controller

INTRODUCTION

Transient stability improvement through power oscillation damping plays vital role in improving the quality of power system. Application of Power System Stabilizers (PSS) has been one of the first measures to enhance damping of power swings. Investigations by Hauer (1987) and Noroozian *et al*. (1996) shows that, with increasing transmission line loading over long distances, the use of conventional PSS might in some cases not provide sufficient damping for inter-area power swings. The possibility of controlling transmittable power using Thyristor Controlled Series Capacitor (TCSC) and Static Var System (SVC) implies its potential application for improving transient stability and power oscillation damping. To damp power oscillations a supplementary control signal should be added to the SVC regulator. The damping effect of an SVC explained by Larsen and Chow (1987) and Noroozian and Anderson (1994) has the following features:

- SVC becomes more effective for controlling power swings at higher levels of power transfer.
- Effectiveness of SVC depends on placement.
- SVC design to damp the inter-area modes might excite the local modes.
- SVC damping effect depends on load characteristics.

Kimbark (1966) stated that the transient stability could be improved by a switched series capacitor. The damping effect of TCSC explained by Angquist (1993) has the following features:

- TCSC becomes more effective at high levels of power transfer.
- Location of TCSC does not affect damping effect.
- Damping effect is not sensitive to load characteristic.
- TCSC design to damp the inter-area modes does not excite the local modes.
- Effectiveness is higher than SVC.

Artificial neural networks are applied to SVC by Wang (1995) for improving power system damping. The Unified Power Flow Controller (UPFC) is a member of FACTS family with attractive features. Schauder *et al*. (1998) showed that the device can independently control many parameters, so it is the combination of STATCOM and Static Synchronous Series Compensator (SSSC). These devices offer an alternative mean to mitigate power system oscillations. Much research in this domain has been realized (Machowski *et al*., 1996; Noroozian *et al*., 1997). This research shows that UPFC is an effective device for this aim. Various methods of reference identification of the series part, in order to improve the transient stability of the system based on: Optimal

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parameters presented by Mihalic*et al.* (1996), state variables approach by Machowski *et al.* (1998) and also Injection model by Noroozian *et al.* (1997) were developed. Padiyar and Uma Rao (1999) and Sen and Stacey (1998) explained the modeling and control of UPFC for transient stability. Identification method based on state variables and using the local measurements was proposed by Gholipour and Saadate (2005). No work has been reported in applying FLC bang-bang control to UPFC and robustness. A successful attempt was made by us to extend the above control strategy for UPFC. The control inputs are based on rotor-angle signals that are estimated from voltage and power measurements. As in case of particle oscillations on a concave surface, the extent of oscillations can be modeled by particle's total energy, kinetic energy and potential energy. These energies can be represented using simple Lyapunov functions in terms of parameters such as the velocity and displacement of the particle. Damping the total Lyapunov function will also damp system oscillations. The FLC design is based on Lyapunov function analysis and is simulated on a single generator power system model.

This study explains briefly the formulation of Lyapunov energy function for UPFC and fuzzy logic control design for the single generator system under consideration. The method for estimation of rotor angle and rotor speed using locally measured voltage and power is also explained. The simulation studies are performed using MATLAB software in the research laboratory of Robin Research Trust. The results show that UPFC with fuzzy bang-bang controller is an effective technique for suppressing rotor angle oscillations when compared to existing methods discussed above. Robustness of the proposed algorithm with respect to type of fault, loading condition and network structure is the unique feature of this research work.

System model: A single generator power system model is shown in Fig. 1. This system is used to illustrate control concepts of system oscillations, influence of the UPFC on the generator and bang-bang control design for damping oscillations. We assumed a reduced model of the synchronous generator. The voltage behind the transient reactance of the generator is $V\angle 0$ and the voltage at the infinite bus is $W\angle\delta$. Under steady state conditions, the mechanical power P_m equals the electrical power P_e and $d\omega/dt = 0$.

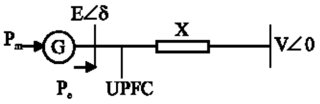

Fig. 1: Model of power system

With a severe fault on the transmission line, power output from the generator will reduce to zero. This will lead to instability, unless the fault is cleared before the clearing time. System oscillations can be described by:

$$\frac{d\omega}{dt} = \frac{1}{2H}\left[P_m - \frac{EV}{X}\sin\delta\right] \tag{1}$$

Where H is the inertia constant for the generator; δ is the rotor angle; ω is the rotor speed; X is the reactance of the line; and P_m is the constant mechanical power input.

