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Fuzzy-Pi Based Direct-Output-Voltage Control Strategy for Statcom Used In Utility Distribution System

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Abstract: *This paper describes the control strategy for the static synchronous compensator (STATCOM) used in utility distribution systems is investigated, fuzzy-PI-based direct output-voltage (DOV) control strategy is presented. Based on power balancing principle, this DOV control strategy cannot only reduce the active and reactive current control loops of a conventional double-loop control strategy but also achieve to regulate dc-link voltage and maintain the voltages at the point of common coupling (PCC). In order to effectively improve the immunity capability of this DOV control strategy to the uncertainties in system parameters, two fuzzy PI controllers are separately employed to maintain the voltages at the PCC and to simultaneously regulate dc-link voltage. The mathematical model of conventional double loop control, Direct-Output-Voltage (DOV) control, Fuzzy-PI based control is studied. The control scheme for the above approaches is implemented using MATLAB Simulink platform. The simulation results of the models are presented and compared.*

Keywords: *Converters, MATLAB, fuzzy control, static VAR compensators*

I. Introduction

Recently, with the growth of nonlinear loads in industrial manufactures, the electric power quality has become more and more important. As one of the most common issues about the electric power quality, voltage fluctuations influence domestic lighting and sensitive apparatus in transmission and distribution systems [3].

As a key component for the implementation of a flexible ac transmission system, the main function of a static synchronous compensator (STATCOM) is to regulate the voltages at the point of common coupling (PCC) in transmission and distribution systems. It achieves such an objective by drawing controllable reactive currents from power systems. In contrast with other traditional static reactive power generators, such as the static VAR compensator using thyristor-controlled reactors, the STATCOM also has an intrinsic ability to exchange active power with power systems. To effectively improve the STATCOM performance, previous researchers mainly focus on its topology and control strategy.

In large-capacity applications, multi-pulse inverters, such as 24- and 48-pulse inverters, are widely used to achieve lower harmonic distortions [4] [5].Electromagnetic interfaces constituted by complex phase-shifting transformers, however, are required to connect multi-pulse inverters and power systems. Therefore, many inherent benefits of multilevel inverters have led to an increasing interest in the STATCOM applications. At present, there are four multilevel configurations: diode-clamped (neutral point clamed)[6], flying capacitor [7], cascade H- bridge[8], and hybrid multilevel inverters[10]. Two technical challenges in the application of multilevel inverters, nevertheless, are the unbalanced voltages across dc-link capacitors and lots of sensors to measure every dc link voltage [11]. In recent years, significant progresses have been made in power Semiconductor technologies, which results in an emergence of the 4.5-kV insulated-gate bipolar transistor. This development of power devices helps to apply the STATCOM with a two-level inverter in utility distribution systems.

In the double –loop control strategy, the outer loop forms the desired active and reactive current commands to maintain the voltages at the PCC and to compensate the STATCOM losses, and the inner loop realizes to control inverter currents with zero steady-state errors. However, this control strategy not only needs four PI controllers in its control system so that the tuning of PI parameters should be done empirically or by trial and error, but also has a coupling relationship between the active current and the reactive current, and thus, it is hard to maintain the voltages at the PCC with small effects on the dc-link voltage. To obtain decoupling control, nonlinear control strategies are widely used by linearized models via the feedbacks near steady-state operating points [13]. However, it is not easy to tune controller parameters because these approaches still need four PI controllers. Based on power balancing principle [14] have given a direct-output-voltage (DOV) control strategy for the STATCOM to reduce its active and reactive current control loops. However, this control strategy does not implement the decoupling control, and its control performance may not be satisfactory due to the uncertainties in system parameters. Therefore, a novel fuzzy-PI-based DOV control strategy for the STATCOM used in utility distribution systems is proposed.

