

A Comparison of Conventional, Direct-Output-Voltage and Fuzzy-PI Control Strategies for D-STATCOM

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Abstract—This paper investigates and implements conventional and advanced methods for the control of D-STATCOM. The mathematical model of conventional double loop control, Direct-Output-Voltage (DOV) control, Decoupled DOV, Fuzzy-PI and Decoupled Fuzzy-PI based control is studied. The control scheme for the above approaches is implemented using Matlab Simulink platform. The dynamic response of the models are presented and compared.

Index Terms— Control , D-STATCOM, Fuzzy-PI, Voltage source converters.

I. INTRODUCTION

NON-LINEAR loads used in industries, adversely effect the quality of power delivered to consumers. One of the most common effects of deteriorating power quality is that of voltage fluctuation which causes flickering of domestic lightings and negatively influences appliances on distribution and transmission systems. With the development of power electronic devices, several solutions for the above problem have been proposed [1].

The power electronic devices used to mitigate this problem are basically voltage source converter (VSC) based devices, connected in series or parallel with the transmission line and controlled using a digital controller. One of the many applications of VSCs is static synchronous compensator (STATCOM). The main function of a STATCOM in transmission and distribution networks is to regulate the line voltage at the point of common coupling (PCC). It achieves this objective by drawing controlled reactive current from the line. In contrast to conventional static reactive power generators such as static VAR generators (SVC), STATCOM also has an intrinsic ability to exchange active power with the line. To effectively improve STATCOM performance, researchers have mainly concentrated on its topology and control strategy.

Depending on the power system parameter to be controlled, various control strategies have been proposed for STATCOM which can be used for bus voltage regulation, reactive power compensation and power factor correction [2]-[5]. The output voltage control strategies of STATCOM are mainly classified into two types: (a) phase angle control – in which the modulation index of pulse-width modulated VSC is kept constant and phase angle acts as the control input ; (b) hybrid

control – in which both phase angle and modulation index are controlled.

In the aspect of hybrid control strategy, Schauder and Mehta [4] have proposed a typical double loop control strategy, where outer loop gives desired active and reactive currents to control PCC voltage and the inner loop realizes control of inverter currents with zero steady state errors. Both current and voltage sensors are required in this strategy resulting in four PI controllers. Further in this category, Chen and Hsu [3] have given a direct-output-voltage (DOV) control strategy for the STATCOM to eliminate the active and reactive current feedback loops. Two PI controllers are required in this for the voltage control loop. The STATCOM output voltage is computed using an algebraic algorithm based on power balancing principle. In both the above strategies, a coupling relationship exists between the active and reactive currents. To improve the system control performance, a novel fuzzy-PI-based DOV control strategy for STATCOM used in utility distribution systems has been proposed in [2]. The strategy employs a decoupling control loop for obtaining decoupled active and reactive currents.

This paper evaluates the Double loop control strategy [4], DOV control strategy [3], Fuzzy-PI-based DOV and Decoupled DOV and Decoupled fuzzy-PI-based DOV [2] for STATCOM used in distribution system. The control scheme for these strategies is studied and implemented using Matlab Simulink. The dynamic response of the models are presented and compared.

II. SYSTEM CONFIGURATION AND STATCOM DYNAMIC MODEL

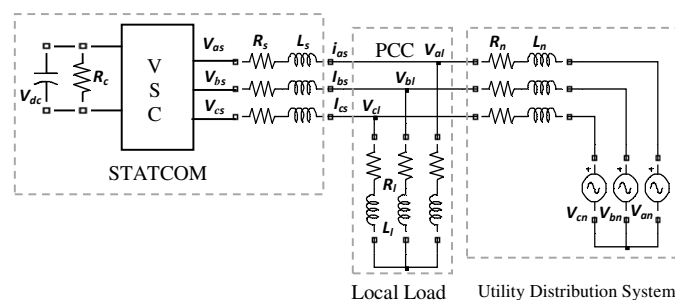


Fig 1. STATCOM connected to load and distribution system

Fig. 1 shows the single line diagram of STATCOM connected to the utility distribution system where L_s represents leakage inductance of actual coupling transformer; R_s gives conduction losses of the inverter and the coupling transformer; R_c denotes the sum of switching losses in inverter and power losses in the capacitor; R_l, L_l local load.

