Robust and Intelligent Control Methods to Improve the Performance of a Unified Power Flow Controller

C. BENACHAIBA, AHMED M. A. HAIDAR, M. L. DOUMBIA

Abstract— The important factor disturbing the modern power systems today is load flow control. The Unified Power Flow Controller (UPFC) is an effective way for controlling the power flow and can provide damping capability during transient conditions. The UPFC is controlled conventionally using PI controller. This paper presents two robust controllers to improve the performance of the UPFC. The first is a RST controller based on the principle of pole placement and the second is an intelligent controller based on the principle of fuzzy logic optimized by Genetic Algorithm (GA).

***Index Terms*—About Shunt and Series active filter, UPFC, PI and RST controllers, Fuzzy logic, GA**

I. INTRODUCTION

WITH the increasing complexities in power systems across the globe and the growing need to provide stable, secure, controlled, economic, and high-quality electric power, in the late 1980s the Electric Power Research Institute (EPRI) has introduced a new technology program known as Flexible AC Transmission System (FACTS). In this context the FACTS [1], [2] controllers are going to play a critical role in power systems. FACTS devices enhance the stability of the power system both with its fast control characteristics and with its continuous compensating capability. The two main objectives of FACTS technology are to control power flow and increase the transmission capacity over an existing transmission corridor [3].

Increase in current has led to the increase of power in a line leading to total increase of system's transmission loss.

Past researches had addressed these phenomena in terms of alleviating transmission loss, voltage profile and voltage stability improvement. Among the effective techniques are reactive power support scheme through the implementation of generator reactive power support and shunt capacitor placement. On the other hand, readjustment of transformer tap ratio and installation of flexible ac transmission systems is able to alter the transmission line parameters which eventually improve the power system performance in terms of minimizing the loss, voltage stability and voltage profile improvement [4]–[7].

Gyugyi proposed the Unified Power Flow Controller (UPFC) which is a new generation of FACTS devices in 1991 [8]. It is a device, which can control simultaneously all three parameters of power transmission line (impedance, voltage and phase angle) [9], [10]. This device combines together the features of two other FACTS devices: the Static Synchronous Compensator (STATCOM) and the Static Synchronous Series Compensator (SSSC). Practically, these two devices are two Voltage Source Inverters (VSI's) connected respectively in shunt with the transmission line through a shunt transformer and in series with the transmission line through a series transformer. These are connected to each other by a common DC link, which is a typical storage capacitor. The shunt inverter is used for voltage regulation at the point of connection, injecting reactive power flow into the line and to balance the real power flow exchanged between the series inverter and the transmission line. Thus, the UPFC can fulfill functions of reactive shunt compensation, active and reactive series compensation and phase shifting. Besides, the UPFC provides a secondary but important function damping control to suppress power system oscillations, thus, improving the transient stability of power system.

The UPFC has been profoundly recognized as one of the most technically promising devices in the flexible ac transmission systems (FACTs) family [11]–[13]. The objective of FACTs devices is to bring a system under control and to transmit power as ordered by the control centers, it also allows increasing of the usable transmission capacity to its thermal limits. UPFCs have the capability to control voltage magnitude and phase angle. Besides, UPFC can independently provide either positive or negative reactive power injections. Many advantages in power system operation and planning can immediately be realized by achieving the function of globally regulating the power flows and simultaneously supporting the bus voltages. Such advantages include the minimization of system losses without generation rescheduling, elimination of line overloads and low voltage profiles.

II. DYNAMIC MODEL OF THE UPFC

Unified power flow controller is a generalized synchronous voltage source, represented at the fundamental frequency by voltage phasor V with controllable magnitude V ($0 \leq V \leq V\max$) and angle α ($0 \leq \alpha \leq 2\pi$), in series with the transmission line. The UPFC consists of two voltage-

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sourced inverters. These back-to-back inverters are operated from a common DC link provided by a DC storage capacitor. This arrangement functions as an ideal ac-to-ac power inverter in which the real power can freely flow in either direction between the ac terminals of the two inverters, and each inverter can independently generate (or absorb) reactive power at its own ac output terminal. The series inverter provides the main function of the UPFC by injecting a voltage V with controllable magnitude V and phase angle α in series with the line via an insertion transformer.

