JEPECS
Journal of Electric Power and Energy Conversion Systems

JOURNAL OF ELECTRIC POWER AND ENERGY CONVERSION SYSTEMS (JEPECS)
JEPECS VOL. 1, NO. 3, PP. 99-106, AUTUMN 2016
ISSN: 2345-4830 print/2345-4733 online

Effect of Distributed Power-Flow Controller (DPFC) on Power System Stability

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Distributed flexible AC-transmission system (D-FACTS) is a recently advanced FACTS device with high flexibility and smaller size. The DPFC can control power flow in transmission lines, regulate bus voltages and it can also enhance stability margin in power grids. Adaptive-neural network-based fuzzy inference system (ANFIS) combines features of artificial neural network and fuzzy controller. The ANFIS is nonlinear controller that can improve stability of the power system under different operating conditions. This paper presents the application of the neuro-fuzzy in DPFC-auxiliary controller to improve stability of power systems using wide area measurements provided by PMUs. This controller is implemented in a two power system test case. The simulations show that DPFC based ANFIS-auxiliary controller in series or, and shunt converter can damp oscillations and increase stability in a wide range of system operating conditions rather than the classic-auxiliary controller used conventionally in the DPFC.

Keywords: Auxiliary FLC-controller, Distributed Power Flow Controller (DPFC), Distributed Flexible AC Transmission System (D-FACTS) Devices, Adaptive-neural Network-based Fuzzy Inference System (ANFIS), And Power System Stability.

Received July 2016; Revised Jan. 2017; Accepted March 2017.

I INTRODUCTION

The flexible AC transmission systems (FACTS) devices can propose more control functions; including voltage regulation, power flow control and improving stability and dynamic behavior of advanced power systems while their important capabilities are reactive power compensation, voltage control and power flow control [1].

The UPFC is mainly used to control the power flow in a transmission system. The UPFC located between two buses is used to control the active and reactive powers flowing in transmission line while controlling voltage at the main bus. It consists of two converters, one connected in shunt and other in series between two buses. The shunt and series converters can exchange power through a DC link [2].

Distributed FACTS (D-FACTS) devices use a similar approach for implementing high power FACTS devices. The D-FACTS devices with lower costs and more flexibility can enhance the reliability and controllability of transmission and distribution systems. These devices improve asset utilization and end-user power quality with minimizing system cost and environmental effects [3], [4]. The concept of a distributed power flow controller (DPFC) is utilized to illustrate the flexibility of a D-FACTS device. The DPFC has the same control capability as the UPFC, which adjusts the line impedance, the bus voltage angles, and the bus voltage magnitude. It is composed of multiple small-size single-phase converters instead of the one large-size three-phase series and shunt converter as in the UPFC. It places in transmission lines in a distributed method [5].

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The main application of DPFC lies in its ability in controlling the power flow through the grid. This capability can be used for more efficient usage of existing power grids which faced new challenges as the penetration of renewable power generation increased substantially in recent years. However, DPFC can propose a wide range of benefits to the grid and act as one of main equipment of the future smarter transmission grid. Power oscillation damping and dynamic stability enhancement using FACTS devices such as gate-controlled series capacitors (GCSC), SVC, STATCOM and UPFC has been well elaborated in the literature [6-9]. A unified model for the analysis of FACTS devices in damping power system oscillations and different control techniques for damping undesirable inter-area oscillations in power systems have been proposed by means of power system stabilizers (PSS), SVCs, STATCOMs and DPFC [10-13].

Power systems containing generators and power electronics based FACTS devices are large-scale nonlinear and multivariable systems with dynamic characteristics over a wide range of operating conditions. The conventional linear control techniques (classic or PI controller) have been widely used to design the internal controllers of FACTS devices [1], [2].

Nonlinear controllers such as fuzzy logic controllers, neural networks, Adaptive neuro-fuzzy interface system (ANFIS) and etc. can provide better performance in systems with nonlinear behavior. These controllers also need no mathematical model of the system and are robust against all disturbances. ANFIS has abilities such as learning, adaptation and to make inferences [14-17].