The UPFC configuration is shown in Fig. 2, which comprises of two voltage source converters connected back to back through a common dc bus. The converter-1 is called shunt converter and converter -2 is called series converter. The arrangement functions as an ideal ac to ac power converter in which real power can freely flow in either direction between the ac terminals of the two converters and each converter can independently generate (or absorb) reactive power at its own ac output terminal. Converter-2 provides the main function the UPFC by injecting a voltage V_{pq} with controllable magnitude $|V_{pq}|$ and phase angle p in series with the line via. a insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through this voltage source resulting in reactive and real power exchange between it and its ac system. The reactive power exchanged at the ac terminal (i.e., at the terminal of series injection transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power, which appears at the dc link as a positive or negative real power demand.

The basic function of converter-1 is to supply or absorb the real power demanded by converter-2 at the common dc link to support the real power exchange resulting from the series voltage injection. Converter-1

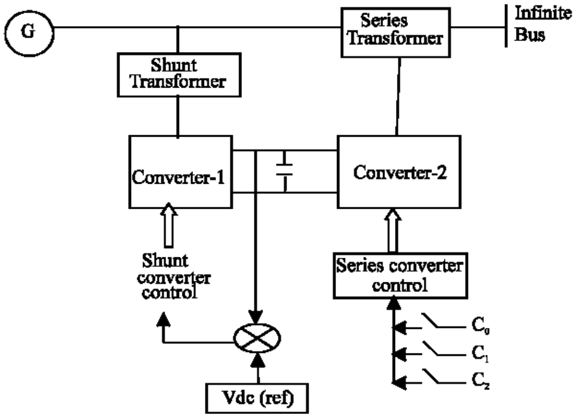

Fig. 2: Basic UPFC control scheme

can also generate or absorb controllable reactive power if desired and thereby provide independent compensation for the line.

The superior operating characteristics of UPFC are due to its unique ability to inject an AC compensating voltage vector with arbitrary magnitude and angle in series with the line up on command, subject only to equipment rating limit with suitable electronic control. The UPFC can cause the series injected voltage vector to vary rapidly and continuously in magnitude and/or angle as desired. Thus it is not only able to establish an operating point within a wide range of possible P,Q conditions on the line, but also has the inherent capability to transition rapidly from one such achievable operating point to any other.

The basic UPFC can be represented as a two-port device as shown by Fig. 3 with a controllable voltage source V_{se} in series with the line and a controllable shunt current source I_{sh}. Since the UPFC as a whole does not absorb or generate any real power, the dc capacitor voltage is maintained a constant.

The shunt converter can be controlled for maintaining constant voltage in sending-end bus. In this paper this aspect is not considered and it is controlled only to maintain dc bus voltage at the desired level. Changing state of switches C0, C1 or C2 as shown in Fig. 2 can regulate the voltage injected by the series controller. The output of series converter can be bang-bang controlled to three different values:

V_{series} : When switch C_0 is closed.
$V_{series} = V_{max}/2$: When switch C_1 is closed.
$V_{series} = V_{max}$: When switch C_2 is closed.

Where V_{series} is the voltage injected by the UPFC; V_{max} is the maximum voltage injection capacity of UPFC.

The target of damping control is to conduct proper switching of C_0, C_1 or C_2 at strategic times as to quickly damp out system oscillations.

Formulation of Lyapunov energy functions: The swing equation can be written as

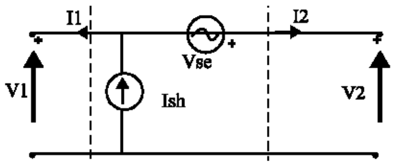

Fig. 3: Simulation model of UPFC

$$2H\frac{d\omega}{dt} = P_m - P_e\left(V_{series},\delta\right) \tag{2}$$

As V_{series} is varied the terminal voltage and hence P_e varies.

