



Application of TRIZ Thinking Method to Unified Power Flow Controllers by Converting into DPFC and FSO-DPFC

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Abstract

This paper introduces an innovative and creative systematic thinking method based on TRIZ thinking technique which can improve the performance of unified power flow controllers (UPFC). This new device is called distributed power flow controller (DPFC). The difference between UPFC and DPFC lies in exchanging three-phase series converter with single-phase converters that are distributed along the transmission line. This is based on one of the 40 principles of TRIZ innovative thinking technique, called segmentation. The basic changes, occurring in the DPFC, compared to UPFC are eliminating common DC-link between the series and shunt converters, and replacing three-phase series converters with single-phase series converter. These changes, lead to more economic and more reliable system. Similar to UPFC, the DPFC adjusts line impedance, transmission angle and bus voltage simultaneously. The DPFC design procedure based on differences with UPFC is described and DPFC advantages in mitigation of transmission line voltage sag and fluctuation are shown; while in some cases, simulation results of using UPFCs, DSTATCOM, TCSC and SVC indicate voltage sags. Finally, this paper introduces one innovatively DPFC called fuzzy self-organized DPFC (FSO-DPFC) to solve the most important problem of DPFC. DPFC series converter with and without FSO controller (FSO-DPFC) are simulated. The simulation results of using FSO-DPFC, compared to traditional DPFC, shows more system ability to mitigate disturbances in the central controller signals.

Keywords: TRIZ Technique, FACTS, DPFC, FSO-DPFC, Fuzzy Self Organized, UPFC, Series Converter, Shunt Converter

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1. Introduction

Electrical energy demand rising and transmission lines aging increase the importance of power flow control [1,2]. It is necessary to take into account both economical and power environmental issues in establishing any power system [3,4]. It is essential to review traditional methods and create new concepts emphasizing more efficient use of the already existing power system resources with no reduction in system stability and security [5,6]. Flexible ac transmission system (FACTS) devices can effectively control the electrical power flow [7,8]. There are many kinds of FACTS devices operating based on the line specifications [9,10] which enhance transmission capacity and control power flow over designated transmission routes [11,12].

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utilizing ultra-capacitors, also known more generally as electrochemical capacitors [13,14].

TRIZ technique is an innovative problem solving method containing 40 principles. It claims that most inventions and new works have one or more of 40 principles of TRIZ [15,16]. This technique has been used in various studies [17,18].

A study to identify 8 different appropriate TRIZ-based strategies for solar energy investment for commercial and non-commercial users is presented in [19], the main motivation of which is to determine the weights of solar energy investment strategies. The results show that mechanical system replacement is found to be the most effective TRIZ-based investment strategy for solar energy projects in both commercial and non-commercial aspects.

Dynamic voltage restorer (DVR) device is considered as a case of electrical engineering field in

[20] to investigate and develop a TRIZ-based guidance framework, which helps to solve the problems of DVR devices. The proposed sector specific guidelines in particular segment of electrical engineering will be closer, more comprehensible and particularly linked to key parameters of that sector.

This paper introduces distributed power flow controller (DPFC) according to segmentation principle of TRIZ thinking technique, which is more economic and reliable system compared to the traditional method. Furthermore, simulation results will show that the voltage sag in the DPFC is considerably decreased which is better than those presented in unified power flow controller (UPFC), TCSC and SVC. It is observed that there is about 30% voltage sag between 0.2 and 0.3 when UPFC is applied [21,22].

The most important contribution of this paper is innovatively using fuzzy self-organized controller (FSOC) on the DPFC called fuzzy self-organized distributed power flow controller (FSO-DPFC). The most important drawback of DPFC is its disability in providing proper response due to the large distance between the central controller and DPFC series converters. It means that there are disturbances in the control signals which must be mitigated. Because the series converters operate outdoors, the communication (wireless or PLC) between the central controller and series converters is susceptible to disturbances, such as lightning and geomagnetic storm. This paper has been organized as follows. Section 2 introduces the TRIZ technique and background of the systematic thinking method in DPFC and its merits. Section 3 proceeds to DPFC concept and in section 4 structure and calculation of optimal number of FSO-DPFC series units and FSOC are indicated. Section 5 presents the simulation results. Finally, section 6 concludes the paper.

