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A Novel and Robust Model of the GUPFC Controller System Based on Adaptive Fuzzy Logic- PI Controller to Enhance the Control System Performance in Following Reference Active and Reactive Power

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Abstract: The optimal electrical power transmission problem in electrical energy transmission lines has led to increased attention to the use of flexible alternating current transmission systems (FACTS) and the design of double- and multi-circuit lines. Hence, recently, multi-converter FACTS devices have been utilized in the literature to control voltage and power of multi-circuit transmission lines. A generalized unified power flow controller (GUPFC) is one of such emerging FACTS devices that can manage voltage and power control crisis in multi-circuit lines. The GUPFC is the most advanced generation of FACTS, which will be able to control active and reactive power in at least two circuits and voltage in one circuit with the best quality possible and satisfy the operator's all requests. This paper, for the first time, presents the use of an adaptive control system design based on the proportional-integral (PI) controller and fuzzy system to enhance the fast and dynamic responsiveness of the system. PI systems alone cannot control the GUPFC under different operation conditions such as when the default reference values of active and reactive power are changed, or transient faults occur, or a transmission line experience outage. Thus, the use of a fuzzy controller, as a powerful tool, is very efficient in solving the mentioned problems. To analyze the proposed algorithm's results, a test system and a GUPFC based on a 48-pulse voltage source converter (VSC) are implemented in the MATLAB/Simulink environment. The satisfactory results obtained in the simulation section verify the correct performance of the suggested method.

Keywords: FACTS- GUPFC, PI controller, Fuzzy Logic (FL), Adaptive FL-PI controller

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1. Introduction

1.1 Research Motivation

Because of the ever-increasing growth in the number of electricity consumers during recent decades, electricity transmission is one of the major crises of electricity supply organizations and companies over the world. Also, in most cases, the distance between generation and consumption centers is very long, the cost of electrical energy transmission is considerably high and imposes a significant financial burden. In the last two decades, the use of flexible alternating current transmission systems (FACTS) devices has made it possible to avoid the high cost of power transmission and high losses by investment in installing power compensation equipment. The plan to employ multi-circuit transmission lines and multi-converter FACTS devices to satisfy the desired constraints of operators is a very interesting and useful idea that many countries are currently planning and studying.

1.2 Literature Review

In 2000, Fardanesh proposed a new concept on the most complete and advanced type of multi-converter FACTS devices, called the GUPFC. This device is the most developed type of FACTS devices, which has five degrees-of-freedom of operation, including active and reactive power control of two circuits and voltage control of one circuit [1]. Since introducing the device, various papers have been published focusing on different aspects of it. In 2001, mathematical modeling of GUPFC for optimal power flow studies was presented [2]. The algorithm considered in this paper is a nonlinear internal point that is completely solved. Later, in 2004, the authors in [3] presented the optimal allocation scheme of the GUPFC based on Newton-Raphson power flow analysis. Due to the violation of system operating limits in power flow equations, the design used in this paper proposes a suitable location for the management of line congestion based on modeling Newton-Raphson power flow equations using the current and voltage injection model. Then, in the same year, 2004, Fardanesh discussed the optimal operation, sizing, and performance of multi-converter FACTS devices [4], and introduced GUPFC as the best compensator with desirable capabilities. Meanwhile, one of the problems that caused the numerical instability of the power flow equations was the small coupling impedance of shunt and series converters of the GUPFC, which was discussed in 2006, and the problem was solved by using an impedance compensating method [5]. The use of fuzzy systems in the control system of the GUPFC based on the base fuzzification functions was then suggested in 2009 aiming at reducing the overshoot and settling time [6]. Khedrzadeh et al. [7] examined the effect of the presence of GUPFC in a double-circuit transmission line on distance relay performance. In the same study, it is shown that traditional distance protection schemes in lines equipped with this compensator are inefficient, but no solution is provided by the authors to tackle the challenge. In 2013, a scheme to reduce the sub-synchronous resonance phenomenon using GUPFC was proposed [8]. The results presented in this reference illustrate that the GUPFC reduces the sub-synchronous resonance phenomenon in a multi-machine system by repelling the network resonant frequency using series converters. In 2014, a design was suggested to calculate the power quality index in the presence of GUPFC during steady-state and transient conditions using a dynamic harmonic domain (DHD) technique in the dq framework. The advantage of the DHD model proposed in this work is that it provides a direct way to simultaneously calculate the steady-state values of harmonics and the transient response of harmonics to perturbation [9]. In 2015, an optimal allocation strategy based on transmission line loadings and busbar voltage range changes was also proposed to improve the system's safety by minimizing the system's power loss in the presence of GUPFC using Particle Swarm Optimization (PSO) method [10]. In the same year, 2015, a novel optimization plan was proposed to solve the Multi-area Multi-fuel Economic–Emission Dispatch problem and minimize the total power losses [11]. This method utilizes a uniform distribution to determine the control parameters and uses a two-step initialization process. Another paper published in 2015 indicated the successful effect of GUPFC on small-signal stability of the power system [12]. In 2016, using a systemic approach, the available transfer capability (ATC) scheme in transmission lines compensated by GUPFC was introduced to prevent congestion in transmission lines [13]. In the same year, 2016, the GUPFC modeling design in the hybrid current power mismatch Newton-Raphson formulation (HPCIM) was proposed. This has greatly reduced the complexity of software programming and the possibility of numerical instabilities [14]. In 2017, the GUPFC limitations violation management plan was introduced for the Newton-Raphson power flow by presenting an extended model of the GUPFC. The main advantage of the established model is that the main and symmetric structure of Jacobin and admittance matrices can be used without changing the original Jacobin matrix. As a result, power flow complexities are reduced [15]. In 2019, the development plan of the detailed GUPFC model for modeling in MATLAB software in the time domain was presented [16]. Also, in 2019, a scheme to improve transient stability using a GUPFC equipped with ANFIS controller was introduced. To this end, a controllable compensator is designed to increase the transient stability margin and dampen transient oscillations in the power system using the Lyapunov stability criterion. Since the transient energy function of the system is a suitable tool to investigate the stability problem, the optimization of the GUPFC energy function has been considered to achieve the highest transient stability margin [17]. In 2020, Abasi et al. [18-19] presented fault detection, classification, and location based on synchronous phasors theory for GUPFC-compensated DCTLs. In these studies, the FSDI sign analysis was used to detect the faulty section. Also, loci indices of active and reactive power measured at terminals of each circuit are incorporated to detect the faulty phases. Finally, in 2020, Abasi et al. [20-21] proposed a complete and accurate design of the GUPFC modeling based on 48- and 72-pulse voltage source converters