The injected voltage acts essentially as a synchronous ac voltage source. The transmission line current flows through voltage source resulting in reactive and active power exchange between this source and ac system. The inverter generates the reactive power exchanged at the ac terminal internally. The active 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 shunt inverter is to supply or absorb the real power demanded by series inverter at the common DC link to support the real power exchange resulting from series voltage injection. This DC link demand of series inverter is converted back to ac by shunt inverter and coupled to the transmission line bus via a shunt-connected transformer. In addition, the shunt inverter can also generate or absorb controllable reactive power, if it is desired and thereby provides independent shunt reactive compensation for the line.

The main control parameters of UPFC are voltage magnitude (V), phase angle (α) and real and reactive power. The control of these parameters can be achieved by injecting series voltage with appropriate magnitude and phase angle. The injected voltage is transformed into dq reference frame, which is split into Ed and Eq. These coordinates can be used to control the power flow. The controllers of UPFC for shunt and series branch VSIs are described below.

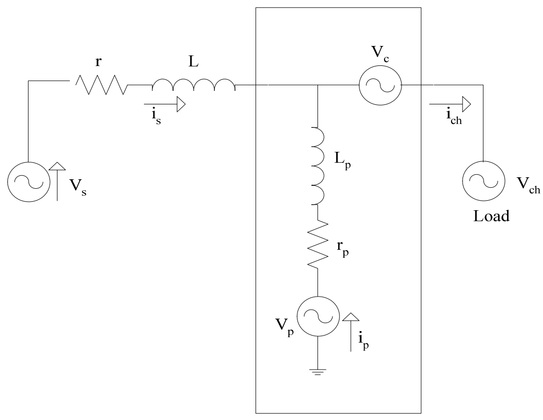

Fig. 1. Equivalent circuit of the UPFC

Applying Kirchhoff law on equivalent circuit shown in Figure 1, the three dynamic equations of the UPFC can be obtained as,

$$\begin{aligned} V_{s1} - V_{c1} - V_{ch1} &= ri_{s1} + L\frac{di_{s1}}{dt} \\ V_{s2} - V_{c2} - V_{ch2} &= ri_{s2} + L\frac{di_{s2}}{dt} \\ V_{s3} - V_{c3} - V_{ch3} &= ri_{s3} + L\frac{di_{s3}}{dt} \end{aligned} \tag{1}$$

The dynamic equations of the shunt compensator is,

$$\begin{aligned} V_{P1} - V_{c1} - V_{ch1} &= r_P i_{P1} + L_P\frac{di_{P1}}{dt} \\ V_{P2} - V_{c2} - V_{ch2} &= r_P i_{P2} + L_P\frac{di_{P2}}{dt} \\ V_{P3} - V_{c3} - V_{ch3} &= r_P i_{P3} + L_P\frac{di_{P3}}{dt} \end{aligned} \tag{2}$$

The dynamic equations of DC circuit is,

$$\begin{aligned} \frac{1}{2}c\frac{dV_{dc}^{\ 2}}{dt} &= P_e - P_{eP} \\ P_e &= V_{c1}i_{ch1} + V_{c2}i_{ch2} + V_{c3}i_{ch3} \\ P_{ep} &= V_{P1}i_{P1} + V_{P2}i_{P2} + V_{P3}i_{P3} \end{aligned} \tag{3}$$

Where,
V_{dc}: DC voltage
Pe: Power absorbed by the series compensator and supplied to the common circuit
P_{ep} : active power provided by the shunt compensator and absorbed by the series compensator

Assuming no active power consumed by capacitors and inverters, the matrix representation of this equations system are:

The matrix representation of the series compensator is,

$$\frac{d}{dt}\begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L} & 0 & 0 \\ 0 & -\frac{r}{L} & 0 \\ 0 & 0 & -\frac{r}{L} \end{bmatrix} . \begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix} + \frac{1}{L}\begin{bmatrix} V_{s1} & -V_{c1} & -V_{ch1} \\ V_{s2} & -V_{c2} & -V_{ch2} \\ V_{s3} & -V_{c3} & -V_{ch3} \end{bmatrix} \tag{4}$$

The matrix representation of the shunt compensator is,

$$\frac{d}{dt}\begin{bmatrix} i_{P1} \\ i_{P2} \\ i_{P3} \end{bmatrix} = \begin{bmatrix} -\frac{r_P}{L} & 0 & 0 \\ 0 & -\frac{r_P}{L} & 0 \\ 0 & 0 & -\frac{r_P}{L} \end{bmatrix} . \begin{bmatrix} i_{P1} \\ i_{P2} \\ i_{P3} \end{bmatrix} + \frac{1}{L_P}\begin{bmatrix} V_{P1} & -V_{c1} & -V_{ch1} \\ V_{P2} & -V_{c2} & -V_{ch2} \\ V_{P3} & -V_{c3} & -V_{ch3} \end{bmatrix} \tag{5}$$

Using Park transformation, the two equations (1) and (2), will be written as,

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{r}{L} & \omega \\ -\omega & -\frac{r}{L} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{dq} \end{bmatrix} + \frac{1}{L}\begin{bmatrix} V_{sd} & -V_{cd} & -V_{chd} \\ V_{sq} & -V_{cq} & -V_{chq} \end{bmatrix} \tag{6}$$

$$\frac{d}{dt}\begin{bmatrix} i_{Pd} \\ i_{Pq} \end{bmatrix} = \begin{bmatrix} -\frac{r_P}{L_P} & \omega \\ -\omega & -\frac{r_P}{L_P} \end{bmatrix} \begin{bmatrix} i_{Pd} \\ i_{Pq} \end{bmatrix} + \frac{1}{L_P}\begin{bmatrix} V_{Pd} & -V_{cd} & -V_{chd} \\ V_{Pq} & -V_{cq} & -V_{chq} \end{bmatrix} \tag{7}$$

The dynamic equations of the continuous circuit are:

$$\frac{dV_{dc}}{dt} = \frac{3}{2CV_{dc}}\left(V_{cd}i_{chd} + V_{cq}i_{chq} - V_{Pd}i_{Pd} - V_{Pq}i_{Pq}\right) \tag{8}$$

Where,

$$\begin{aligned} i_{chd} &= i_{sd} + i_{Pd} \\ i_{chq} &= i_{sq} + i_{Pq} \end{aligned} \tag{9}$$

The generated and absorbed instantaneous active and reactive powers are given below:
The generated active and reactive powers are:

$$P_s = \frac{3}{2}\left(V_{sd} i_{sd} + V_{sq} i_{sq}\right) \tag{10}$$

$$Q_s = \frac{3}{2}\left(V_{sq} i_{sd} - V_{sd} i_{sq}\right) \tag{11}$$

The absorbed active and reactive powers are:

$$P_{ch} = \frac{3}{2}\left(V_{chd} i_{chd} + V_{chq} i_{chq}\right) \tag{12}$$

$$P_{ch} = \frac{3}{2}\left(V_{chd} i_{chd} + V_{chq} i_{chq}\right) \tag{13}$$

III. UPFC CONTROLLER BASED ON POLE PLACEMENT

The block diagram with a RST controller is depicted in Fig. 2.