We will multiply Eq. 2 by $\omega = d\delta/dt$ and cancel dt on both sides to get the equation:

$$2Hd\omega = \left[P_m - P_e\left(V_{series},\delta\right)\right]d\delta \tag{3}$$

Suppose δ swings between δ_{min} and δmax and the final equilibrium is δ_p. Integrate the above equation, considering:

$$\omega\left(\delta_{min}\right) = 0; \omega\left(\delta_{max}\right) = 0 \tag{4}$$

$$H\omega^2 = \int_{\delta_{max}}^{\delta}\left[P_m - P_e\left(V_{series},\delta\right)\right]d\delta \qquad \delta > \delta_p \tag{5}$$

$$H\omega^2 = \int_{\delta_{min}}^{\delta}\left[P_m - P_e\left(V_{series},\delta\right)\right]d\delta \qquad \delta > \delta_p \tag{6}$$

The first part of Lyapunov function is defined as

$$\in_T(\omega) = H\,\omega^2 \tag{7}$$

The second part Lyapunov function is defined as

$$\in_2\left(\delta\right) = \int_{\delta_p}^{\delta}\left[p_e\left(V_{0series},\delta\right) - P_m\right]d\delta \tag{8}$$

The total Lyapunov function is defined as

$$\in_T(\delta, \omega) = \in_1(\omega) + \in_2(\delta) \tag{9}$$

When the system network is identical to the post-fault network, i.e., $V_{series} = V_{0series}$

$$\begin{aligned} &\frac{d\in_T\left(\delta,\omega\right)}{dt} = \frac{d\in_1\left(\omega\right)}{dt} + \frac{d\in_2\left(\delta\right)}{dt} \\ &\frac{d\in_T\left(\delta,\omega\right)}{dt} = \omega\left[P_m - P_e\left(V_{series},\delta\right)\right] \\ &\left|V_{series} = V_{0series} + \omega\left[P_e\left(V_{series},\delta\right) - P_m\right]\right. \\ &\frac{d\in_T\left(\delta,\omega\right)}{dt} = \omega\left[P_e\left(V_{0series},\delta\right) - P_e\left(V_{series},\delta\right)\right] \end{aligned} \tag{10}$$

The objective of Lyapunov function optimization is to minimize

$$\frac{d\varepsilon_T(\delta,\omega)}{dt}$$

and drive ϵ_T to zero. The bang-bang control can only be near optimal since only discrete control C_0, C_1 or C_2 is applied to the system.

FLC DESIGN

The ultimate objective of this research is to implement FLC at the line in which UPFC is connected. The inputs to FLC are δ and ω from the single generator with reference to voltage at UPFC terminals. For the output, the FLC will choose one of the three switch states from C_0, C_1 and C_2 through competition. A simple fuzzy logic scheme comprises three functioning blocks, namely fuzzification, implication and inference and selection of control. Input data are processed through these three blocks sequentially.

Fuzzification: Crisp input data need to be converted into membership grades to which they belong to each of the associated linguistic levels. These levels are represented by fuzzy sets. Fuzzification serves as data preprocessor for implications of linguistic rules in a latter stage. There are 14 distinct linguistic levels, namely $A_{1-14,}$ for input δ and 8 distinct linguistic levels, namelyB_{1-8}, for ω. Membership functions for the corresponding fuzzy sets are distinct and triangular. A heuristic trial-and-error procedure is needed to find the appropriate fuzzy partitioning by comparing the present and desired response for FLC.

Implication and inferencing: Various fuzzified inputs are fed into a fuzzy rule base for implication and inferencing. Linguistic control rules are constructed based on observations of dynamic behaviors and switching curves. With the use of two state inputs (δ and ω), we obtain a two-dimensional rule base with 14×8 linguistic levels as in Table 1. The rule base is a collection of fuzzy conditional statements in the form of 'if-then' rules. Each rule carries a weight α_{ii} (called firing strength), which is a measure of the contribution of i^{th} rule to the overall fuzzy control action. The firing strength α_i is defined as:

$$\alpha_i = \mu_A(x_0)\Lambda\mu_B(y_0) \tag{11}$$

Where $A\varepsilon\ \delta$, $B\varepsilon\ \omega$; μ denotes grade of membership defined for input state (δ and ω); x_0 and y_0 are the input variables used at a particular time instant; and Λ is the fuzzy 'ANS' operator.