FACTS device like STATCOM can improve the power quality issues and reduced the voltage sags and swells. To maintain the voltage at PCC two level inverter with STATCOM can be used due to difficulties with multilevel inverter. Double loop & DOV control techniques are used to improve the voltage profile .As compared to double loop strategy, DOV control strategy needs only two PI controllers & outer loop should be removed hence we can achieve better voltage profile at PCC. For better voltage profile than DOV control system decoupled fuzzy PI technique is used because in this strategy two limiters are included to avoid overload operations.

II. System Configuration And Statcom Dynamic Model

A. System Configuration

Fig-1 shows the STATCOM configuration applied to the PCC of a utility distribution system which is represented by a three-phase voltage source behind series resistance (*Rn*) and inductance (*Ln*) in each phase. The STATCOM system in parallel with a three phase *RL* local load consists of a dc-link capacitor, a two-level inverter, and series resistances (*Rs*) as well as inductances (*Ls*) in three lines connecting to the PCC. In this circuit, *Ls* accounts for the leakage inductance of an actual coupling transformer, *Rs* represents conduction losses of the inverter and the coupling transformer, and *Rc* denotes the sum of switching losses in the inverter and power losses in the capacitor.

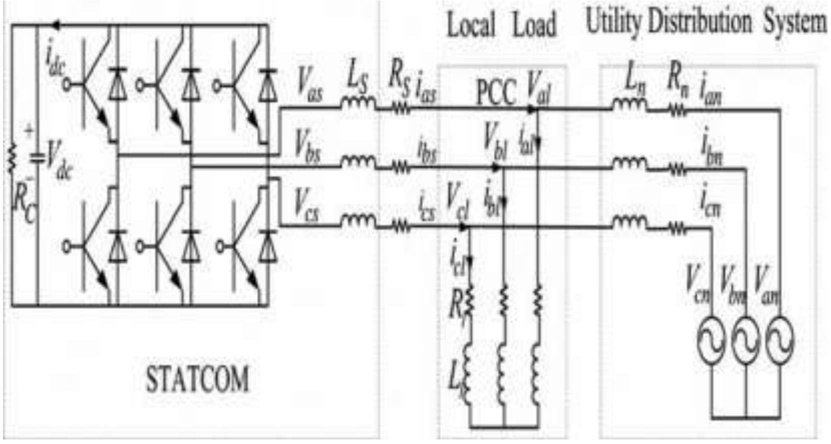

Fig1: Schematic representation for a two-level STATCOM connected to the PCC of a utility distribution system

B. Statcom Dynamic Model

In this section, a mathematical model for the STATCOM system in Fig-1 is developed to deduce the conventional double-loop control strategy and an improved DOV control strategy. In terms of Fig-1, the following dynamic equations can be obtained:

Ls dias/dt = -Rsias + Vas -Val…(1)

Ls dibs/dt = -Rsibs + Vbs -Vbl…(2)

Ls dics/dt = -Rsics + Vcs –Vcl…(3)

By using the abc−dq transformation with its d-axis aligned to the voltage vector of the PCC, full equations in (1),(2),& (3) can be described in the synchronously rotating reference frame as follows:

Ls dids/dt = -Rsids+wLsiqs + Vds -Vdl…(4)

Ls diqs/dt = - Rsiqs-wLsids + Vqs –Vql…(5)

Where ids and iqs represent the d- and q-axis currents, which correspond to three-phase STATCOM output currents (ias, ibs, and ics); ω is the synchronously rotating angle speed of the voltage vector of the PCC; vds and vqs account for the d- and q-axis voltages, which correspond to three-phase STATCOM output voltages (vas, vbs, and vcs); and vdl and vql denote the d- and q-axis voltages, which correspond to three-phase load voltages (val, vbl, and vcl), namely, the voltages at the PCC (vPCCa, vPCCb, and vPCCc).

III. Conventional Double-Loop And Improved Dov Control Strategy

A. Conventional Double-Loop Control Strategy and Its Characteristics

In a typical double-loop control strategy, the outer loop forms the desired active and reactive current commands to maintain the voltages at the PCC and to compensate the STATCOM losses, and the inner loop realizes to control inverter currents with zero steady-state errors. Double-loop control algorithm provide a current inner loop, and a capacitor voltage outer loop. To provide control of the current inner loop, proportional-integral (PI) and resonant controllers are used.