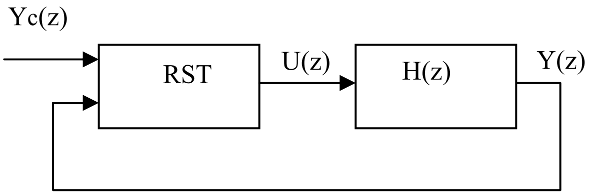

Fig. 2. Blocks diagram of RST controller

As seen form this fig. 2, Yc(z), U(z) and Y(z) represents reference value, control value and real value. H(z) designates the sampled transfer function of the process to adjust the given by the following formula:

$$H(z) = \left(1 - z^{-1}\right) Z\left\{L^{-1}\left[G(s)/s\right]\right\} \tag{14 a}$$

$$H(z) = \frac{B(z)}{A(z)} \tag{14 b}$$

The degree of *A(z)* is strictly bigger than *B(z)*. *G(s)* is the transfer function of the system that can be adjusted.

In general the transfer function in closed loop is given by the following relations:

$$\frac{Y(z)}{Y_c(z)} = \frac{B(z)T(z)}{A(z)R(z) + B(z)S(z)} \tag{15}$$

The polynomial *R(z)* is chosen of degree ρ

$$R(z) = z^{\rho} + r_1 z^{\rho-1} + \dots.. + r_{\rho} \tag{16}$$

Let's denote σ the degree of the polynomial *S(z)*

$$S(z) = s_o z^{\sigma} + s_1 z^{\sigma-1} + \dots.. + s_{\sigma}$$

And either τ the degree of the polynomial *T(z)*

$$T(z) = t_o z^{\tau} + t_1 z^{\tau-1} + \dots.. + t_{\tau} \tag{17}$$

The analogical transfer function of the system is:

$$G(s) = \frac{1}{s + 40} \tag{18}$$

The sampled transfer function according to “(14),” is:

$$H(z) = \frac{0.016}{z - 0.36} \tag{19}$$

With,
A sampling period h= 0.025 s, the factor of amortization a = 20 and the stroke of clock k_a=5

$$C = \exp\left(\ln\left(\frac{20}{5}\right)\right) = -0.55 \tag{20}$$

With,

$$R(z) = 1, \quad S(z) = S_o, \quad A_o(z) = 1$$

The Diophantine equation is:

$$(z - 0.36)\ 1 + 0.016 S_o = (z - 0.55)\ 1 \tag{21}$$

Therefore,

$$S_o = -11.75$$

And,

$$T(z) = B'_m(z) A_o(z) = 28.125$$

$$\frac{Y(z)}{Y_c(z)} = \frac{B(z)T(z)}{A(z)R(z) + B(z)S(z)} = \frac{0.45}{z - 0.55} \tag{22}$$

IV. UPFC FYZZY CONTROLER OPTMIZED BY GA

Fig. 3 displays the blocks diagram of a GA-based self-learning fuzzy PI control system. The GA generates a population uncertain of chromosomes [14]. These chromosomes are injected in the fuzzy controller. After stages of calculation (Normalization, fuzzification, inference, defuzzification and denormalization), the controller output signal commands the system. The GA estimates the fitness function (Minimization of the total error between the actual output voltage and the reference voltage). After the valuation of all chromosomes of this initial population a new generation will be formed while applying the genetic operators (Selection, crossover and mutation). This process repeats itself until the satisfaction of stop criteria of the GA. Fig. 4 shows the triangular membership functions for each fuzzy subset in which these functions are symmetric functions with respect to the vertical axis for the sake of easy implementation.