(SVCs). The designs presented in these works utilize accurate time-domain modeling in MATLAB software and integral-proportional controller (PI) to establish various constraints on the operation, power flow, and power quality.

1.3 Challenges and the Necessity of the Research

According to the literature review on different fields of GUPFC, as can be seen, most of the studies address power flow modeling of this compensator and few references deal with the dynamic modeling of this device in the time domain. Some issues with this device include dynamic control under different operating modes, the slow response of the control system during transient disturbances, and unstable operation in steady-state conditions. The main reason behind all these challenges is the use of PI controllers. This problem can be addressed by adapting the control system to Fuzzy-PI for some GUPFC converters and not all of them.

1.4 Contributions and Novelty

The main contribution of this paper is designing an adaptive control model based on Fuzzy-PI control theory for GUPFC control system to improve system dynamic behavior, increase the speed of response to operating mode changes and reduce steady-state error in following reference active and reactive power signals of the converters of this compensator. In this paper, the control coefficients of PI blocks embedded in series converters are adjusted to satisfy the operating constraints using fuzzy logic in different conditions. In the proposed method, inputs to the fuzzy logic include the error between the real value and the calculated value and the error derivative, and its outputs adjust the values of the PI controller coefficients.

1.5 Organization of the Paper

The paper is organized as follows. Section 2 introduces the control system and power electronics of the GUPFC. In Section 3, the proposed control design is introduced along with complete fuzzy rules. In Section 4, after describing the simulation system, the software simulation results are presented. Section 5 gives some future work and conclusions of the paper are provided in Section 6.

2. Three-Converter FACTS GUPFC-Devices

The GUPFC is the most advanced and complicated generation of the FACTS family. As shown in Fig. 1, this device can control active and reactive power in a double-circuit line using three converters. Two of three converters are in series with each of the circuits and one of them is connected in shunt to one of the double-circuit lines. These converters are connected via a DC link, which balances active power in the GUPFC.

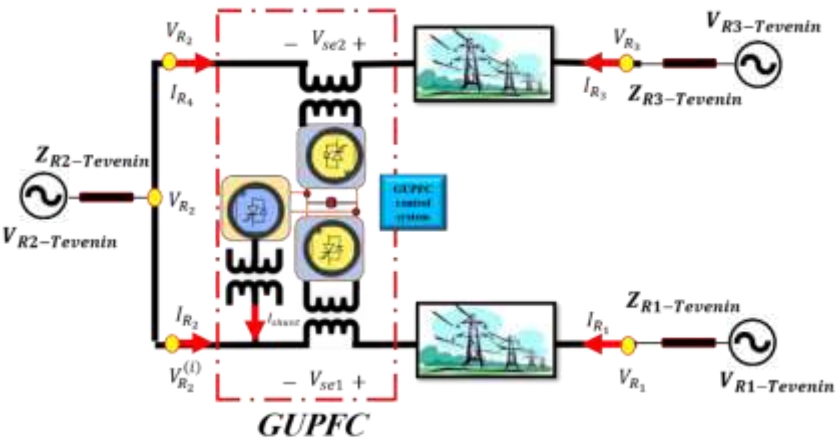


Fig. 1 - Model of a transmission line compensated by a GUPFC

Referring to Fig. 2, the main task of the shunt converter is to control the voltage of Bus 2, which performs this operation by exchanging reactive power with the grid; in other words, this is done by controlling the DC-link voltage. To achieve this, initially, the desired ωt phase angle is calculated using the phase-locked-loop (PLL) to synchronize the voltage and current. Then, the three-phase current and voltage inputs to the shunt converter are converted to real and reactive components using the abc-dq0 transformation. The measured voltage in the bus connected to the shunt converter is then instantaneously compared with the reference voltage and is given as input to the PI controller to calculate the error signal to generate the reference reactive current. The calculated reactive current through the bus connected to the shunt converter is compared with the reference reactive current obtained in the previous step and the difference error between the two is given as the input of the PI controller to produce the corresponding alpha phase angle of the inverter’s voltage.