Table 1: Two-dimensional fuzzy control rules

δ	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}
B_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1
B_2	C_1	C_1	C_1	C_1	C_2	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1
B_3	C_1	C_1	C_1	C_2	C_2	C_2	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1
B_4	C_1	C_1	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1	C_1	C_1	C_1	C_1
B_5	C_2	C_2	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1	C_1	C_1	C_2	C_1
B_6	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_1	C_1	C_1	C_2	C_2	C_1
B_7	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_1	C_2	C_2	C_2	C_1
B_8	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_1

The membership value of each possible switching state C_0, C_1 and C_2 for the FLC is obtained as:

$$\begin{aligned} \mu_i(C_0) &= \Sigma\ \alpha_i/4\ i = 49, 50, 63, 64 \\ \mu_i(C_1) &= \Sigma\ \alpha_i/55\ i = 1, 2, 3 \\ \mu_i(C_2) &= \Sigma\ \alpha_i/52\ i = 19, 32, 33 \end{aligned} \tag{12}$$

Selection of control: The main purpose of selection of control is to choose a non-fuzzy discrete control that best responds to current system oscillations. The final discrete FLC output indicates the final switching state chosen from C_0, C_1 and C_2. The choice is competitive and only one switching state with highest membership μ_i among C_0, C_1 and C_2 is chosen.

ESTIMATION OF GENERATOR PHASE ANGLES AND SPEEDS

In this study, we show how rotor angle δ and rotor speed ω can be evaluated using locally measured voltage and power. The voltage drop across line at the n^{th} sampling time is:

$$V_{12}(nT) = \frac{jX}{V_1(nT)}\left[P_{12}(nT) - jQ_{12}(nT)\right] \tag{13}$$

Where V_1 is taken as reference (p.u.); T is the sampling time (s).
The rotor angle is

$$\delta(nT) = \tan^{-1}\left[\frac{\operatorname{Im}(V_{12}(nT))}{V_1 + \operatorname{Re}(V_{12}(nT))}\right] \tag{14}$$

The rotor speed is

$$\omega(nT) = \frac{1}{T}\left[\delta(nT) - \delta((n-1)T)\right] \tag{15}$$

RESULT AND DISCUSSION

To test the validity of the control algorithm of the UPFC described above, a single generator infinite bus power system shown in Fig. 1 has been simulated using

Table 2: Generator characteristic

S_n (MVA)	1000	X'_d (p.u)	0.32
V_n (KV)	15.7	X'_q (p.u)	0.32
X_d (p.u)	1.896	X''_d (p.u)	0.213
X_q (p.u)	1.896	X''_q (p.u)	0.213
X_1 (p.u)	0.26	t'_d (S)	1.083
X_2 (p.u)	0.0914	t'_q (S)	1.1
R_n (p.u)	0.00242	t''_d (S)	0.135
J (Kg m^2)	10^5	t''_q (S)	0.135

MATLAB software in the research laboratory of Robin Research Trust. The generator rating is 1000 MVA, equivalent of 4 generators in parallel, each of 250 MVA capacity. Each generator is directly connected to a transformer of 250 MVA. The transmission line is 500 km long and is 400 KV. The parameters of generator, transformer and lines are given below (Noroozian and Anderson, 1994)

Transformer (T):

Voltage ratio = 15.7/400 KV; Rated power = 1000MVA;

Resistance = 0.0059 p.u;

Inductance = 0.127 p.u.

The characteristics of the generator are shown in Table 2.

Where S_n denotes rating of generator; V_n denotes rated voltage of generator; X_d denotes direct axis reactance; X_q denotes quadrature axis reactance; J denotes moment of inertia; X'_d denotes direct axis transient reactance; X'_q denotes quadrature axis transient reactance; X''_d denotes direct axis sub-transient reactance; X''_q denotes quadrature axis sub-transient reactance; t'_d denotes direct axis transient time constant; t'_q denotes quadrature axis transient time constant; t''_d denotes direct axis sub-transient time constant; t''_q quadrature axis sub-transient time constant; X_0 denotes zero sequence reactance; X_2 denotes negative sequence reactance and r_n denotes stator resistance.

Transmission line: Resistance = 3.2Ω 100^{-1} km; Inductance = 103 mH 100^{-1} km; Capacitance = 1.1 μF 100 km^{-1}.

The base of voltage and power for per-unit calculation is V_{base} = 15.7 KV (at generator output bus) and S_{base} = 1000 MVA.