For a balanced three phase system, the three phase voltages and currents can be described as –

$$f_{a=} |f| \cos(\omega t + \theta_s) \quad (1)$$

$$f_{b=} |f| \cos\left(\omega t + \theta_s - \frac{2\pi}{3}\right) \quad (2)$$

$$f_{c=} |f| \cos\left(\omega t + \theta_s + \frac{2\pi}{3}\right) \quad (3)$$

Transforming the a - b - c co-ordinates to q - d - 0 co-ordinates using Park's transformation, we get –

$$f_{qdo} = P \cdot f_{abc} \quad (4)$$

Where,

$$P = \frac{2}{3} \begin{bmatrix} \cos(\omega t + \theta) & \cos\left(\omega t + \theta - \frac{2\pi}{3}\right) & \cos\left(\omega t + \theta + \frac{2\pi}{3}\right) \\ \sin(\omega t + \theta) & \sin\left(\omega t + \theta - \frac{2\pi}{3}\right) & \sin\left(\omega t + \theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Substituting (1) – (3) into (4), we have –

$$f_{q=} |f| \cos(\theta - \theta_s) \quad (5)$$

$$f_{d=} |f| \sin(\theta - \theta_s) \quad (6)$$

From fig 1. Following dynamic equation can be obtained:

$$\left. \begin{aligned} L_s \frac{di_{as}}{dt} &= -R_s i_{as} + v_{as} - v_{al} \\ L_s \frac{di_{bs}}{dt} &= -R_s i_{bs} + v_{bs} - v_{bl} \\ L_s \frac{di_{cs}}{dt} &= -R_s i_{cs} + v_{cs} - v_{cl} \end{aligned} \right\} \quad (7)$$

By using abc-dq transformation with its d-axis aligned to the voltage vector of the PCC [4], equation (7) can be described in synchronously rotating reference frame as –

$$\left. \begin{aligned} L_s \frac{di_{ds}}{dt} &= -R_s i_{ds} + \omega L_s i_{qs} + v_{ds} - v_{dl} \\ L_s \frac{di_{qs}}{dt} &= -R_s i_{qs} - \omega L_s i_{ds} + v_{qs} - v_{ql} \end{aligned} \right\} \quad (8)$$

Where, $i_{ds}, i_{qs}, v_{ds}, v_{qs}$ denote d - and q -axis STATCOM output currents and voltages respectively; ω is the synchronously rotating angle speed of the voltage vector of PCC; v_{dl}, v_{ql} are the load voltages.

III. CONTROL STRATEGIES

A. Double Loop Control Strategy

Using classical phasor definition of [4], under balanced steady-state condition, the instantaneous active and reactive power of load are given by

$$\left. \begin{aligned} P_l &= \frac{3}{2}(v_{dl} i_{ds} + v_{ql} i_{qs}) \\ Q_l &= \frac{3}{2}(v_{dl} i_{qs} - v_{ql} i_{ds}) \end{aligned} \right\} \quad (9)$$

Consider a new synchronous reference frame such that the d -axis is always coincident with the voltage vector of PCC and the q -axis is in quadrature with it [4]. For this, substituting $\theta = \theta_s + \pi/2$ in (5) and (6), we get-

$$\left. \begin{aligned} v_{dl} &= |v| \\ v_{ql} &= 0 \end{aligned} \right\} \quad (10)$$

Substituting (10) in (8), we get,

$$\left. \begin{aligned} L_s \frac{di_{ds}}{dt} &= -R_s i_{ds} + \omega L_s i_{qs} + v_{ds} - v_{dl} \\ L_s \frac{di_{qs}}{dt} &= -R_s i_{qs} - \omega L_s i_{ds} + v_{qs} \end{aligned} \right\} \quad (11)$$

Substituting (10) in (9), we get,

$$\left. \begin{aligned} P_l &= \frac{3}{2}(v_{dl} i_{ds}) \\ Q_l &= \frac{3}{2}(v_{dl} i_{qs}) \end{aligned} \right\} \quad (12)$$

Thus, active power can be controlled by controlling d -axis current (i_{ds}) and reactive power by controlling q -axis current (i_{qs}).