Another component used in this converter is D-alpha, which is generated by applying the average value of the DC-link voltage and the average reactive current to the PI controller. Finally, the last component required to produce a pulse is the Sigma fire pulse generating system. Sigma is in one sense the same as the modulation index, which ultimately affects the output voltage amplitude of the converter, which is 172.5.

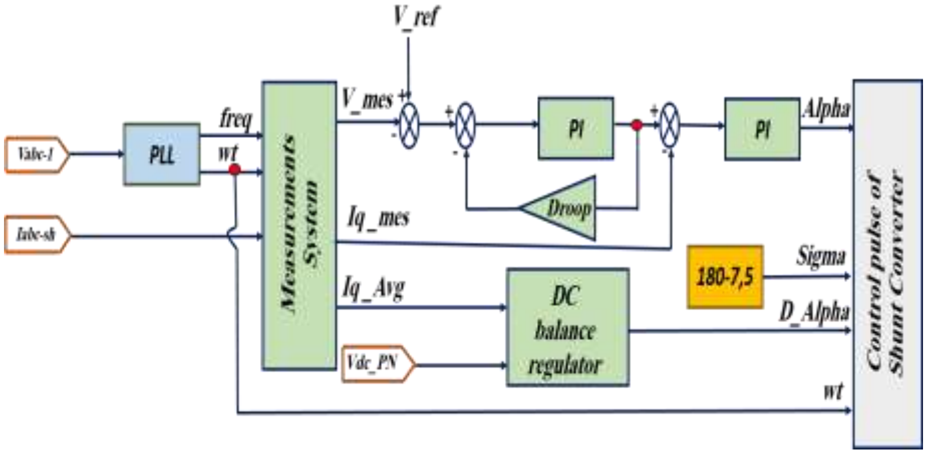


Fig. 2 - The control system of the GUPFC's shunt converter

Based on Fig. 1, which is the basic model of the GUPFC, the GUPFC includes two series converters, both of which behave similarly in terms of the control system. In this section, we will examine only one series converter and the second series converter is similar to the first one.

According to Fig. 3, the series converter is used to automatically control the power flow and regulate the current flowing through the transmission line. In this converter, similar to the shunt converter, the desired ωt angle for synchronizing voltage and current is calculated using the three-phase voltage measured from the bus connected to one side of the series converter and PLL. Then, using the abc-dq0 transformation, the real and reactive components of the three-phase current and voltage of the buses can be calculated. Referring to Fig. 3, using the reference active power, the reference reactive power, the real voltage, and the reactive voltage, the reference real and reactive currents can be calculated. These currents are compared with their counterparts measured from the bus and the error signal is input to the PI controller to calculate the reference real and reactive voltages. These voltages are then controlled using a limiter to prevent possible system instability. Finally, real and imaginary voltage limiter outputs are utilized to calculate alpha and sigma. Because the value of D_Alpha is calculated by a shunt converter, we consider it zero in this section.

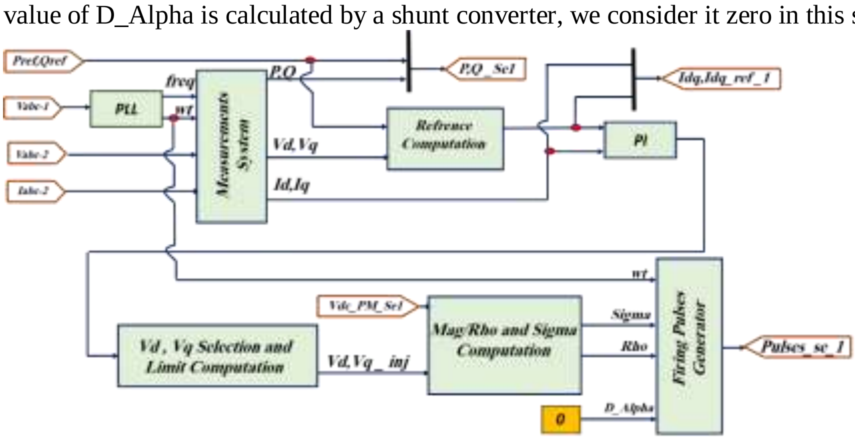


Fig. 3 - Series converter controller design for GUPFC compensator

The inverter system considered in this compensator is a 48-pulse GTO voltage source converter, shown in Fig. 4, which consists of four three-level inverters and four phase-shifting transformers [22-25]. With the help of a three-level GTO link, all the inverters considered in this converter can produce three-phase voltage with a quasi-sine square waveform. The secondary winding of the phase-shifting transformer uses three phase sequences of the voltage waves in series with the primary winding and produces an almost sine voltage. The voltage wave amplitude can be one of these three values: DC-link voltage, negative DC-link voltage, and zero. The zero-voltage interval per quarter cycle can be defined as dead time, which is a value between 0° and 90°.