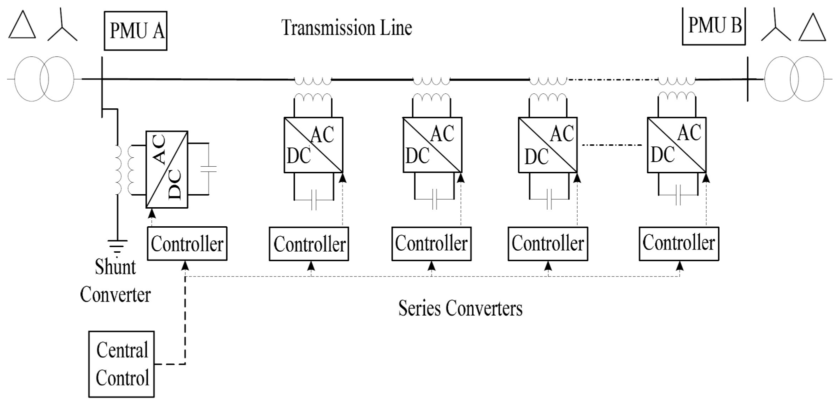

Figure 1: DPFC structure and components in a power system

This paper presents an effective control scheme for DPFC in a power system with ANFIS-damping controller to present adequate damping in power systems under various operating conditions. The damping characteristics of a conventional PID damping controller and the designed ANFIS-damping controller is compared which shows excellent performance of the proposed controller.

This paper is organized as follows; the structure and main components of DPFC is introduced in Section II. The control strategy of the DPFC is expressed in section III. Design procedure of damping controller based on PID and ANFIS controllers are presented in Sections IV and V respectively. Simulation results and comparative analysis of the studied system response with PID and the designed ANFIS-damping controllers in a two area power system and three machines, 9 buses system (WSCC) are described in Section VI. Specific important conclusions of the paper are drawn in Section VII.

II D-FACTS DEVICE

Distributed power flow controller (DPFC) is derived from the UPFC with a same concept and functionality. The DPFC have the capability of controlling main system parameters i.e. power flow, bus voltage angle and magnitude. The common DC link between the shunt and series converters is eliminated in the DPFC [5]. Low cost, high reliability and high control capability are main characteristics of the DPFC in contrast to the UPFC [5].

Fig. 1 shows a conceptual schematic of a DPFC used in a transmission line for managing power flow by controlling the line impedance, bus voltage angle and magnitude in a transmission line.

Active and reactive power exchange between the shunt and series converters in the DPFC is implemented through third harmonic currents. In a three-phase system, the 3^{rd} harmonic in each phase is identical, which means they treated as zero-sequence components. The zero-sequence harmonic can be filtered by $Y - \Delta$ transformers which are placed in two sides of the DPFC [15].

The common DC link of the UPFC is eliminated in the DPFC configuration and series converters are distributed along the transmission line. The DPFC consists of one shunt and several series-connected single phase converters. The shunt converter is similar to a STATCOM, while the series converter uses the distributed synchronous series compensator (DSSC) concept. The DPFC uses several single-phase converters instead of one three-phase converter and they are independent from each other [5], [12-13]. The converters of the series units (DSSC) are connected to the transmission line by single-turn transformers and inject a controllable voltage directly into the line. Most of the voltage injected by a DSSC unit is in quadrature with the line current to control power flow in transmission line by inserting inductive or capacitive impedance [13].

III THE CONTROL STRATEGY OF DPFC

The central control unit generates reference signals for the shunt and series converters of the DPFC to regulate the bus voltage and to control power flow in transmission line. All the reference signals generated by the central control unit are corresponded to the fundamental frequency components.

A The Series Converter Controller

Fig. 2 shows control system of the series converter [3], [13], [18], [19]. The phase-locked loop (PLL) in the series converter extracts phase angle (θ) from the line current. The phase shifter changes the phase θ to $\theta - 90^0$ to increase power flow in transmission line. The voltage regulator regulates DC voltage and it tracks the reference DC-voltage. Hence, The DSSC injects a series voltage in quadrature with the line current and consequently can control active and reactive power in the transmission line.