From (11) and (12), the schematic configuration for double loop control strategy [4] is as shown in the Fig 2.

B. Direct-Output-Voltage (DOV) Control Strategy

Using the power balancing principle [3], the instantaneous output power of STATCOM ($P_s + jQ_s$) is the sum of power consumed by R_s, L_s ($P_{RL} + jQ_{RL}$) and power delivered to the load ($P_l + jQ_l$).

$$\left. \begin{aligned} P_s &= P_{RL} + P_l \\ Q_s &= Q_{RL} + Q_l \end{aligned} \right\} \quad (13)$$

The instantaneous output power of STATCOM is given by

$$\left. \begin{aligned} P_s &= \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \\ Q_s &= \frac{3}{2}(v_{ds} i_{qs} - v_{qs} i_{ds}) \end{aligned} \right\} \quad (14)$$

The instantaneous power consumed by R_s and L_s is expressed as [3]

$$\left. \begin{aligned} P_{RL} &= \frac{3}{2} R_s i^2 = \frac{3}{2} R_s (i_{ds}^2 + i_{qs}^2) \\ Q_{RL} &= \frac{3}{2} \omega L_s i^2 = \frac{3}{2} \omega L_s (i_{ds}^2 + i_{qs}^2) \end{aligned} \right\} \quad (15)$$

Substituting (12), (14), (15) into (13) we get,

$$\left. \begin{aligned} v_{ds} &= R_s i_{ds} - \omega L_s i_{qs} + v_{dl} \\ v_{qs} &= R_s i_{qs} + \omega L_s i_{ds} \end{aligned} \right\} \quad (16)$$

Thus, the output voltage commands of STATCOM (v_{ds}, v_{qs}) can be obtained by controlling the STATCOM current commands (i_{ds}, i_{qs}), R_s, L_s and v_{dl} as shown in Fig. 3.