According to the definitions of instantaneous active and reactive power, the instantaneous power of load terminal is given as follow:

pl = $\frac{3}{2}$ (Vdlids + Vqliqs)… (6)

ql = $\frac{3}{2}$ (Vdliqs - Vqlids)… (7)

Where a constant 3/2 is chosen so that the definition coincides with the classical phasor definition under a balanced steady state condition[12].

Considering that the *d*-axis is always coincident with the voltage vector of the PCC and the *q*-axis is in quadrature with it, the following equation can be obtained:
Vql = 0…(8)

Therefore, equations (4) to (6) can be separately simplified as follow:
Ls dids/dt = -Rsids+wLsiqs + Vds -Vdl…(9)

Ls diqs/dt = - Rsiqs-wLsids + Vqs…(10)

pl = $\frac{3}{2}$ Vdlids…(11)

ql = $\frac{3}{2}$ Vdliqs…(12)

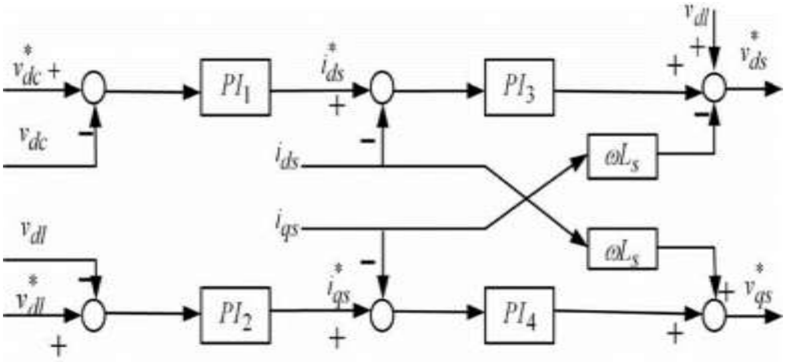

Fig-2: Schematic configuration of the double-loop control strategy

Apparently, we can achieve to control the active power by controlling the *d*-axis current (*i*ds) and to regulate the voltages at the PCC (namely to control the reactive power) by controlling the *q*-axis current (*i*qs).

Based on the aforementioned analysis results and formulas (9) to (12), the conventional double-loop control strategy can be obtained, which is shown in Fig.2 (resistances in formula (9) & (10) are neglected for simplicity) [12].

From Fig.2, some characteristics of the double-loop control strategy can be concluded in the following:

1) The *d*- and *q*-axis currents (i.e., *i*ds and *i*qs) are coupled with each other; thus, it is difficult to independently maintain the voltages at the PCC with small impacts on the dc-link voltage. That is to say, the STATCOM system cannot quickly compensate the required reactive power.

2) There are four PI controllers in the STATCOM control system; therefore, the tuning of PI parameters should be achieved empirically or by trial and error.

Any change in the load affects the dc-link voltage directly. The sudden removal of load would result in an increase in the dc-link voltage above the reference value, whereas a sudden increase in load would reduce the dc-link voltage below its reference value. By this way any change in load would affect dc –link voltage, therefore voltage at PCC is hard to maintain.

B. DOV Control Strategy and Its Characteristics

Similar to the analysis method mentioned earlier, the instantaneous output power of the STATCOM system can be obtained as:

ps = $\frac{3}{2}$ (Vdsids + Vqsiqs) … (13)

qs = $\frac{3}{2}$ (Vdsiqs - Vqsids) … (14)

The instantaneous power consumed by the connecting resistance *Rs* and the connecting inductance *Ls* can be expressed as:

pRL = $\frac{3}{2}$ R��(ids^2 + iqs^2) … (15)

qRL = $\frac{3}{2}$ ��L��(ids^2 + iqs^2) … (16)