B The Shunt Converter Controller

Fig. 3 indicates block diagram of the shunt converter controller in the DPFC [5], [19-21]. When the $|V_t| > |V_{ref}|$, the reactive power flows from the AC system to the STATCOM and the STATCOM operates as an inductive load. When $|V_t| < |V_{ref}|$, reactive power flows from STATCOM to the AC system and STATCOM operates as a capacitive load. The shunt converter's control system aims to inject a controllable reactive current to the grid and keeping the capacitor DC voltage at a constant level [5].

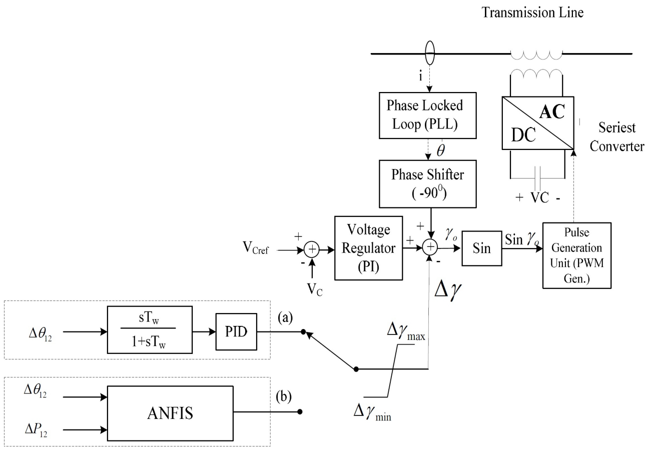

Figure 2: Block diagram of the series converter (DSSC) with (a) PID damping controller and (b) with ANFIS damping controller

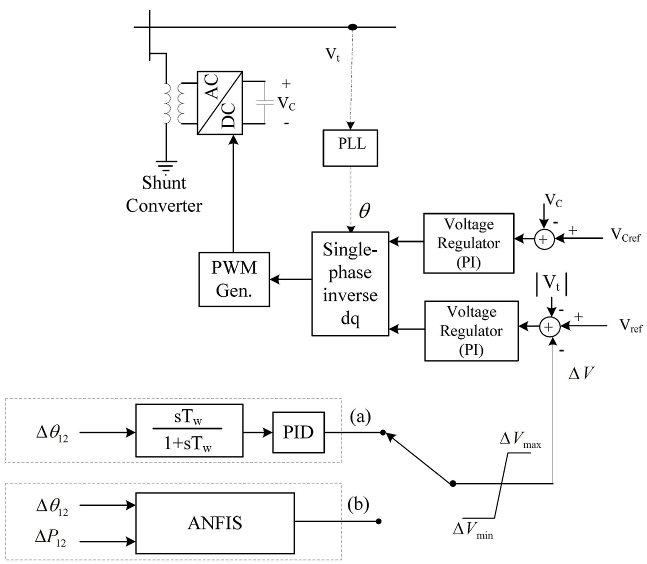

Figure 3: Block diagram of the shunt converter (STATCOM) with (a) PID damping controller and (b) with ANFIS damping controller

IV DESIGN OF A PID DAMPING CONTROLLER FOR SERIES AND SHUNT CONVERTER

For damping power oscillations and enhancing power system stability, an auxiliary controller could be added to the main controller of the DPFC [18-22]. The conventional PID damping controller consists of a washout and PID block.

Synchronized phasor measurements units (PMUs) provide state measurements including voltage magnitude, voltage phase angle, and frequency [23], [24]. Wide-area feedback consisting of phase angle and frequency measurements from PMUs in the areas is used for designing auxiliary controller to damp the oscillations [25], [26].

The input of auxiliary damping controller is the deviations of voltage phase angle $\Delta\theta_{12}$ ($\theta_1 - \theta_2$) between two buses of synchronous machines (areas of a power system). Its output is a damping signal to the main control system in order to improve the system damping. The deviations of phase angle $\Delta\theta_{12}$ are obtained from PMUs.

To make the series and/or shunt converter able to mitigate low frequency power oscillations and improving power system stability, an auxiliary control loop has been added in the main series and/or shunt controller of the DPFC as shown in Fig. 2(a) and Fig. 3(a). The transfer function H(s) of the PID damping controller is as follows [22], [27]:

$$H(s) = \frac{sT_w}{1+sT_w}\left(K_P + \frac{K_I}{s} + s\cdot K_D\right) \quad (1)$$

Where T_w is the time constant of the washout term which acts as a high-pass filter. Parameters K_P, K_I and K_D are the proportional gain, integral gain, and derivative gain of the damping controller respectively.