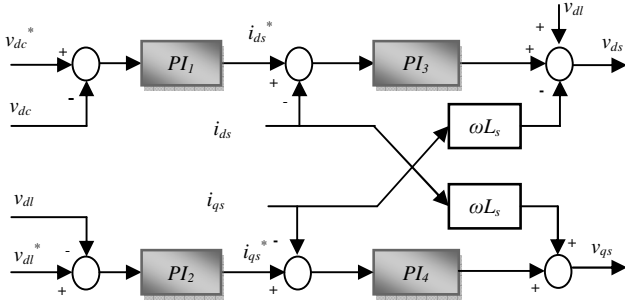


Fig. 2. Schematic configuration of double-loop control strategy

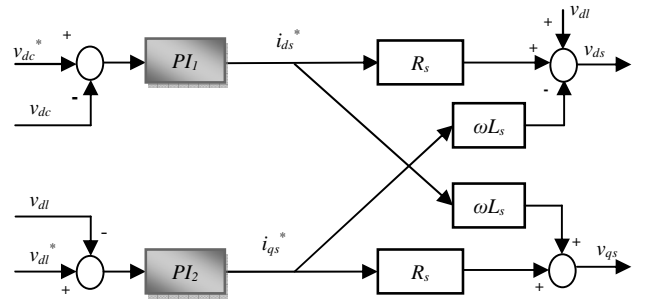


Fig. 3. Schematic configuration of DOV control strategy

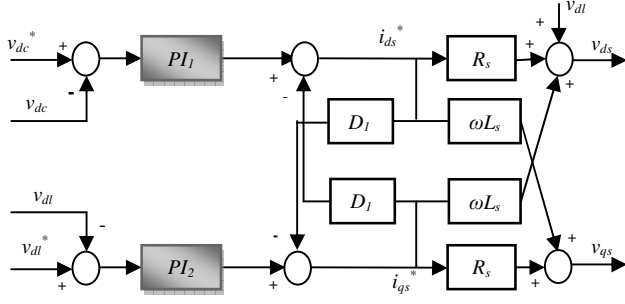


Fig. 4. Schematic configuration of Decoupled DOV control strategy

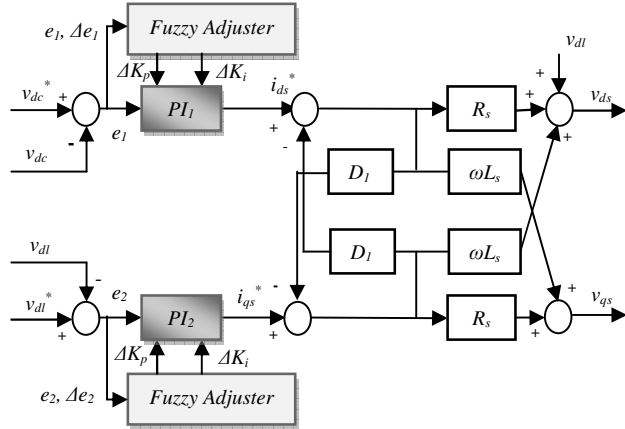


Fig. 6. Schematic of Decoupled Fuzzy-PI-based-DOV control strategy

C. Decoupled DOV Control Strategy

From Fig. 2 and Fig. 3, a coupling relationship exists between the active and reactive voltage commands of STATCOM. This is due to i_{ds} and i_{qs} . To cancel out the interaction effects due to i_{ds} and i_{qs} on regulating dc-link voltage and maintaining PCC voltage, a decoupler can be introduced in the circuit as [2]. In order to achieve decoupling control following equation has been suggested in [2] –

$$\frac{1}{D_1 D_2 - 1} \begin{bmatrix} R_s & -\omega L_s \\ \omega L_s & R_s \end{bmatrix} \begin{bmatrix} -1 & D_2 \\ D_1 & -1 \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \quad (17)$$

Where, the decoupler as derived in [2] is,

$$\left. \begin{aligned} D_1 &= \frac{\omega L_s}{R_s} \\ D_2 &= -\frac{\omega L_s}{R_s} \end{aligned} \right\} \quad (18)$$

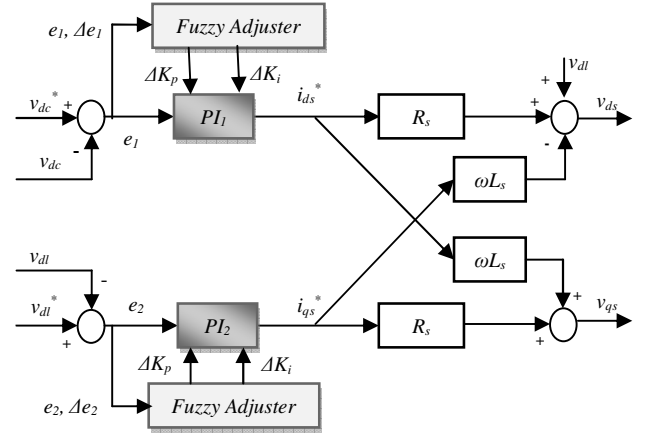


Fig. 5. Schematic configuration of Fuzzy-PI-based-DOV control strategy

The schematic configuration of Decoupled DOV control strategy [2] is as shown in Fig 4.

D. Fuzzy-PI-based-DOV Control Strategy

To improve the static and dynamic performance of STATCOM, a fuzzy adjuster can be added to the PI controllers of control system Fig. 4. The fuzzy-PI controllers are used to regulate the dc-link voltage and maintain the PCC voltage as shown in the schematic configuration in Fig. 5.

Error e and change in error Δe act as inputs to the fuzzy adjuster. Outputs of fuzzy ΔK_p and ΔK_i are added with the corresponding outputs K_p^* and K_i^* of PI controller, i.e.,

$$\left. \begin{aligned} K_p &= K_p^* + \Delta K_p \\ K_i &= K_i^* + \Delta K_i \end{aligned} \right\} \quad (19)$$

The input and output membership functions used for the fuzzy variables are as shown in Fig. 7 below.