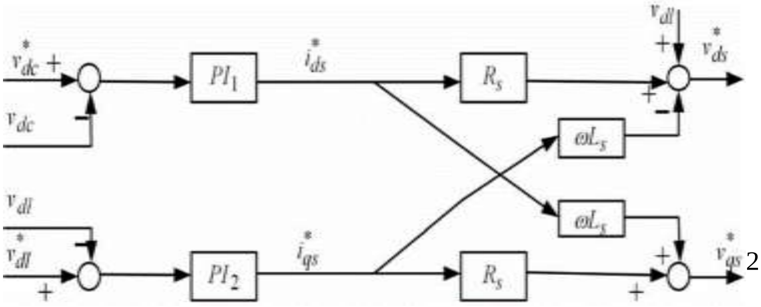

Fig 3 Schematic configuration of the DOV control strategy

According to power balancing principle, the instantaneous output power of the STATCOM (i.e., *ps* + j*qs*) is the sum of the instantaneous power consumed by *Rs* as well as *Ls* (i.e., *pRL* + j*qRL*) and that of the load terminal (i.e., *pl* + j*ql*).

ps = pRL + pl… (17)

qs = qRL + ql… (18)

Substituting equations (11) to (16) into equation (17) & (18) yields

Vds= Rsids- wLsiqs+ Vdl… (19)

Vqs= Rsiqs-+wLsids… (20)

From equation (10), it is obvious that the output voltages of the STATCOM (i.e., v_{ds} and v_{qs}) can be directly obtained from the output currents of the STATCOM (i.e., i_{ds} and i_{qs}) together with R_S, L_S, and v_{dl}. That is to say, the transformation from i_{ds} and i_{qs} to v_{ds} and v_{qs} can be realized by equation (19) & (20).

IV. Fuzzy- Pi-Based Controller Design

As is known to everyone, the traditional PI controller is widely used in industrial applications for its simplicity and reliability. However, in practice, a traditional PI controller with constant parameters may not be robust enough due to the variations of design parameters. To improve the static and dynamic performances of the STATCOM with this improved DOV control strategy, two fuzzy PI controllers have been adopted to separately regulate the dc-link voltage and maintain the voltages at the PCC.

A fuzzy adjustor is used to adjust the parameters of proportional gain K_P and integral gain K_I based on the error e and the change of error Δe

$$K_P = K_P^{*} + \Delta K_P$$

$$K_I = K_I^{*} + \Delta K_I$$

Where K_P *and* K_I are the reference values of fuzzy-PI-based controllers. In this paper, K_P and K_I are calculated offline based on the Ziegler–Nichols method.

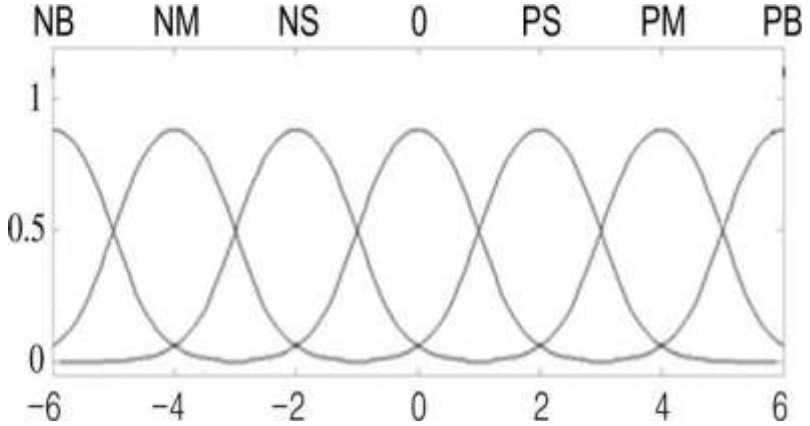

Fig.4 Membership functions of fuzzy variables

The error e and the change of error Δe are used as numerical variables from the real system. To convert these numerical variables into linguistic variables, the following seven fuzzy Sets are chosen: negative big (NB), negative medium (NM), negative small (NS), zero (ZE), and positive small (PS), positive medium (PM), and positive big (PB).To ensure the sensitivity and robustness of controllers, the membership function is shown in Fig. 4.