The classic PID controller explained in this section may not stabilize the power system under parameter variations and nonlinear disturbances satisfactorily as presented in section VI.

V DESIGN OF A ANFIS DAMPING CONTROLLER FOR SERIES AND SHUNT CONVERTERS

The Adaptive neuro-fuzzy interface system (ANFIS) technique provides a procedure for fuzzy modeling procedure to learn information about a data set, in order to compute the membership function parameters that best allow the associated fuzzy inference system to track the given input-output data. ANFIS uses either back propagation (BP) or a combination of least squares (LS) estimation and back propagation called hybrid method for membership function parameter estimation. The neuro-fuzzy controller controls the plant in an optimal approach in the presence of noise and uncertainty. For the most part, the neuro-fuzzy controller can be adapted/tuned online while controlling the plant [28-31].

In the ANFIS, the forward pass learning estimates the consequent parameters and backward pass learning updates the premise parameters. The generic fuzzy rules of ANFIS are:

R^1: IF x is A_1 and y is B_1 then $f_1 = a_1x + b_1 + c_1$

R^2: IF x is A_2 and y is B_2 then $f_2 = a_2x + b_2 + c_2$

Where x, y are inputs, A_i, B_i are membership functions, and a_i, b_i, c_i are consequent parameters [28].

Fig. 4 indicates the structure of adaptive network based on fuzzy inference system (ANFIS). The ANFIS network is consisted of five layers. Each layer contains different nodes described by the node function. Let $O_{j\cdot i}$ denotes the output of the ith node in layer j [32]:

Layer 1: every node i is an adaptive node with node function:

$$O_{1,i} = \mu_{Ai}(x) \quad (2)$$

$$O_{1,i} = \mu_{Bi}(y) \quad (3)$$

In our model, Gaussian membership function is used as:

$$\mu_{Ai}(x) = \exp\left(-\frac{1}{2}(\frac{x-c_i}{\sigma_i})^2\right) \quad (4)$$

Layer 2: each node II multiplies incoming signals and sends the product out.

$$O_{2,i} = \omega_i = \mu_{Ai}(x)\cdot\mu_{Bi}(y) \quad (5)$$

Layer 3: each node computes the ratio of the ith rule's firing strength to the sum of all rules' firing strengths

$$O_{3,i} = \overline{\omega_i} = \frac{\omega_i}{\omega_1 + \omega_2} \tag{6}$$

Each output is calculated by product of normalized weights and consequent part.
Layer 4: Every node i in this layer is an adaptive node with a node function:

$$O_{4,i} = \overline{\omega}_i \cdot f_i = \overline{\omega}_i(a_i x + b_i + c_i) \tag{7}$$

Where $\overline{\omega_i}$ is the normalized output of layer 3.
Layer 5: the single node $\sum$ computes the final output as the summation of all incoming signals.

$$O_{5,i} = \sum_i \overline{\omega_i} \cdot f_i = \frac{\sum_i \omega_i \cdot f_i}{\sum_i \omega_i} \tag{8}$$

Therefore, an adaptive network is functionally equivalent to Sugeno-fuzzy inference system.

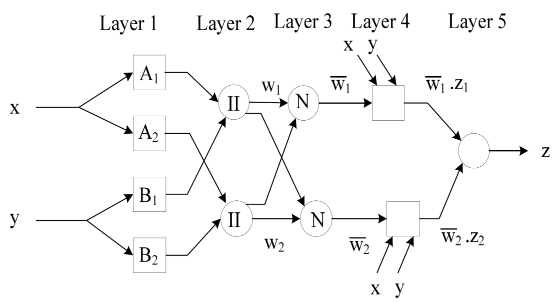

Figure 4: The structure of adaptive-network-based on fuzzy

In the proposed damping controller, a two-input, one-output FLC is considered. The input signals for the fuzzy controller are the phase angle deviations of the bus voltages ($\Delta\theta_{12}$) and active power deviations (ΔP_{12}) to generate the modulated control input $\Delta\gamma$/ΔV in Fig. 2(b) and Fig. 3(b).