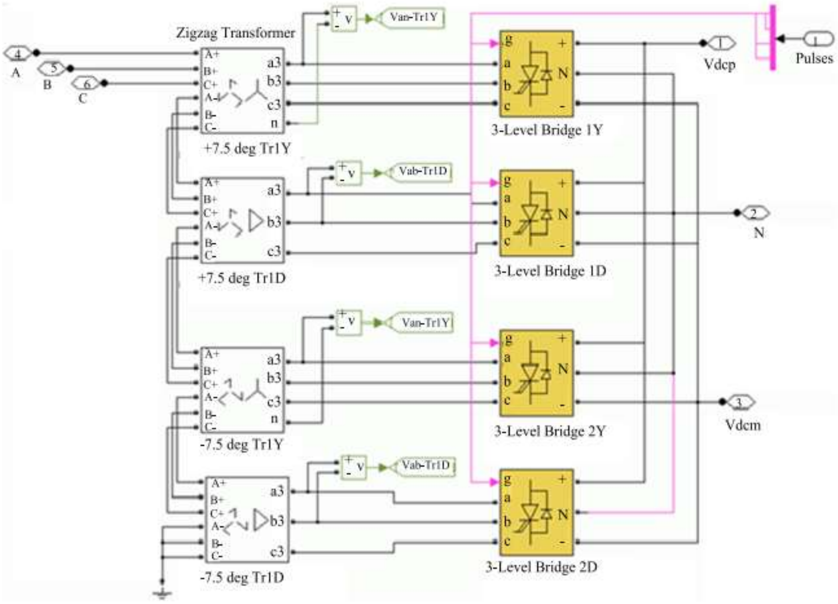


Fig. 4 - Model of the GUPFC's voltage source inverter for the shunt converter

3. Fuzzy Control Block Model of Series Converters

The design considered in this paper addresses the control of direct and quadrature axis current components of series converters 1 and 2. The method is applied to Kp and Ki parameters to change them during system control, helping to better adaptation of the PI controller with the system's nonlinear operation [26-27]. By adjusting PI parameters, the fuzzy controller can assist the whole control system to adapt itself with all conditions based on reducing error and its derivative. Fig. 5 illustrates the control block diagram of series converter 1 based on the FCL-PI control design. The suggested design for the block diagram of the control system of series converter 2 is similar to the block diagram shown in Fig. 5, except that they have different inputs.

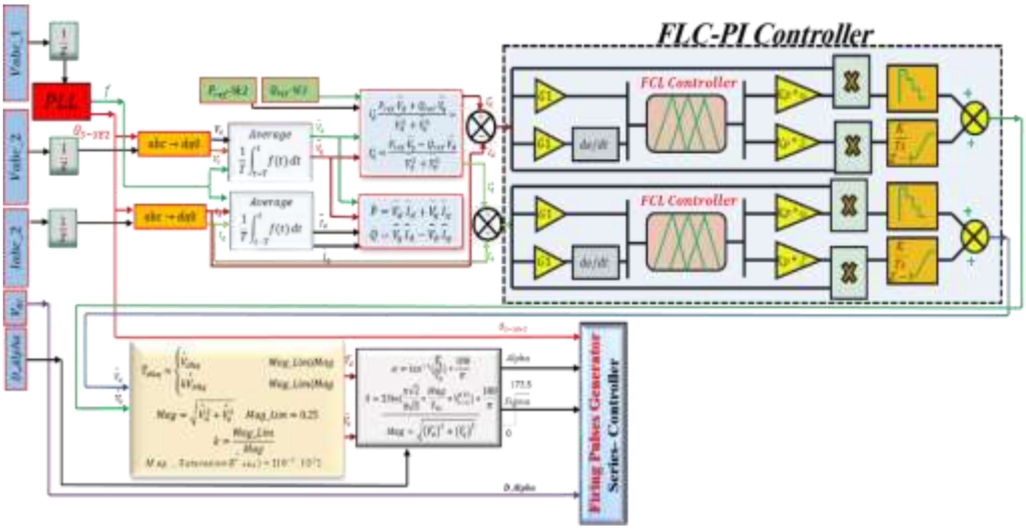


Fig. 5 - Control block diagram of the series converter 1 based on the FCL-PI control design

Parameters of the PI control are normalized in the range [0, 1] using the following linear transforms:

$$K_p = (K_p - K_{p-min})/(K_{p-max} - K_{p-min}) \quad (1)$$
$$K_i = (K_i - K_{i-min})/(K_{i-max} - K_{i-min}) \quad (2)$$

The inputs to the FL include the error e and its derivative, and the outputs are normalized values of Kp and Ki. Membership functions for the input e (Fig. 6) and de/dt (Fig. 7) are defined in the range [-1, 1] and the definition of membership functions for the outputs are provided in the range [0, 1] (Fig. 8) [28-30]. Seven membership functions (NB, NM, NS, ZZ, PS, PM, and PB) with linguistic variables are assigned to physical quantities of fuzzification in the proposed controller. Letters N, P, B, M, S, and Z respectively represent negative, positive, large, medium, small, and zero quantities. Fuzzy inputs are converted into a single fuzzy rule base to characterize the relationship between fuzzy inputs and fuzzy outputs. The fuzzy rule base of the incremental FL is fixed, as tabulated in Tables 1 and 2.