2. Theory of inventive problem solving (TRIZ Technique)

TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) is the Russian abbreviation word which means "a problem solving, analysing and forecasting tool derived from the study of patterns of invention in the global patent literature" and its founder was Altshuller. In some cases, TRIZ is replaced by "the theory of inventive problem solving". This theory originates from the study of over 40,000 patent abstracts which results in contradiction matrix and 40 principles of invention which can innovatively solve the most problems. In other words, TRIZ is the worldwide theory of inventive problem solving, which can help the engineers to realize technology innovation [23,24]. The TRIZ technique has been shown in Fig. 1 [25,26].

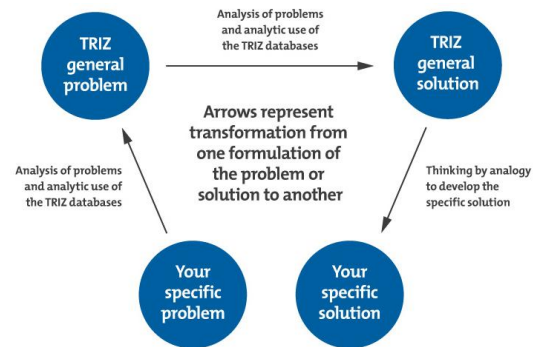


Fig. 1. TRIZ technique for problem solving

It is noted that the TRIZ technique in electrical engineering is converting the physical concepts of the TRIZ principles into electrical concepts. It is necessary to be familiar with both TRIZ and electrical engineering topics. For example, the concept of segmentation is converted into three-phase series converter requiring a large space compared to the multi single-phase series converters; the latter is distributed along the transmission line (no large space).

UPFC is one of the efficient FACTS devices, consisting of two important FACTS devices: STATCOM and SSSC [27,28]. This can be put in the combination principle group of the TRIZ principles. Applying combination principle to these two FACTS devices result in suitable features which is combination features of STATCOM and SSSC. It controls both the active and reactive power flow in the transmission line simultaneously and independently. Utilization of UPFC can result in significant reliability benefits in modern power systems [29,30].

They are one of the incomparable FACTS devices which actually have FACTS concept in three features of transmission system parameters controlling. They are voltage, impedance and phase-angle [31,32]. However, due to the reliability and cost issues, they have not been widely used in transmission lines. To solve this problem, a new FACTS device called DPFC has been recently introduced [33,34].

Since three-phase series converter has been replaced by a single-phase series converter in this structure, it was realized that the segmentation principle of the TRIZ principles has been used, where the advantages of this problem solving technique (TRIZ) is shown as follows:

A) Low cost: because of the lower voltage isolation and low rating of single-phase series converter compared to three-phase series converter.

B) Increasing flexibility: due to eliminating the common DC-link between the shunt and series

converters which provides independent placement of series and shunt converters.

C) Less space: due to optimal deployment where one shunt converter is placed in the previous position, there is no need for any space for UPFC three-phase series converter and single-phase converters are distributed along transmission line.

D) Increasing reliability: for series converter multiplicity because poly series converter is distributed along the line; if some of them fail to operate the remaining converters continue to operate.

3. DPFC concept

DPFCs and UPFCs have identical structure, and both have series and shunt controllers to control the voltage, impedance and phase angle [35,36]. To improve the UPFC and decrease its undesired features, the DPFC is proposed; some merits of DPFC in comparison with UPFC were mentioned in section, 2 [37,38]. Difference of UPFC and DPFC includes eliminating dc-link, distributing series converters along the transmission line and changing the controlling system. Based on these differences, it is preferred to consider the series converter of DPFC in details and other parts of DPFC in abstract [39,40].

A. Shunt converter of DPFC

The shunt converter shown in Fig. 2 is a three-phase converter connected to a single-phase converter. Structure and operation of these converters are similar to the STATCOM and shunt converter of the UPFCs [41,42]. To absorb active power of transmission line, the three-phase converter of the DPFC is connected to the Δ -side of the transformer in the DPFC shunt converter (similar to STATCOM), with fundamental frequency. The single-phase converter is located between the ground and neutral point of the Y- Δ transformer in order to inject the third-harmonic current into the grid [43,44].