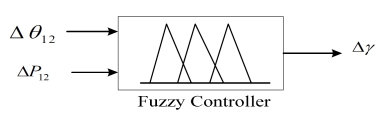

Figure 5: Fuzzy-supplementary damping controller

The membership functions (MFs) and the consequent models in fuzzy controller are tuned based on behavior of the DPFC and observations. The fuzzy controller uses 25 rules and 5 MFs in each variable to compute output and exhibits good performance. Five linguistic variables for each input and output variable are defined, namely, Positive Big (PB), Positive Medium (PM), Zero (Z), Negative Medium (NM), and Negative Big (NB). Also, the centroid defuzzification strategy was used in this fuzzy controller to generate auxiliary signal $\Delta\gamma$ in DSSC and ΔV in shunt unit (STATCOM) main control systems.
To design the ANFIS controller, some data sets are required; the training data have been achieved by sampling from input variables $\Delta\theta_{12}$, ΔP_{12} and from output variable $\Delta\gamma$ (in series converter) or ΔV (in shunt converter) controller.
A hybrid learning algorithm (BP and LS) is used for training to optimize MFs and rules (inference system) of the fuzzy controller and transform the FLC to ANFIS controller. The ANFIS damping controller with a fewer number of rules and MFs (system with 9 rules and 3 MFs).can provide the same level of performance as the original one. After reducing the rules, the computation becomes faster and hence, takes less memory.

VI Results of Simulation and Discussion

Fig. 6 shows a two area power system with DPFC in the main interconnection transmission line used here for analyzing the proposed controller performance. A 1000 MW hydraulic generation plant (Gen-1) is connected to a load center via a long 500 kV, 700 km transmission line. The load center is a 5000 MW resistive load. The load is fed by the remote 1000 MVA plant and a local generation of 5000 MVA (plant Gen-2). A load flow has been done on this system with plant Gen-1 producing 950 MW and plant Gen-2 generates 4046 MW. The line transmits 944 MW and its surge impedance loading (SIL) is 977 MW [1], [32]. Simulation for dynamic and transient-stability analysis has been done in MATLAB/Simulink environment.

A Dynamic Stability Analysis

For analysing the behaviour of the proposed controller, different disturbances with different operational conditions are studied and the most sever one is reported. It is assumed that a self-clearing three phase fault to ground with fault resistance of 5Ω is occurred near bus A in the system under study and the fault is cleared after 85 milliseconds. Fig. 7 compares power system parameters in two cases i.e. with and without DPFC located in the transmission line but without any auxilary controller in the DPFC. The effect of DPFC in improving system stability during the fault can be observed. Indeed the instability of power system without DPFC is occurred immeduately after fault clearing and the stability margin of the simulated two area power systen with DPFC is more than the one without DPFC. The DPFC without auxillary controller cannot satabilize the power systen in transisent analysis.
In fact the DPFC provides a delay of about one second in phase angle deviation in this system. However with the proposed controller, system stability will improve significantly as in Fig. 8.
In an attempt to verify the performance of the proposed controller in damping power system oscillations, damping controller based PID (classic) and proposed ANFIS controller are incorporated in the DPFC and their effect on power system behavior is shown in Fig. 8. It compares the results using DPFC with different damping controllers. The damping controller has been inserted in series and/ or shunt converter (converters) of the DPFC.

B Transient Stability Analysis

Here it is assumed that a self-clearing three-phase fault with fault impedance of 0.1Ω and with 85 milliseconds duration is occurred at bus (A) near machine Gen-1. Fig. 9 shows a considerable improvement in power system transient stability by using