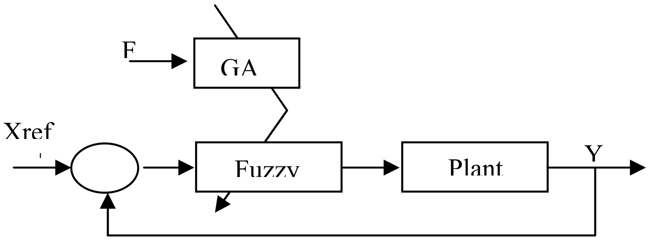

Fig. 3. Blocks diagram of a GA-based self-learning

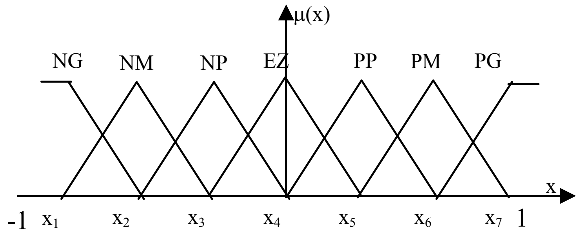

Fig. 4. Triangular fuzzy membership functions

The parameters x_1, x_2, x_3, x_4, x_5, x_6, x_7 are the picks of every membership functions respectively *NB, NM, NS, Z, PS, PM, PB*. As membership functions are symmetrical, the only parameters that can be defined are x_5, x_6 and x_7, the other will be deducted as follows:

$x_1 = -x_7$; $x_2 = -x_6$; $x_3 = -x_5$; $x_4 = 0$

V. ILLUSTRATIVE EXAMPLE

In order to evaluate the performance of the proposed controller, a simulation is performed using SIMULINK software program for the UPFC system shown in the figure 1. The data of the system is give as follows:

Supply Voltage: V_s=220 V,
Load voltage : V_{ch}=220 V
DC voltage : V_{dc}=280 V
Network frequency: f=50 Hz
Line resistance: R=40Ω
Line inductance: L=0.01H
Shunt filter resistance: R_p=0.3Ω
Shunt transformer inductance: L_p=0.01H
Common circuit capacitor *DC*: C=2000μF

For the purpose of comparison, the system responses are presented for PI conventional controller, RST controller and PI-Fuzzy based on GA controller. The characteristics of each controller are presented below:

- The gain and integral time constants of the PI controller are K_p =0.5, T_i =2000
- The values of polynomials R, S and T of the RST controller are R=1, S=11.75 and T=28.125
- The PI-Fuzzy based on GA controller is formed by two inputs error (*e*) and change of error (*Δe*) and one output. Table 1 presents the optimized Fuzzy decision.

TABLE 1
THE DECISION TABLE

Δu		**e**						
		NB	NM	NS	Z	PS	PM	PB
Δe	PB	**Z**	PS	PM	PB	PB	PB	PB
	PM	NS	**Z**	PS	PM	PB	PB	PB
	PS	NM	NS	**Z**	PS	PM	PB	PB
	Z	NB	NM	NS	**Z**	PS	PM	PB
	NS	NB	NB	NM	NS	**Z**	PS	PM
	NM	NB	NB	NM	NM	NS	**Z**	PS
	NB	NB	NB	NB	NB	NM	NS	**Z**

As seen from table 1, each interval of each variable is divided on seven membership functions: Negative Big (*NB*), Negative Medium (*NM*), Negative Small (*NS*), Zero (*Z*), Positive Small (*PS*), Positive Medium (*PM*) and Positive Big (*PB*). The actual output current is compared with the reference current to produce an error signal and a change of error signal defined as:

$$e(k) = I_{ref} - I(k) \tag{23}$$

$$\Delta e(k) = e(k) - e(k-1) \tag{24}$$

The fitness function *F* to maximize is defined as in "(25)," and the table 2 displays AG parameters

$$F = \frac{1}{\sum_{k=1}^{n} e^2(k)} \tag{25}$$

TABLE 2
AG PARAMETERS

Parameter	Value
Population size	5
Selection	Roulette
Mutation rate	0.003
Crossover rate	0.6
Generation number	25
Tolerance	10^{-6}

The following figures show results of the different controllers. Fig. 5 shows the variation of the active power. The response of the UPFC conventional controller (b) presents amplification to every variation of the load, while response of the other RST (c) and PI-Fuzzy based on GA (b) are identical, smooth and perfectly follow the reference (a). The same remark for the variation of the reactive power is illustrated on fig. 6. For direct and quadratic currents depicted on fig. 7 and 8 respectively, the response of the PI conventional controller is characterized by amplification to every change of the load. It is necessary to signal that response of the RST and PI-Fuzzy based on GA are identical at every instant of the simulation.