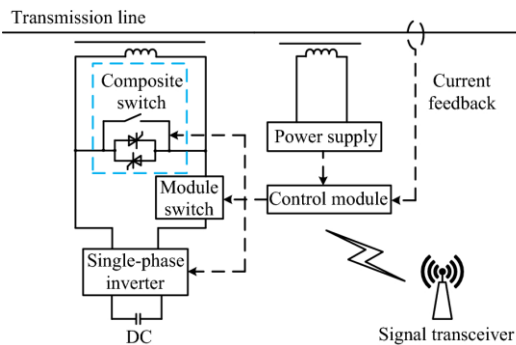


Fig. 2. Shunt converter

B. DPFC controller

To control the DPFC, it is divided into three segments including central, shunt and series controllers. The series converters have separable series controllers connected to the central controller for receiving the reference voltage. Series controller adjusts the DC voltage capacitor at fundamental frequency. Furthermore, fundamental frequency is used to inject series voltage to the transmission line by DPFC. The reason is that due to the large distance between the central controller and series converters, the control signal (V_d, V_q) disturbances are so probable; in fact the short come of the traditional DPFCs controller is its disability to match with these disturbances on the controller signal; so to overcome this problem the FSO-DPFC is designed and introduced, Which the central controller signal disturbances will not effect on the transmission voltage quality [45,46].

Central controller is used to generate reference voltage signal for series converters and reference current signal for shunt converter at the fundamental frequency. Shunt controller injects a constant third harmonic current into the line to supply active power to series converters. Similar to STATCOM, the power is controlled by a shunt compensator, by controlling voltage amplitude, reactive power exchange between the power flow controller and transmission line [47,48].

This paper focuses on the DPFC series converters and their control signals came from central controller. The reasons include importance of the series converter role in DPFCs and approximation of the other DPFC's elements with some of the FACTS devices such as UPFC and STATCOM.

4. Structure of DPFC series units

To control the line parameters, a shunt converter and some series converters with their controllers are used as shown in Fig. 3. One important factor in the design of DPFC is calculation of the number of series converters as described below.

A. Calculation of optimal number of series converters

Minimum number of series converters versus line parameters is calculated as follows [49]:

a) The total maximum ac voltage ($V_{se-f-max}$) injected by all series converters is as follows:

$$V_{se-f-max} = \frac{S_\gamma V_n}{X_f} \quad (1)$$

where X_f is the line impedance at the fundamental frequency, V_n is the nominal bus voltages and S_γ is the control range of power flow.

b) The maximum active power of all series converters (P_{se-max}) is obtained as follows:

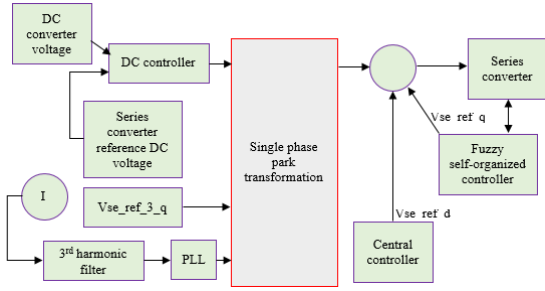


Fig. 3. Structure of series converter controller with FSO

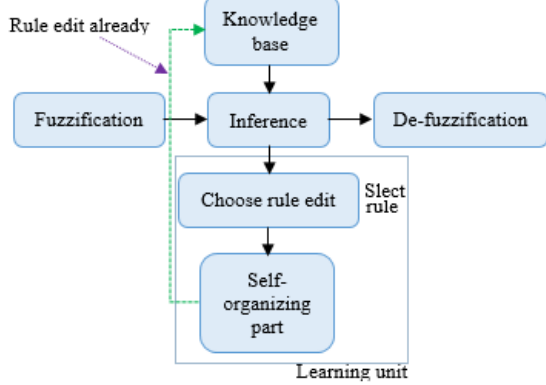


Fig. 4. Fuzzy self-organizing controller

$$P_{se-max} = \frac{|X_f| |S_{ro}|}{V_n^2} |S_\gamma| \quad (2)$$

where S_{ro} is the line power without the DPFC.