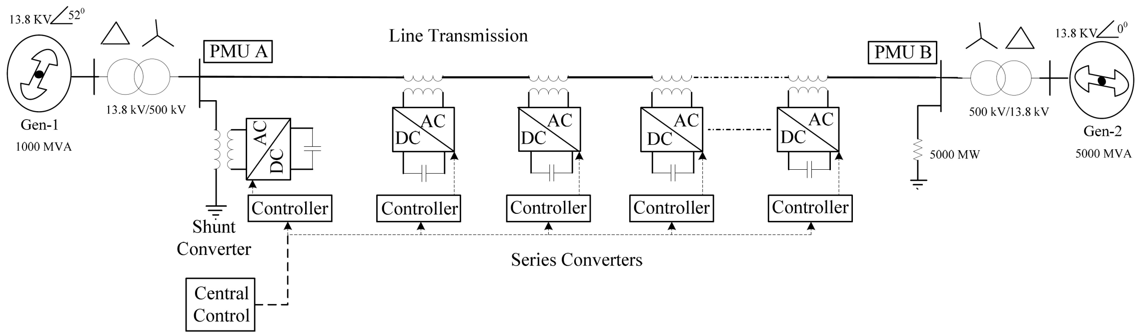

Figure 6: The two area power system used for simulations

the proposed ANFIS auxiliary controller in the DPFC.

Based on above results following conclusions can be summarized:

- The DPFC with ANFIS damping controller in series and/ or shunt converters has a much more influence on oscillation damping ratio than DPFC with PID damping controller over a wide range of disturbances. Also the bus voltage of the power system has been regulated significantly with a DPFC equipped with ANFIS damping controller.
- The series converter with damping controller improves dynamic performance and stability of the power system much more than the shunt converter with damping controller.

Please note that a more detailed analysis on this application could be find in [33].

VII Conclusion

In this paper an ANFIS based auxiliary controller design is proposed for a DPFC to improve dynamic and transient performance of power systems. A combination of both back propagation and least square algorithms has been used for training the ANFIS system. Simulation results show that the proposed DPFC based ANFIS auxiliary controller mitigates low frequency oscillations (LFO) better than conventional controllers. The performance of the neuro-fuzzy controller based DPFC has been compared with classic controller in transient stability analysis also and results shows a better transient behavior of the power system under the study. Therefore it can be concluded that the proposed auxiliary controller improves both dynamic and transient stability of power systems.

The results also show that the DPFC without a specific auxiliary controller can't mitigate oscillations in a power system. It is shown that the DPFC with ANFIS damping controller in series and/ or in shunt converter can effectively damp electromechanical oscillations and improve transient stability.

Also, the series converter with damping controller mitigates low frequency oscillations and shows a better performance than the shunt convertor damping controller. The critical clearing time increases for the proposed controller compared to its conventional controller. For practical implementation, the stochastic communication delay of PMUs should be effectively handled which is considered as future work

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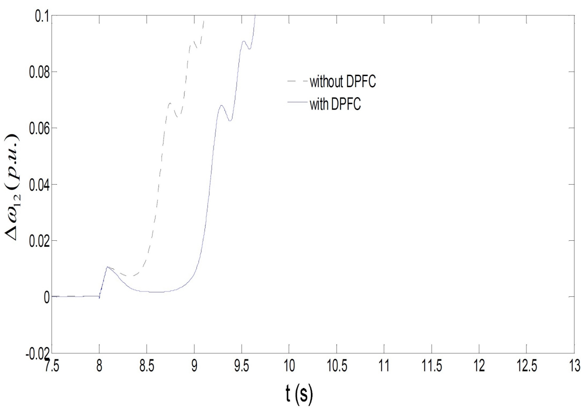
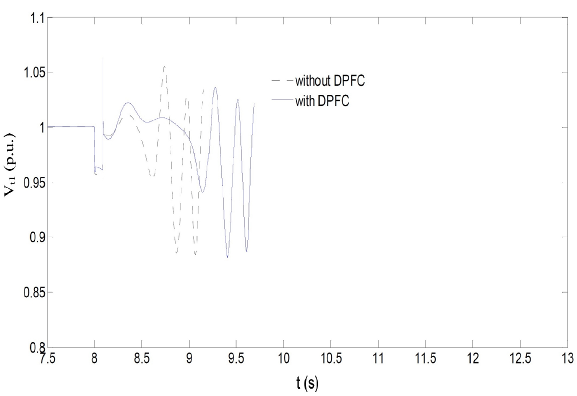


(a)



(b)

Figure 7: Comparison parameters between power system with DPFC and without DPFC a) $\Delta\omega_{12}$, b) ΔV_{t1}