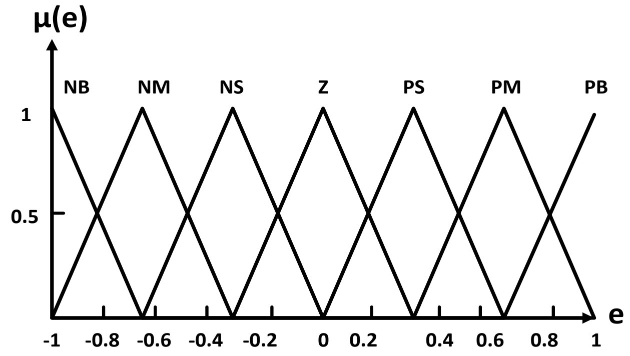


Fig. 6 - Membership function for the input *e*

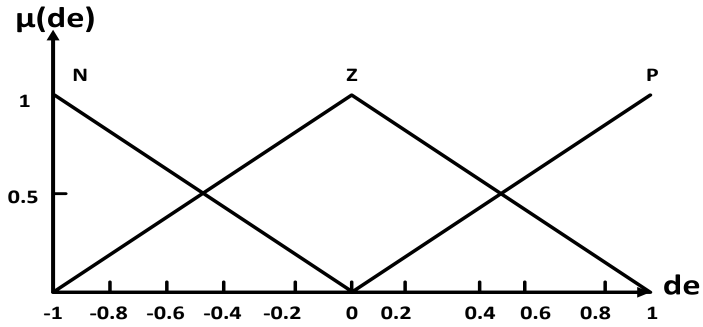


Fig. 7 - Membership function for the input de

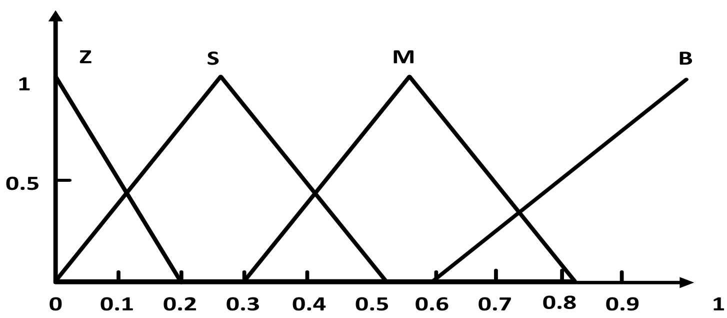


Fig. 8 - Membership function for the outputs Kp and Ki

Table 1 -Fuzzy rule base of the output

de \ e	NB	NM	NS	Z	PS	PM	PB
N	B	M	S	M	S	M	B
Z	B	M	B	Z	B	M	B
P	B	M	B	Z	B	M	B

Table 2 -Fuzzy rule base of the output Ki

de \ e	NB	NM	NS	Z	PS	PM	PB
N	Z	S	M	B	M	S	Z
Z	Z	S	M	B	M	S	Z
P	Z	M	B	B	B	M	Z

4. Introducing the Test System and Presenting Software Simulation Results

4.1 The Test System

Fig. 9 shows the simulation system considered in this paper. The system under study is a 5-bus network that supplied two 200 MW and 300 MW loads using three generators with a voltage level of 500 kV and three transmission lines. As is seen in Fig. 9, the GUPFC is connected to buses B1, B2, and B5. This device includes one shunt converter and two 48-pulse series converters, each exchanging 100 MVA power with the network. The reference active power value of series converters in this simulation during the time between the start of the simulation to 0.25 s is 8.7 p.u. and from t = 0.25 s onwards it is 10 p.u. Also, the reference reactive power value of the series converters from t = 0 to t = 0.5 s is -0.6 p.u., while it is 0.7 p.u. from t = 0.5 s onwards. The reference voltage value of the bus connected to the shunt converter during the whole simulation period is set 1 p.u. The detailed data of the simulation system, including the data of the lines, generators, loads, control system, and power electronics of the GUPFC are provided in the Appendix section.