The considered contingencies are single-phase and three-phase fault on transmission line near sending end bus, while the generator is operating at 70% of its rated capacity. The short-circuit duration in all simulations is considered between t = 0.2 and 0.4 S. The fault is cleared in 0.4 S with operation of transmission line re-closure. This fault period involves the maximum time of reaction of the protection system.

Figure 4 show the responses when a single-phase fault occurs. These curves indicate that the system is unstable, with un-damped oscillations in power lines when UPFC is not in service. Additional control is necessary to stabilize the transients after the fault is cleared. The response after installing UPFC is shown by dotted line, which makes it clear that the series compensation with the proposed fuzzy bang-bang control effectively damps oscillations in power system.

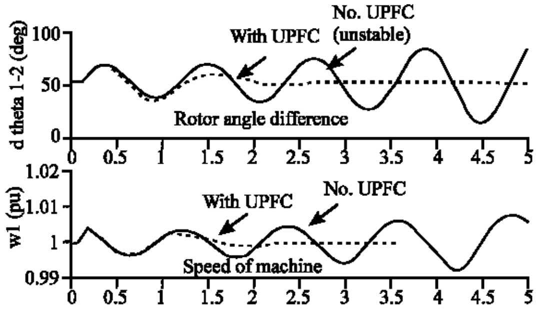

Fig. 4: Simulation results for single-phase fault with and without UPFC

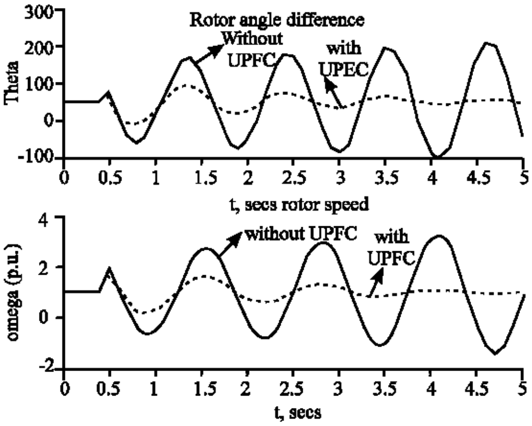

Fig. 5: Simulation results for three-phase fault with and without UPFC

In Fig. 5, the simulation results are shown for three-phase fault with same fault duration and loading conditions. The rotor angle oscillations and rotor speed with and without UPFC proves the effectiveness of the robust control algorithm.

The objective of this research is to develop a control algorithm for damping rotor angle and rotor speed oscillations that arises due to faults, as early as possible using UPFC. From the results for both single phase and three-phase fault, it is evident that the above mentioned objective is satisfied. This is achieved by varying the power transmitted through the line, to counteract the accelerating and decelerating swings of the disturbed machine. That is, when the rotationally oscillating generator accelerates and angle δ increases, the electrical power transmitted must be increased to compensate for the excess mechanical input power. Conversely, when the generator decelerates and angle δ decreases, the electrical power must be decreased to balance the insufficient mechanical input power. Changing the series voltage injected by UPFC in to the line the power transmitted is varied. In the fuzzy bang-bang approach the series injected voltage can take any one of the three values 0, V_{max} or $V_{max}/2$. By properly switching between these values based on inputs δ and ω using Table 1, the oscillations are damped effectively.

The derived control algorithm does not include any parameter depending on network structure, fault location and system loading. Hence, robustness is significant feature of this algorithm compared to the existing approaches. Also this algorithm is simple and easy to implement.

The present research deals with fuzzy logic controller designed for single machine system. But the actual power system comprises of more number of generators. Hence, the fuzzy logic controller designed for single machine system has to be extended to multi-machine system that can be done in future.

CONCLUSION

This study has developed a rule based bang-bang UPFC using FLC for damping power oscillations. The principle is based on Lyapunov function analysis of power system. The conclusion of this study can be summarized as follows:

- The proposed FLC based control strategy based on local input signals can be used for UPFC to damp power swings. Since the controls do not include any parameter, which is dependent on network condition, the performance of such controller is robust with respect to network structure, fault location and system loading.
- The control structure is decentralized and does not need any coordination with other POD devices.
- The maximum load of the system is also increased.
- The structure of proposed algorithm is easy to understand, easy to implement and attractive from a viewpoint of engineering.

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