The seven fuzzy sets used for the fuzzy variables are: negative big (NB), negative medium (NM), negative small (NS), zero (0), positive small (PS), positive medium (PM) and positive big (PB).

The fuzzy control rules that have been used to tune ΔK_p and ΔK_i are based on the following important factors [2].

- 1) For large value of $|e|$, a large ΔK_p is required and vice versa.
- 2) For $e \cdot \Delta e > 0$, a large ΔK_p is required and vice versa.

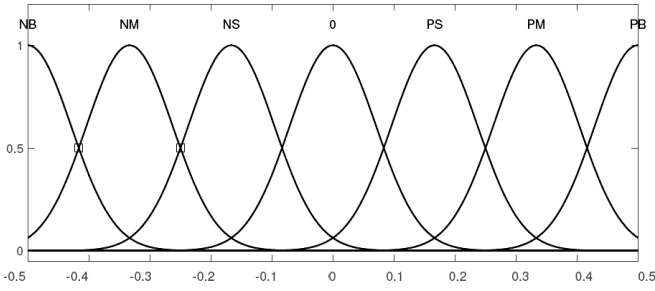


Fig. 7. Membership functions of fuzzy variables

- 3) For large values of $|e|$ and $|\Delta e|$, ΔK_i is set to zero, to avoid control saturation.
- 4) For small value of $|e|$, ΔK_i is effective and ΔK_i is larger when $|e|$ is smaller, which is better to decrease the steady state error.

From the above observations, the tuning rules for ΔK_p and ΔK_i can be obtained as in [2].

The inference method used is the MAX-MIN method. Center of gravity method has been employed to defuzzify the fuzzy variables.

E. Decoupled Fuzzy-PI-based-DOV Control Strategy

Similar to the Decoupled DOV control strategy of Fig. 4, a decoupler can be introduced in the schematic of Fuzzy-PI-based DOV control of Fig. 5. The decouplers D_1 and D_2 are derived as in [2] equations (17) and (18). The schematic configuration of the Decoupled Fuzzy-PI-based-DOV control strategy is as shown in Fig. 6 above.

IV. SYSTEM AND CONTROLLER MODELS

A. System Model

The single line diagram of the system under consideration [5] is as shown in Fig. 8 below.

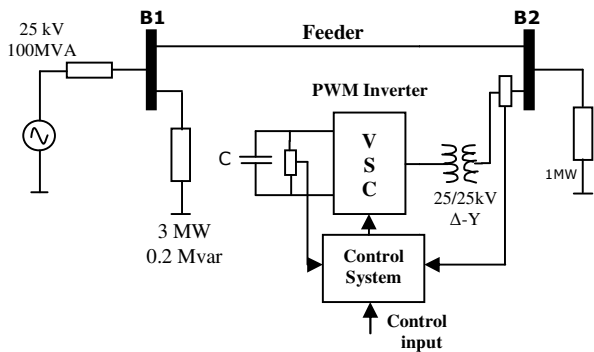


Fig. 8 Single-line diagram of a D-STATCOM connected to distribution system

A 25kV, 100MVA source at bus 1 (B1) is connected to the 1MW load at bus 2 (B2) through a 21-km feeder. A step down transformer of 25kV/600V is connected between B2 and 1MW load through feeder of 2km.

The D-STATCOM mainly consists of voltage source PWM inverter made up of two IGBT bridges. Dc-link voltage is obtained from a 10000 μ F capacitor. The D-STATCOM output

is connected in parallel to the network at PCC (B2) through a step up 25/25kV Δ -Y transformer.

A sinusoidal PWM inverter of carrier frequency 1680 Hz is used to generate pulses for both the IGBT bridges.

B. Controller Model

From the schematic configurations of the control strategies (Fig. 2 to Fig. 6), the control system of D-STATCOM is as shown in Fig. 9.

A discrete 3-phase phase-locked-loop (PLL) circuit is used for obtaining the synchronous reference ($\sin \omega t$ and $\cos \omega t$) necessary for abc - dq transformation.

The measurement block computes the d - and q - axis components of voltages and currents from their corresponding 3-phase values.