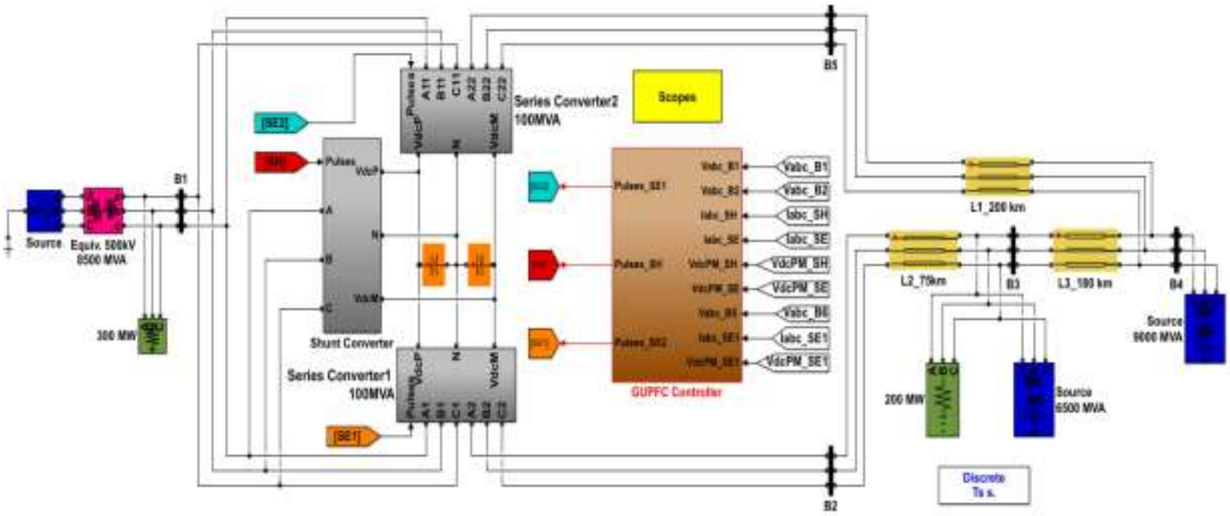
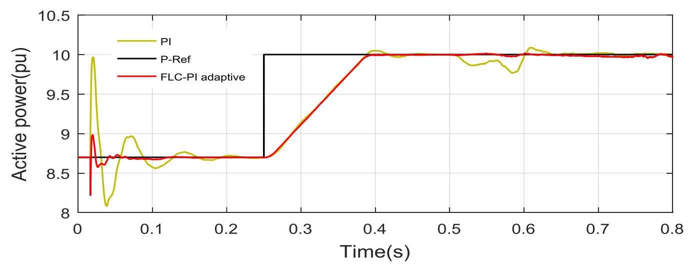


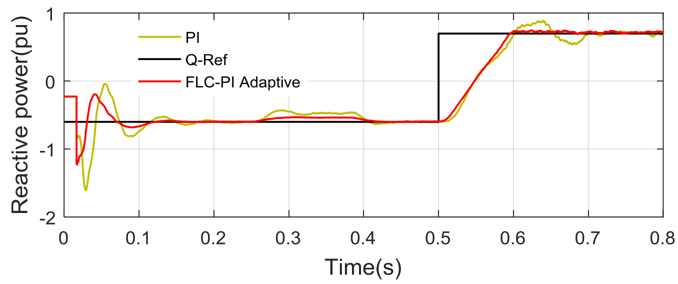
Fig. 9 - Simulation model of the 5-bus transmission network compensated by the GUPFC in MATLAB software

4.2 Simulation Outputs

This section presents the simulation results of the 5-bus test system compensated by a GUPFC. A classic PI controller and an FL-PI controller are used to reduce oscillations and improve power tracking performance using two series converters. Figs. 10-14 illustrate the results of the simulation for a period of 0.8 s for both series converters. The results provided in this subsection consists of active and reactive power tracking of two series converters and active and reactive power flow on the lines between the network buses.

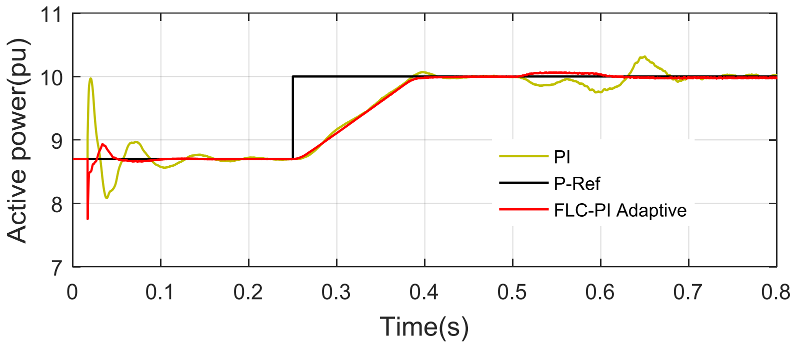


(a)



(b)

Fig. 10 - Diagrams of a) active power, and b) reactive power tracking of series converter 1 using a PI controller and an FL-PI controller