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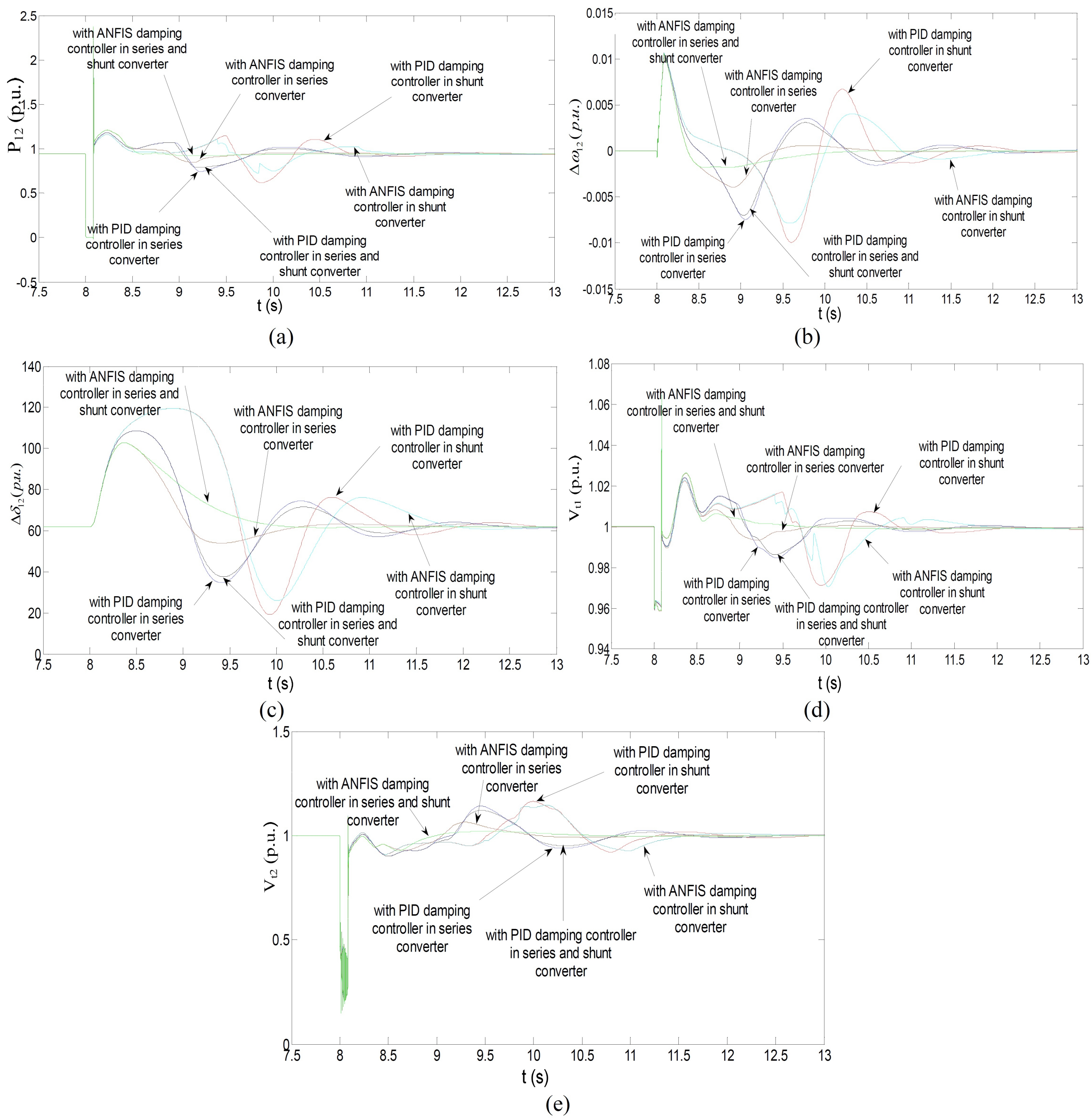

Figure 8: Comparison of power system parameters equipped by a DPFC with different damping controllers in dynamic condition a) P_{12}, b) $\Delta\omega_{12}$, c) $\Delta\delta_{12}$, d) ΔV_{t1} and e) ΔV_{t2}