To regulate the voltage at the PCC (B2) bus, an ac voltage regulator is used. The error signal generated from the measured and reference value of ac voltage is given to a PI or Fuzzy-PI controller (Fig. 2 to 6) which in turn produces I_q reference for the current regulator.

Similar to the ac voltage regulator, I_d reference, produced by the dc voltage regulator, acts as an input to the current regulator block.

To generate the d - and q - axis components of voltages, the current regulator can use two PI controllers as in Fig. 2 for double loop control strategy or the schematics in Fig. 3 to 6.

Modulation index m and phase angle ϕ , obtained from the d - and q - axis components of voltages are then given to the sinusoidal PWM inverter to generate the pulses for the two IGBT bridges.

All the parameters used in the simulation are shown in Appendix I.

V. CASE STUDY

To compare the dynamic performance of system under the various control strategies (III. A to III. E), several simulation studies are carried out using MATLAB/Simulink.

Case 1: In this case, a voltage drop at the PCC is obtained by switching on an inductive load of 10Mvar at 0.2s, while a swell at PCC is obtained by removing the load at 0.4s. Fig. 10 and Fig. 11 show the comparison of the response curves for PCC voltage and dc-link voltage respectively for the various control strategies (Fig. 2 to Fig. 6). It is clear from the response curves that the startup overshoot (0 to 0.05s) for the PCC voltage and the dc-link voltage is maximum for Double Loop control strategy and minimum for decoupled Fuzzy-PI-based DOV control strategy. Fig. 12 shows a comparison of control strategies for PCC voltage and dc-link voltage at startup. Also, from 0.2s to 0.4s when the inductive load is on, the PCC voltage for Double Loop control is 0.99 p.u. whereas for the other control strategies (Fig. 3 to 6) is nearly equal to 1 p.u.

Case 2: In this case, the source voltage is decreased by 0.1p.u. from 0.2s to 0.4s. Fig. 13. shows the response curves for the PCC voltage under Double Loop, DOV and Fuzzy-PI control strategies.