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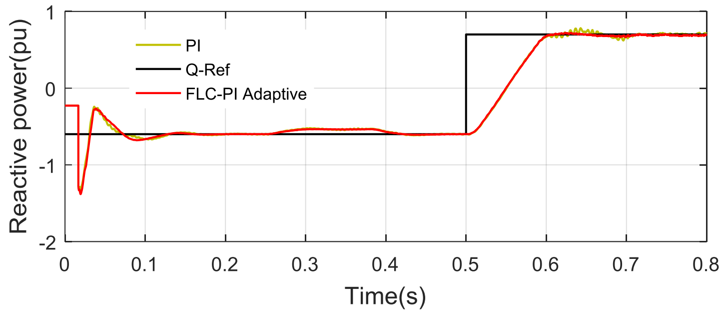
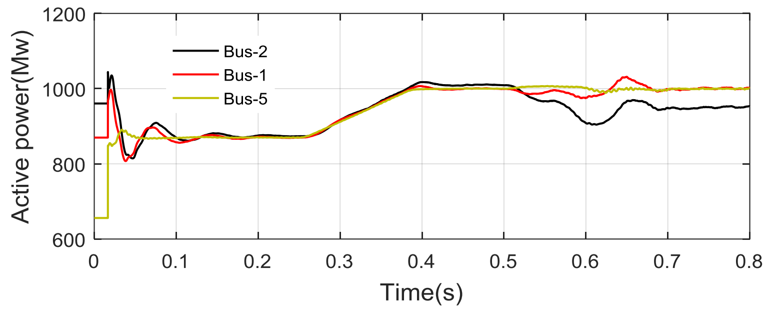
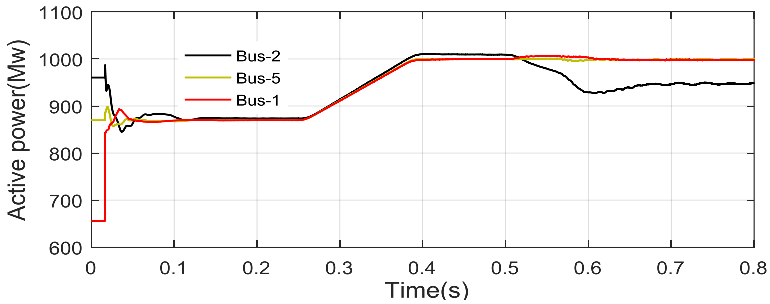


(b)

Fig. 11 - Diagrams of a) active power, and b) reactive power tracking of series converter 2 using a PI controller and an FL-PI controller



(a)



(b)

Fig. 12 - Diagrams of active power flow results related to buses B1, B2, and B5 for two cases: using a) classic PI controller, and b) adaptive FL-PI controller

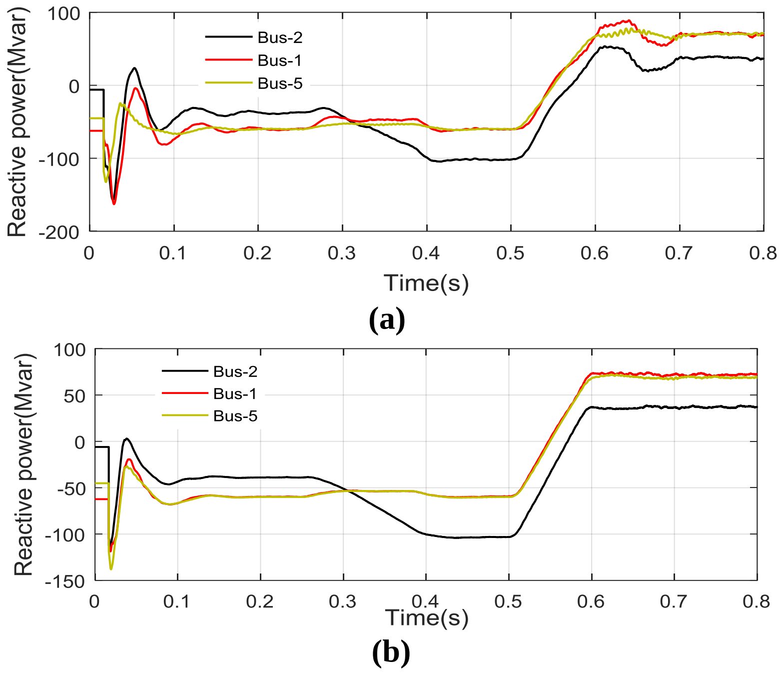


Fig. 13 - Diagrams of reactive power flow results related to buses B1, B2, and B5 for two cases: using a) classic PI controller, and b) adaptive FL-PI controller