c) The maximum third harmonic voltage of series converter ($V_{se-3^{rd}-max}$) used for DC voltage stabilization;

$$|V_{se-3^{rd}-max}| = \frac{P_{se-max}}{I_3} \quad (3)$$

where I_3 is the magnitude of the third harmonic current calculated according to the thermal capacity of the neutral wire.

d) The maximum voltage and current of the converter is the summation of fundamental and third harmonic of voltage and current, as follows:

$$V_{se-max} = V_{se-f-max} + V_{se-3^{rd}-max} \quad (4)$$

$$I_{se-max} = I_{1-max} + I_3 \quad (5)$$

e) The ratio of winding turns of the series converters (T_{trans}) is as follows:

$$T_{trans} = \frac{I_{max}}{I_{MOS}} \quad (6)$$

Since the primary is a single turn (the 1st winding of transformer); I_{max} is the maximum line current and I_{MOS} is the maximum current of the proposed MOSFET.

f) Finally, the optimum number of the distributed series converters to transmission line N is as follows:

$$N = \sqrt{6} \frac{V_{se-max-trans}}{V_{MOS}} \quad (7)$$

where V_{MOS} is the maximum voltage of the proposed MOSFET. The FSO-DPFC series unit contains two basic elements, the series converter and series controller. One basic part of the series unit is FSO and basic input element of series converter controllers is the reference signal of the central controller. In order to improve the transmission line voltage, the controller sends the input signal to the series converter and series converter generates a suitable signal.

The series converter controller measures the line current. Then the third harmonic current in the PLL is used to determine the third harmonic current angle. The classic PLL consists of a voltage controlled oscillator (VCO) and phase compensator [50,51]. The PLL output is used as single-phase Park's transformation rotating reference frame and it is combined with d-component of DC controller output which is used with q-component of $V_{se-ref-3}$ (that considered constant value of zero) [52]. In the final step, the Park's transformation output has combined with $V_{se-ref-f}$ came from central controller, in order to send it to the series converter and improve the line voltage or decrease the voltage sag, harmonics and fluctuations. In the FSO-DPFC, there is a FSO in the series unit which is described in the following section.

B. Fuzzy self-organized controller

As shown in the Fig. 4, first the controller fuzzifies the input data, then the knowledge base rules are modified automatically. The new modified rules are chosen according to the input data, and the output is calculated; finally, de-fuzzification unit produces the output for the V_{se} unit leading to suitable series voltage [53,54]. According to the fuzzification input data, Table 1 with 49 updated rules forms the knowledge base giving the suitable value in each learning revolution. The self-organizing section uses the following equations for changing the rules in the knowledge base [55,56]:

Table 1

Knowledge base and rules at time n_T in learning revolution K								
	<i>de</i>	<i>NB</i>	<i>NM</i>	<i>NS</i>	<i>ZE</i>	<i>PS</i>	<i>PM</i>	<i>PB</i>
E	center	-0.6	-0.4	-0.2	0	0.2	0.4	0.6
NB	-0.6	-0.6	-0.6	-0.6	-0.6	-0.4	-0.2	0
NM	-0.4	-0.6	-0.6	-0.6	-0.4	-0.2	0	0.2
NS	-0.2	-0.6	-0.6	-0.4	-0.2	0	0.2	0.4
ZE	0	-0.6	-0.4	-0.2	0	0.2	0.4	0.6
PS	0.2	-0.4	-0.2	0	0.2	0.4	0.6	0.6
PM	0.4	-0.2	0	0.2	0.4	0.6	0.6	0.6
PB	0.6	0	0.2	0.4	0.6	0.6	0.6	0.6

$$E = \frac{1}{2}[y(t) - y_{sp}]^2 \quad (8)$$

$$\overline{c_L}(k+1) = \overline{c_L}(k) - \alpha \frac{\partial E}{\partial c_L} \quad (9)$$