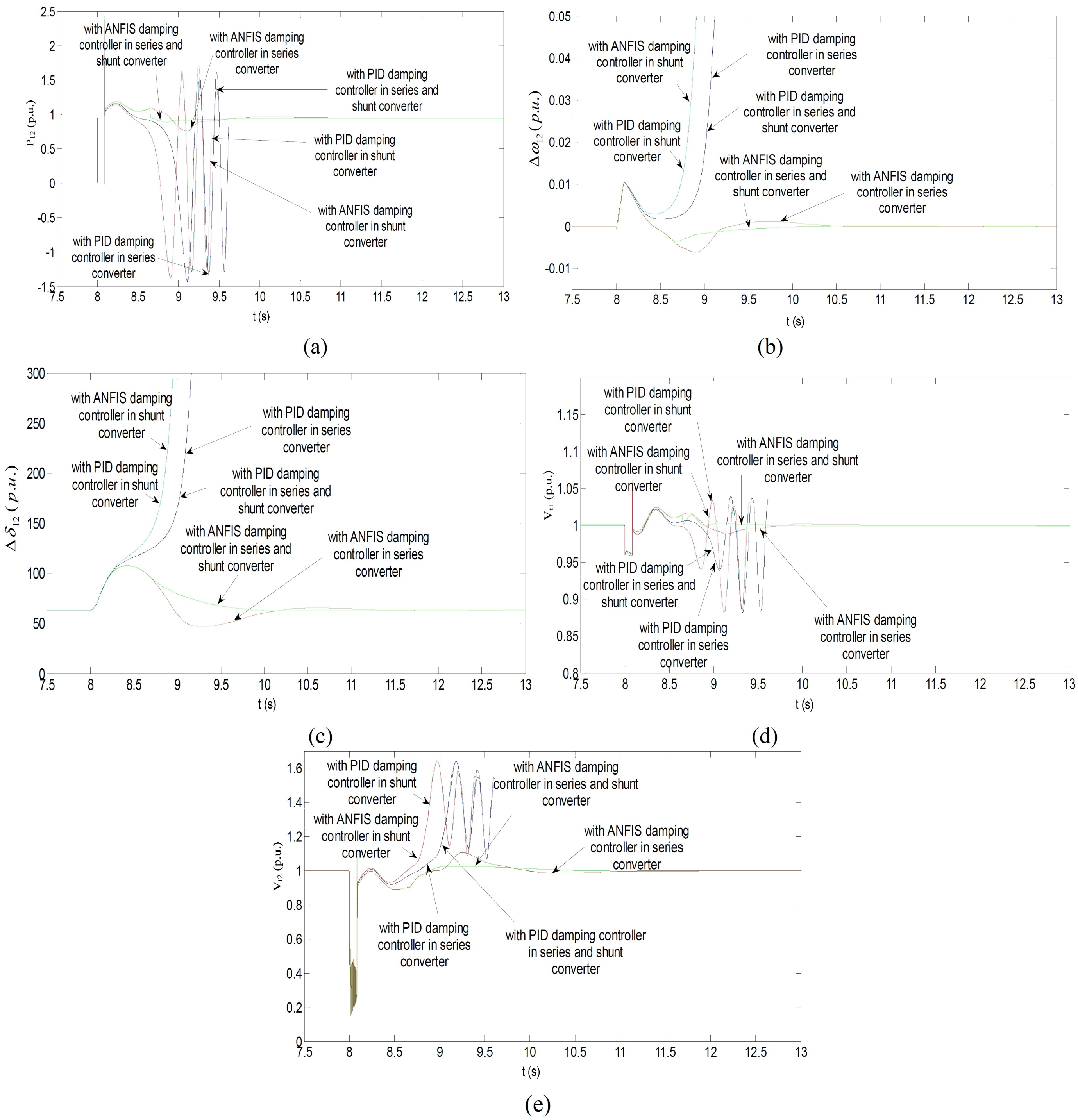

Figure 9: Comparison of power system parameters equiped by a DPFC with different damping controllers in transient condition a) P_{12}, b) $\Delta\omega_{12}$, c) $\Delta\delta_{12}$, d) $\Delta \mathrm{V}_{t1}$ and e) $\Delta \mathrm{V}_{t2}$