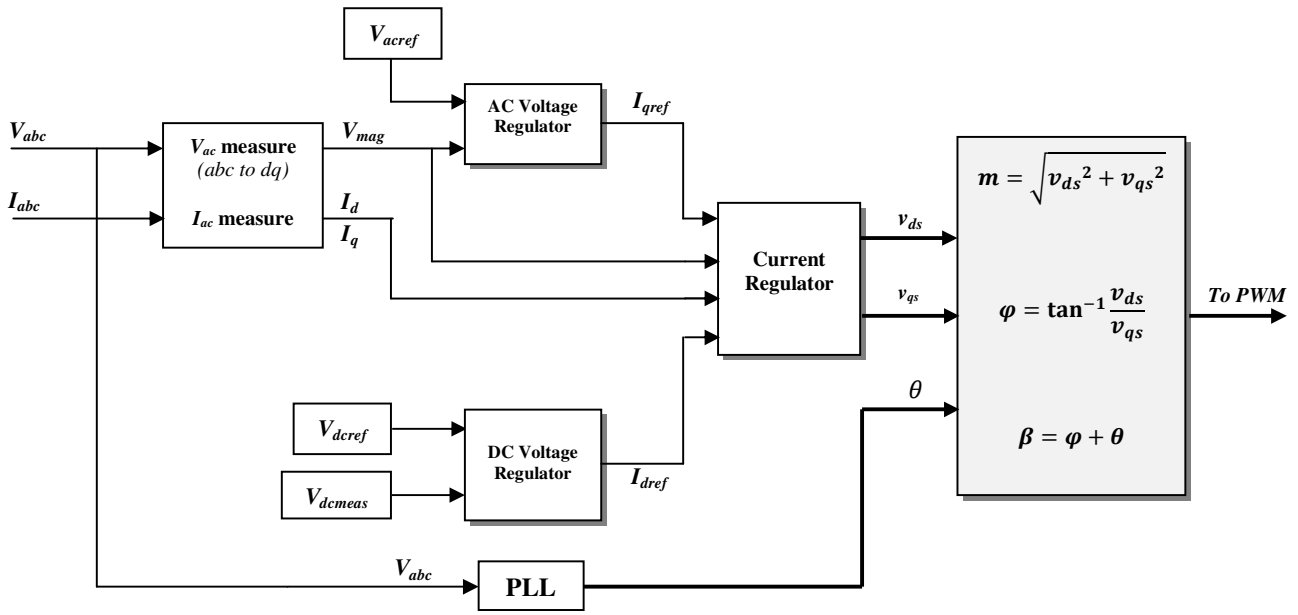


Fig. 9. D-STATCOM Control System

It can be observed from the simulations of Fig. 13 that as compared to the double loop control, DOV and fuzzy-pi offer improved PCC voltage when the source voltage is decreased by 0.1 p.u. from 0.2s to 0.4s.

A comparison of the performance between Double Loop control and Decoupled Fuzzy-PI based DOV control for *startup, case 1* and *case 2* has been quantified in Table I.

VI. SIMULATION RESULTS

Case 1: Inductive load of 10Mvar from 0.2s to 0.4s

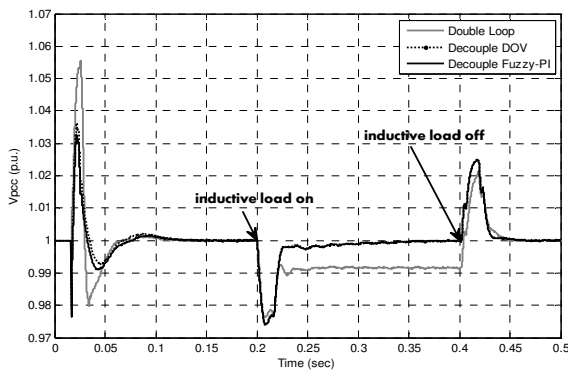
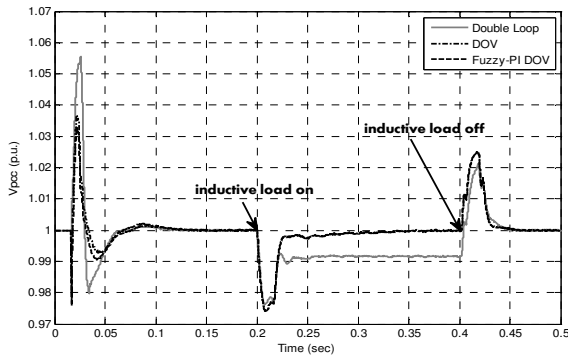


Fig 10. Response curves of PCC voltage (B2 bus)

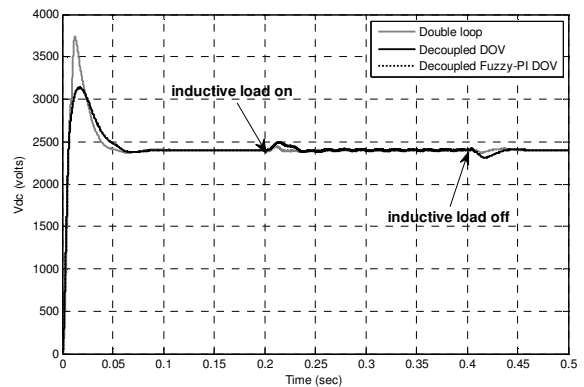
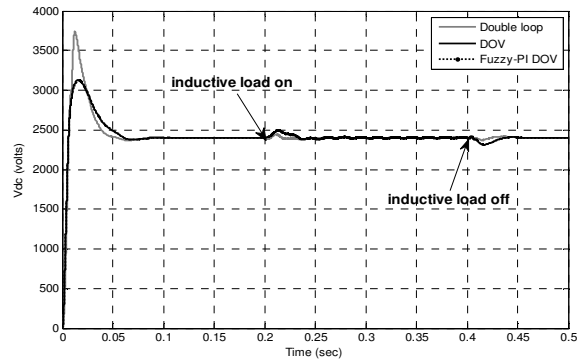


Fig 11. Response curves of v_{dc}

VII. CONCLUSION

This investigation and implementation of conventional and advanced control strategies for D-STATCOM gives the following conclusions. As Double Loop Control strategy has four PI controllers, tuning has to be done empirically or by trial and error method which is time consuming. DOV control strategy requires only two PI controllers as compared to Double Loop. The settling time and maximum peak (Fig. 12) using Decoupled Fuzzy-PI-based DOV control are much lower than Double Loop control. The fuzzy controllers can be further tuned to effectively improve the dynamic performance of the system in case of Fuzzy-PI DOV and Decoupled Fuzzy-PI DOV control strategies.