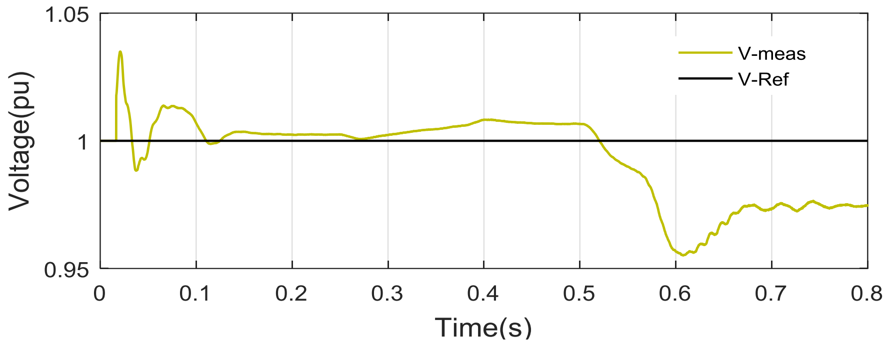


Fig. 14 - Voltage profile diagram of the common connection point (CCP) of Bus B1

As shown in Figs. 10-14, after the start of the simulation, the system reaches balance during a transition period of about 0.15 a, and both series converters follow the specified reference active and reactive power values. Figs. 10 and 11 depict the performance of both adaptive FL-PI controller and classic PI controllers. As it turns out, the oscillation in following the reference values of active and reactive power, when the adaptive FL-PI controller is used, are much less than those of the classical PI, and the successful performance of the proposed controller is shown in this paper. In the following, as shown in Figs. 12 and 13, the amount of active and reactive power oscillation of the bus connected to the GUPFC, when the adaptive FL-PI controller is used, is less than the case the classic PI controller is utilized. In these two figures, as can be seen, without losing the system balance, the system power flow is well performed at times of changes in the reference values of the active and reactive power of the series converters. The Independent yet simultaneous operation of the GUPFC in controlling the power flow of the corresponding lines (the lines on which the GUPFC is placed) is well demonstrated. Improved performance of the proposed adaptive FL-PI controller can be observed in Fig. 10 (a). The active power overshooting in series converter 1 in the case of using the classic PI and FL-PI controllers, respectively, reaches 10 p.u. and 9 p.u., respectively. Similarly, Figure 10(b) shows that the reactive power overshoot in the series converter 1 for the mentioned controllers reaches -0.1 p.u. and -0.3 p.u., respectively. Furthermore, this issue is fully illustrated in Fig. 11 for the series converter 2. Fig. 14 shows the voltage profile of bus B1. As is seen, the voltage of this bus during different time intervals changes within 10% of 1 p.u. According to Fig. 14, at t = 0.6 s, the maximum oscillation happens due to the change in reactive power of the two series converters. It can also be seen that the settling time for the proposed controller is slightly longer in some responses than the PI controller. Nonetheless, the settling time in all cases is less than 0.1 s. To compare the functions of two controllers, the proposed method called Integral Squared Error (ISE) is employed (Table 3).

Table 3 - Splay of ISE

	PI Controller	FL- PI Controller
Active power-series converter- 1	0.08744	0.08683
Reactive power-series converter -1	0.06965	0.06357
Active power-series converter -2	0.0883	0.08735
Reactive power-series converter-2	0.07822	0.07474

5. Future Works

This section aims to introduce future research trends related to the topic under study, which include:
a) design of a GUPFC control algorithm for transient fault periods based on the neuro-fuzzy theory, and
b) design of a fuzzy controller for a five-converter GUPFC to control reactive power and voltage in four-circuit transmission lines.

6. Conclusions

In this article a detailed model of FACTS Based GUPFC with separate control block has been developed and tested in Matlab/Simulink using the d–q control theory, utilizing Fuzzy-PI control strategy for real and reactive power control of series converter 1 and 2 we showed the improvement brought by the adaptive FL- PI controller on the performance of the GUPFC compared to the controller, namely the classic PI. The simulation results showed: a remarkable behavior of the adaptive FL-PI controller in voltage and power flow regulation of the active and reactive power of their references. Thus, the use of such a hybrid solution (PI adjusted by an FL) makes it possible to rationally exploit the advantages of conventional PI with a Fuzzy Logic Adaptive Control Scheme. This ensures coping with network, loading, parameters and operating conditions uncertain conditions. The GUPFC FACTS device can be extended to Renewable Wind/PV Large Farm and Energy Storage EES -Installations and interfacing to Smart power grids.

Acknowledgement

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Appendix:

Table A1 - The detailed data of the test system

Data of transmission lines	
Rated voltage (kV)	500
System frequency (Hz)	60
Length of Line 1 (km)	200
Length of Line 2 (km)	75
Length of Line 3 (km)	180
Resistance of Line 1 [R1 R0](Ohm/km)	[0.01273*2 0.3864]
Inductance of Line 1 [L1 L0] (H/km)	[0.9337e-3 4.1264e-3]
Capacitance of Line 1 [C1 C0] (F/km)	[12.74e-9 7.751e-9]
Resistance of Line 2 [R1 R0] (Ohm/km)	[0.01273*2 0.3864]
Inductance of Line 2 [L1 L0] (H/km)	[0.9337e-3 4.1264e-3]
Capacitance of Line 2 [C1 C0] (F/km)	[12.74e-9 7.751e-9]
Resistance of Line 3 [R1 R0] (Ohm/km)	[0.01273*2 0.3864]
Inductance of Line 3 [L1 L0] (H/km)	[0.9337e-3 4.1264e-3]
Capacitance of Line 2 [C1 C0] (F/km)	[12.74e-9 7.751e-9]
Data of the load	
Consumption power of Load 1 (MW)	**200**
Consumption power of Load 2 (MW)	**300**
Data of the GUPFC's controller when using the classic PI controller	
Gains of the shunt converter's voltage regulator	$K_{p-sh} = 12 * 3$; $K_{i-sh} = 3000 * 3$
Gains of the shunt converter's current regulator	$K_{p-sh} = 5$; $K_{i-sh} = 40$
Gains of the series converter 1's current regulator	$K_{p-se1} = 0.025$; $K_{i-se1} = 1.5 * 4$
Gains of the series converter 2's current regulator	$K_{p-se2} = 0.5 * 0.025$; $K_{i-se2} = 150$
Data of the GUPFC's controller when using the adaptive FLC-PI controller	
Gains of the series converter 1's current regulator	$K_{p-se1} = 0.2$; $K_{i-se1} = 48$
Gains of the series converter 2's current regulator	$K_{p-se2} = 0.1$; $K_{i-se2} = 1200$

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