For designing the control rule bases to tune ΔK_P and ΔK_I, the following important factors have been taken into account.

1) For large value of $|e|$, a large ΔKP is required, and vice Versa.
2) For $e*\Delta e > 0$, a large ΔKP is required, and vice versa.
3) For the large values of $|e|$ and $|\Delta e|$, ΔKI is set to zero, which can avoid control saturation.
4) For small value of $|e|$, ΔKI is effective, and ΔKI is larger when $|e|$ is smaller, which is better to decrease Steady-state error.

Table-I ADJUSTING RULES OF ΔK_P PARAMETER

ΔK_P	N	NM	NS	0	PS	PM	PB
NB	PB	PB	NB	PM	PS	PS	0
NM	PB	PB	NM	PM	PS	0	0
NS	PM	PM	NS	PS	0	NS	NM
0	PM	PS	0	0	NS	NM	NM
PS	PS	PS	0	NS	NS	NM	NM
PM	0	0	NS	NM	NM	NM	NB
PB	0	NS	NS	NM	NM	NB	NB

Table-II ADJUSTING RULES OF ΔK_I PARAMETER

ΔK_I	NB	NM	NS	0	PS	PM	PB
NB	0	0	NB	NM	NM	0	0
NM	0	0	NM	NM	NS	0	0
NS	0	0	NS	NS	0	0	0
0	0	0	NS	NM	PS	0	0
PS	0	0	0	PS	PS	0	0
PM	0	0	PS	PM	PM	0	0
PB	0	0	NS	PM	PB	0	0