In (9), $c_L(k)$ is the membership function of rule “L” at learning revolution of “k” and $C_L(k+1)$ is the membership function of rule “L” at learning revolution of “k+1”; α is the learning rate and $(\partial E/\partial c_L)$ is the differential function for comparing it with c_L calculated as follows:

$$\frac{\partial E}{\partial c_L} = \frac{\mu_L(e) \times \mu_L(ce) \times (y(t) - y_{sp})}{\sum_{L=1}^n (\mu_L(e) \times \mu_L(ce))} \quad (10)$$

where $\mu_L(e)$ is the membership level of rule “L” error, $\mu_L(ce)$ is the membership level of rule “L” changing error, y_{sp} is the required revolution value, and $y(t)$ is the measured revolution value. The learning rate is calculated as follows:

$$\alpha = \text{weight} \times |e(nT) - \overline{c_L}(nT)| \quad (11)$$

1. Because the measured performance value should be affected the learning rate and input changing on learning rate in every period of time. In (11), $e(nT)$ is the error at time nT , $c_L(nT)$ is the fuzzy singleton of output of rule “L” at time nT .

The performance value is the difference between the specific performance value and desired performance value described as follows:

$$\Delta OV = OV_{desired} - OV \quad (12)$$

Weighted value is the measured one with following conditions [57,58]:

If $\Delta OV < 0.3$ then weight is 0.0.

If $\Delta OV \geq 0.3$ and $\Delta OV \leq 0.1$ then weight is 1.0.

If $\Delta OV > 1.0$ and $\Delta OV \leq 3.0$ then weight is 3.0.

If $\Delta OV > 3.0$ then weight is 3.0; [59,60].

5. Simulation Results

Number of series converters per phase can be determined by substituting the appropriate values from Table 2.

Table 2
Values for sample calculation

Power (kW)	Voltage (V)	Reactance (Ω)	Current (A)
$S_r=1000$	$V_n=380$	$X_f=3$	$I_{MOS}=2$
$Q_0=500$	$V_{MOS}=230$	$X_3=3.0084$	$I_{max}=2$
$P_0=1000$		$f=50(\text{Hz})$	$I_{Thermal}=2.2$

According to the above values and (1) to (7), $N=1$ per phase, the number of series converter distributed along the line is 3, according to Table 3, there is economization, because of series capacitor bank, eliminating three-phase series converter transformer and replacing three-phase series converter with single-phase converters. The series converter elements have been simulated using Matlab/Simulink. As shown in Fig. 5, the DPFC and FSO-DPFC series unit are connected in series to the one phase of transmission line. Fig. 6 shows the FSO unit structure which operates as described in section 4, based on the combination of Matlab M-file programming and Simulink. Power system specification which has been used for simulation are shown in Table 4.

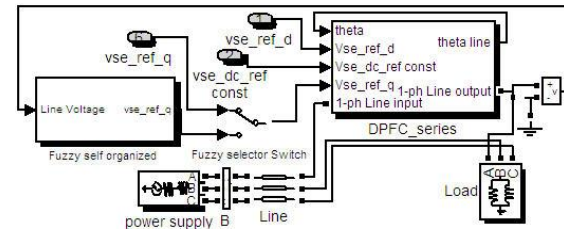


Fig. 5. Simulation of DPFC and FSO-DPFC series unit location on phase-A by Matlab/Simulink

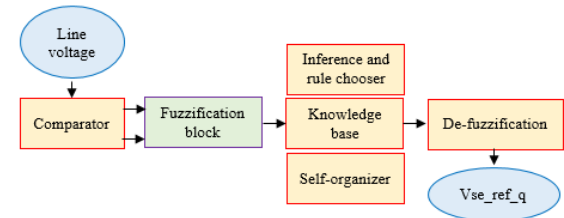


Fig. 6. FSO-DPFC fuzzy self-organized controller unit

Table 3
Comparison of elements in DPFC with UPFC

Components	DPFC	UPFC
Three-phase transformer for shunt converter	2	2
shunt converter	2 (1:3 phase+1: single phase for 3 rd harmonic)	1:3 phase
shunt capacitor bank	1	1
Three-phase transformer for series converter	0	2
series converter	3(single-phase)	1(3-ph)
series capacitor bank	0	1

The next inside layer of the DPFC series unit, shown in Fig. 7 contains the following inputs:

Series controller (contains PI and Integral controllers) needs a constant value for the reference of DC-controller of series converter which is, $V_{se_dc_ref}=0.5$.