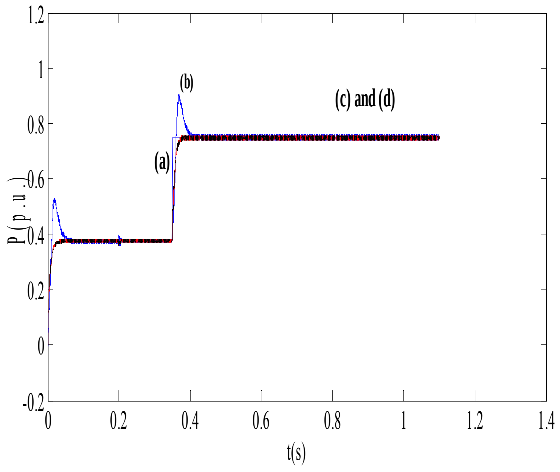

Fig. 5. Instantaneous active powers of the controlled transmission line, (a) Reference, (b) PI controller, (c) RST controller, (d) PI-Fuzzy based on GA controller

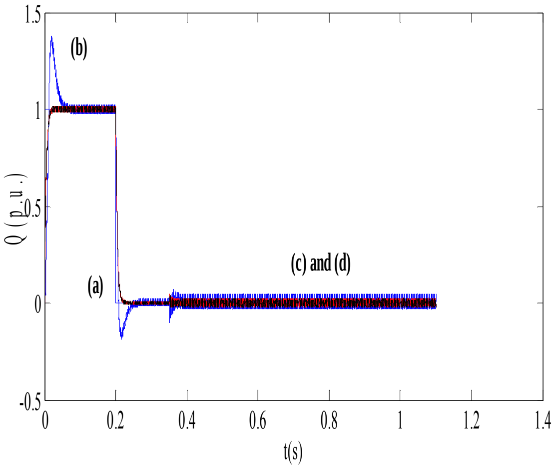

Fig. 6. Instantaneous reactive powers of the controlled transmission line, (a)Reference, (b) PI controller, (c) RST controller, (d) PI-Fuzzy based on GA controller

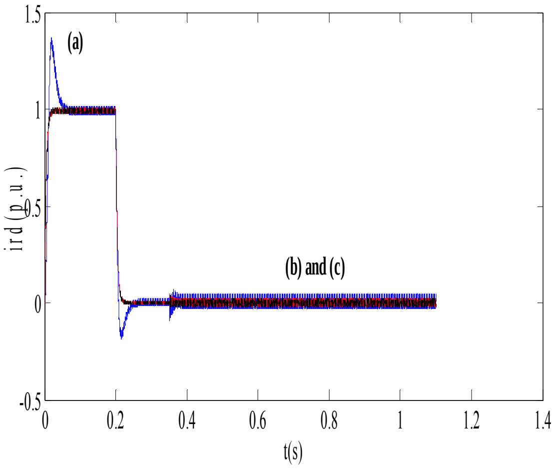

Fig. 7. Instantaneous *d*-axis current component, (a) PI controller, (b) RST controller, (c) PI-Fuzzy based on GA controller

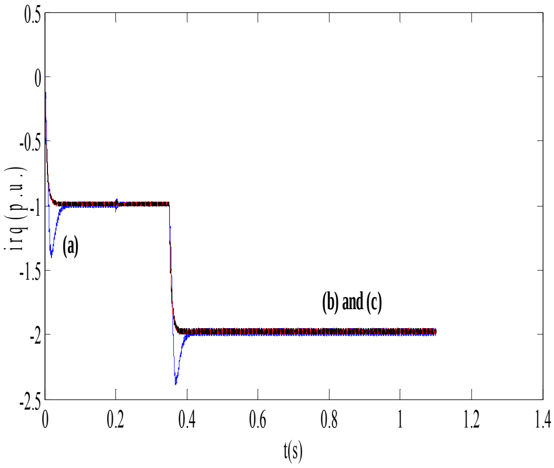

Fig. 8.Instantaneous *q*-axis current component, PI controller, (b) RST controller, (c) PI-Fuzzy based on GA controller