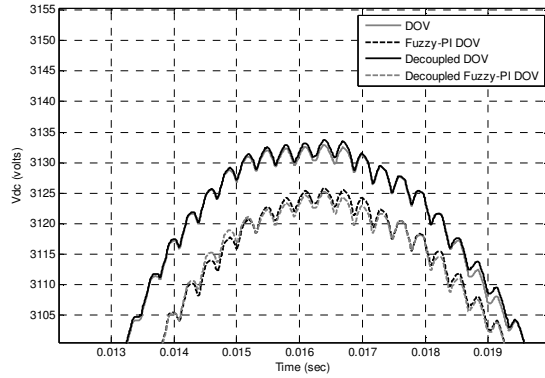
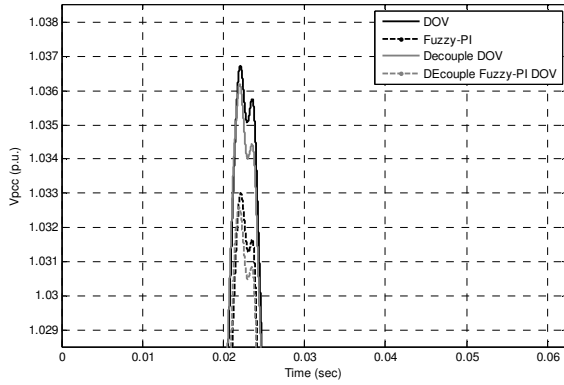


Fig 12. Response curves for V_{pcc} and V_{dc} at startup

Case 2: Source voltage decreased by 0.1 p.u. (0.2 to 0.4s)

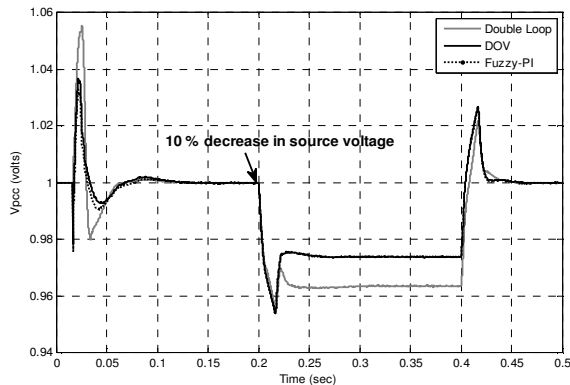


Fig 13. Response curves for V_{pcc}

TABLE I

COMPARISON OF SIMULATION RESULTS

Performance Specification		Double Loop Control		Decouple Fuzzy-PI	
		V_{dc}	V_{pcc}	V_{dc}	V_{pcc}
Startup	Settling Time (s)	0.111 (s)	0.12 (s)	0.094 (s)	0.12 (s)
	Max. peak (Volts / p.u.)	3748 (V)	1.0555 (p.u.)	3125 (V)	1.0326 (p.u.)
Load / Source Variation		V_{pcc} (p.u.)		V_{pcc} (p.u.)	
Case 1	at 0.25 s	0.991		0.997	
	at 0.35 s	0.9914		0.9998	
Case 2	at 0.25 s	0.9630		0.9744	
	at 0.35 s	0.9635		0.9740	

APPENDIX I

AC Source	25kV, 100MVA, 60Hz
Load	1MW
Transformer (load side)	25kV/600V (Δ -Y)
DC Capacitor C	10,000 μ F
DC-link Voltage	2400V
Carrier frequency	1680 Hz
Kind of PWM	SPWM
AC regulator gains	$K_p=0.52$; $K_i=2490$
DC regulator gains	$K_p=0.001$; $K_i=0.15$

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