The reference dq voltage of DPFC series converter (no FSO control) which used in dq components series converter generation have been shown in Fig. 8. The PLL needs the line current as an input, in order to calculate the angle for Park's inverse transformer. Finally, the Park's inverse transformer will generate the series converter voltage, in order to get into the phase-A voltage as shown in Fig. 9. The inputs, using in the DPFC series unit, the voltage will be improved. Fig. 10 shows the voltage, with much sag and fluctuation before using the DPFC series converters in phase-A. It, shows the improved voltage of phase-A with no fluctuation and harmonic, obtained using the DPFC series converter in phase-A.

As pointed-out in [61], the most important DPFC drawback is disturbance or communication failure, series converters may lose their synchronization with the grid, leading to power transmission failure. Accordingly, it is important to find a new method for determining a reliable means of communication between the central controller and the distributed series converters.

In Fig. 11 for showing the disturbance on the one of the central controller signals (V_d), comparing to Fig. 8, the V_d have been changed while V_q have been not changed. In Fig. 12 could see amplitude changes in step time of 0.2 sec and so could see a few voltage sags, because the system could not organize and adjust itself with disturbances of V_d signal.

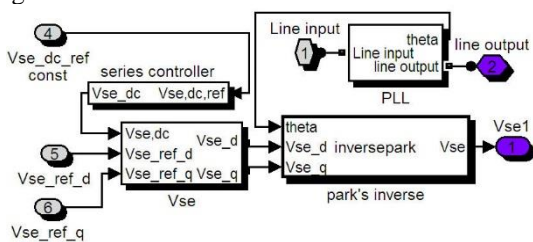


Fig. 7. Elements of FSO-DPFC series unit simulation by Matlab/Simulink

Table 4

Power system specification which has been used for simulation

Parameters	Volt.(ph-ph rms) (PU)	Freq. (HZ)	Additional description
Gen.(3-ph Source)	1(220V)	60	Angle= 3 degree
3-ph Load	1(220V)	60	Y(ground), P=10, Q _L =10 3-ph,
Line	-	60	0.386(ohm/Km), 4(mH/Km), 7(nF/Km), 100 (Km)

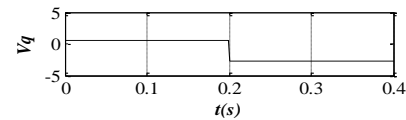
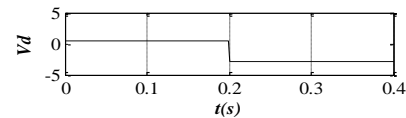


Fig. 8. dq reference voltages of series converter

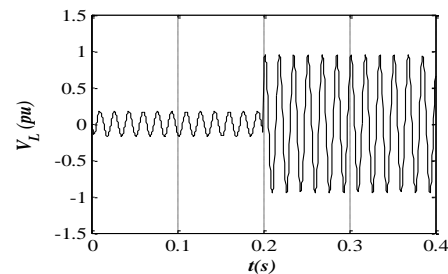


Fig. 9. Line voltage of phase-A before series converter

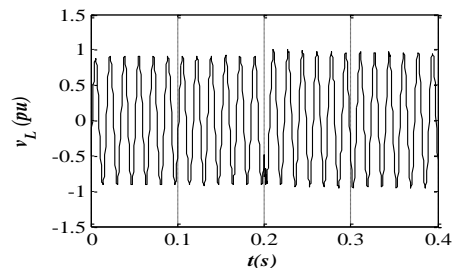


Fig. 10. Line voltage of phase-A, after using series converter

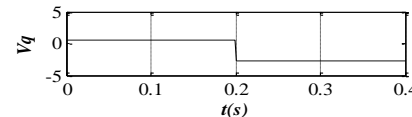
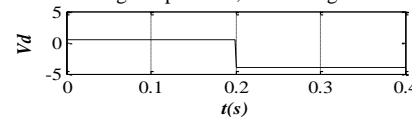


Fig. 11. Changing of the V_d traditional DPFC component (disturbance)