VI. CONCLUSION

The paper discusses the topology and proposed intelligent control technique of a UPFC that operates in simultaneous voltage and current control modes. From the presented results of controllers, it can be concluded that the UPFC indispensable equipment and can satisfy the quality standard of energy due to the fast decision and optimal response. This can be confirmed from the results that show the limitation of the conventional PI controller whereas the controllers RST and PI-Fuzzy based on GA are more effective and a perfectly follow the reference. Therefore, the control operations of UPFC are ideal from both viewpoints. It is however to be mentioned that a UPFC is a very powerful device using the intelligent controller

REFERENCES

[1] N. G. Higorani, "Flexible AC Transmission," *IEEE Spectrum*, April 1993, pp. 40–44.

[2] L. Gyugyi, "Dynamic Compensation of AC Transmission Lines by Solid-State Synchronous Voltage Sources," *IEEE*, 1993, pp. 9.4–911.

[3] S. An; J. Condren, and T. W. Gedra, "An ideal transformer UPFC model, OPF first-order sensitivities, and application to screening for optimal UPFC locations," *IEEE Trans. Power Syst.*, vol. 22, no. 1, p.68–75, Feb. 2007.

[4] Ghadir Radman and Reshma S Raje, "Power flow model/calculation for power systems with multiple FACTS controllers," *Electric Power Systems Research*, Volume 77, Issue 12, October 2007, pp. 1521–1531.

[5] E. Ghollipour, S. Saadat, "Improving transient stability of power systems using UPFC', *IEEE Transactions on Power Delivery* 20, 2005, pp.1677–1682.

[6] H. I. Shaheen, G. I. Rashed, and S. J. Cheng, "Optimal location and parameters setting of unified power flow controller based on evolutionary optimization techniques," in Proc. *IEEE Power Eng. Soc. General Meet.*, Jun. 24–28, 2007, pp. 1–8.

[7] Fujita, H., Watanabe, Y., Akagi, H., "Dynamic Control and Performance of a Unified Power Flow Controller for Stabilizing an AC Transmission System," *IEEE Trans. Power Elect*, vol. 21, no. 4, July 2006, pp.1013–1020.

[8] L. Gyugyi, "A Unified Power Flow Control Concept for Flexible AC Transmission Systems," *IEE Proc*. Part C 139(4), 1992, pp. 323–331.

[9] H. Fujita, H. Akagi, Y. Watanabe, 'Dynamic control and performance of a unified power flow controller for stabilizing an AC transmission system," *IEEE Power Electronics Transactions* 21, 2006, pp. 1013–1020.

[10] Lütfü Saribulut, Ahmet Teke, Mehmet Tümay, "Dynamic control of unified power flow controller under unbalanced network conditions', Simulation Modelling Practice and Theory 19, 2011, pp.817–836.

[11] M. Basu, S.P. Das, G.K. Dubey, "Comparative evaluation of two models of UPQC for suitable interface to enhance power quality,"', *Electric Power Systems Research* 77, 2007, pp. 821–830.

[12] J. Xia, J.H. Chow, A. A Edris, B. Fardanesh, E. Uzunovic, "Transfer path stability enhancement by voltage-sourced converter-based FACTS controllers," *IEEE Power Delivery Transactions* 25, 2010, pp. 1019–2025.

[13] S. An, J. Condren and T.W. Gedra, 'An Ideal Transformer UPFC Model, OPF First-Order Sensitivities and Application to Screening for Optimal UPFC Locations," *IEEE Transactions on Power Systems*, Vol. 22, Issue 1, Feb 2007, pp. 68-75.

[14] J H. Holland 'Adaptation in Naturel and Artificial Systems," University of Michigan Press, Ann Arbor. MI, 1975.