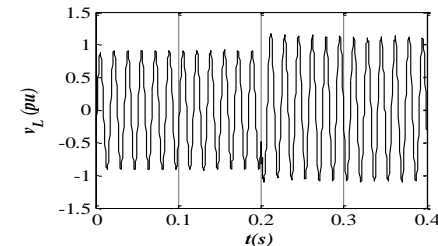


Fig. 12. Result of d components changing (disturbance) in DPFC

While as shown in Fig. 5, we have used FSO controller as a V_q control signal producer. Which FSO controller produce suitable V_q control signal according to line voltage and V_d to compensate V_d disturbances effects on transmission line voltage. So have been shown the V_d in Fig. 13 with same

properties of Fig. 8. In Fig. 15 the shown V_q component is the FSO controller output which applied in to the DPFC for V_q component. Fig. 14 shows the suitable line voltage response which is the result of using FSO-DPFC. Fig. 15 shows the V_d with same properties of Fig. 11. In Fig. 15 the shown V_q component is the FSO controller output which applied in to the DPFC for V_q component. Fig. 16 shows the suitable line voltage response which is the result of using FSO-DPFC. We couldn't see any amplitude changing and voltage sag in Fig. 16 opposite with Fig. 12, while V_d component in both cases (Fig. 11, Fig. 15) have the same properties and comparing to Figs. 8 and 13 because of system error or disturbance, the V_d control signal amplitude have been changed. This segment shows that the line voltage improves using the DPFC series converter which is the segmentation TRIZ technique and FSO-DPFC improves the traditional DPFC in cases which control signal has disturbance.

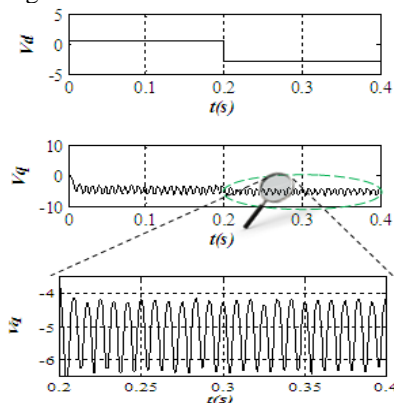


Fig. 13. V_d , V_q components of FSO-DPFC

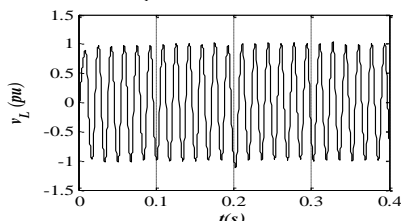


Fig. 14. Line voltage by using the FSO-DPFC and V_d signal

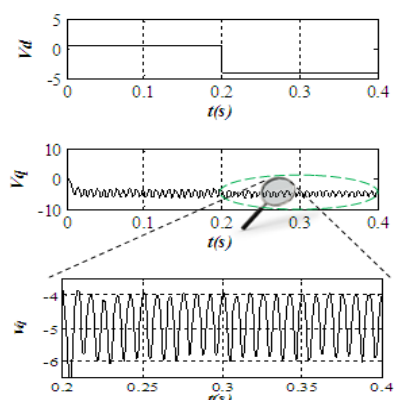


Fig. 15. V_d , V_q components of FSO-DPFC

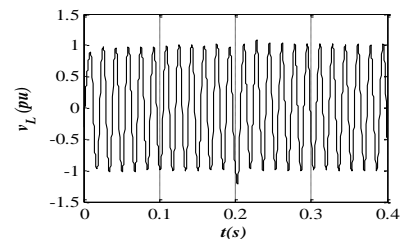


Fig. 16. Line voltage by using the FSO-DPFC while V_d component of control signal have been had disturbance

6. Conclusion

This paper presented the thinking background behind the DPFC design by using TRIZ "segmentation" principle method. It was shown using TRIZ principle in the UPFC has some advantages in DPFC compared to UPFC. These included decreasing converters location space, lower the cost and increase the reliability and flexibility of the system.

The most important problem in traditional DPFCs is disability of system to provide suitable response where there are some disturbances in the control signals; accordingly, by changing the V_d of central control (as a central control signal disturbance), could see changes in simulation results. While by using the innovatively fuzzy self-organized controller in the DPFC can overcome to this problem and get the suitable response without the central control disturbances effects on the transmission line voltage (V_L).

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