V. Simulation & Results

A. Simulation

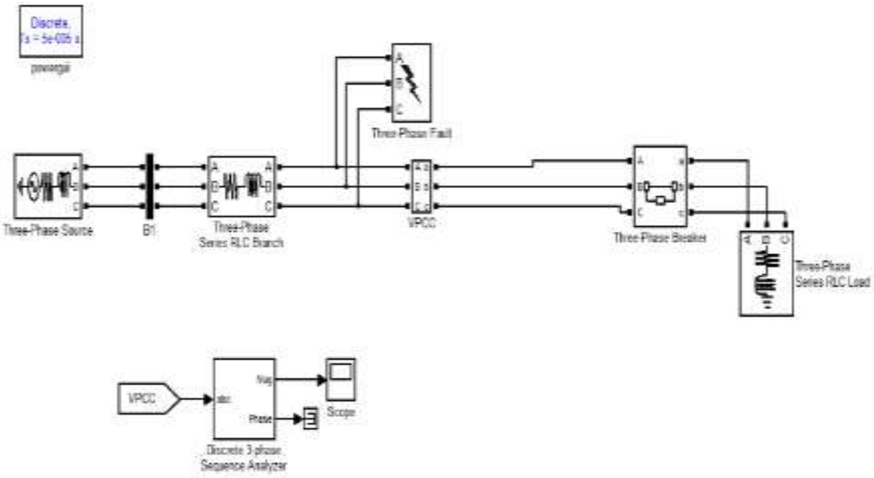

Fig 5: Simulink Model of Utility Distribution System

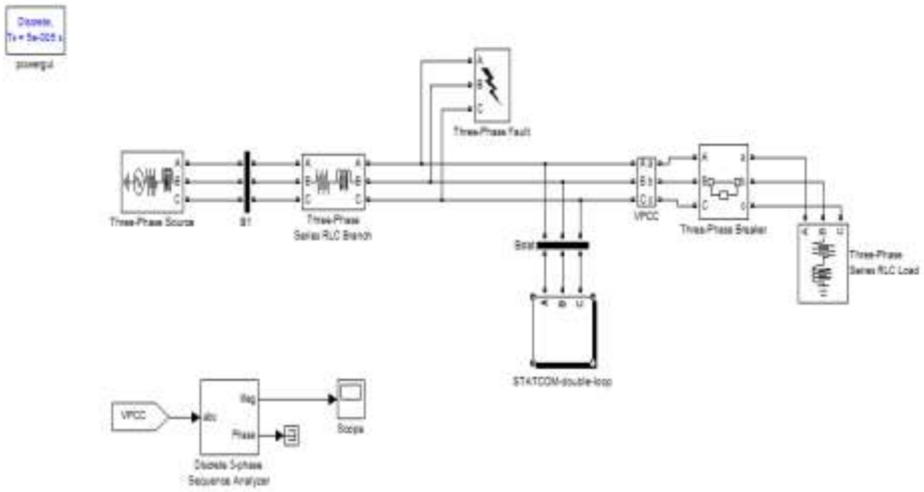

Fig 6: Simulink Model of Double-loop Control Strategy

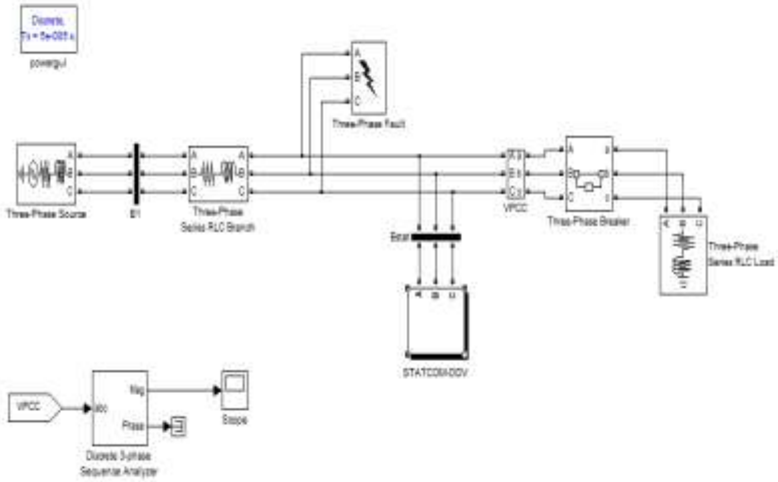

Fig 7: Simulink Model of Direct Output Voltage (DOV) Control Strategy

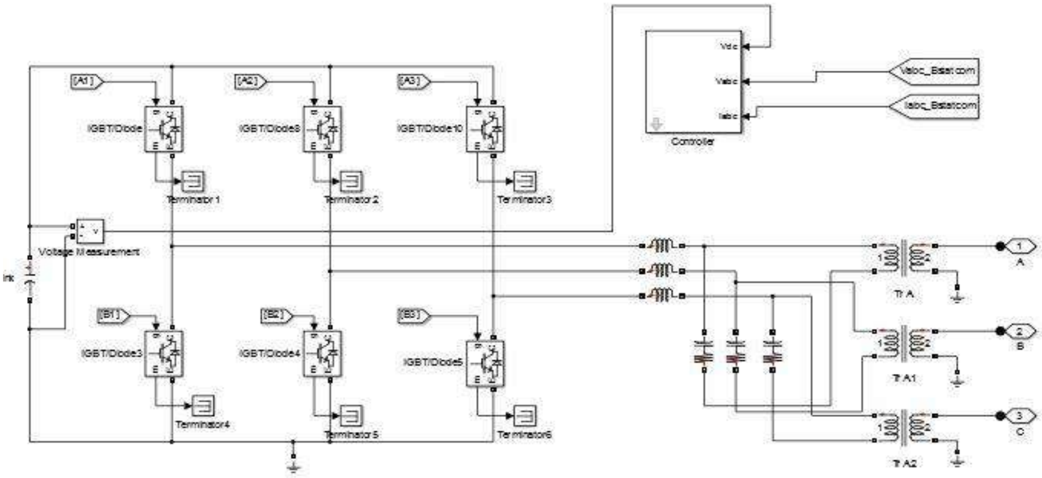

Fig 8: Simulink Model of Two Level Inverter

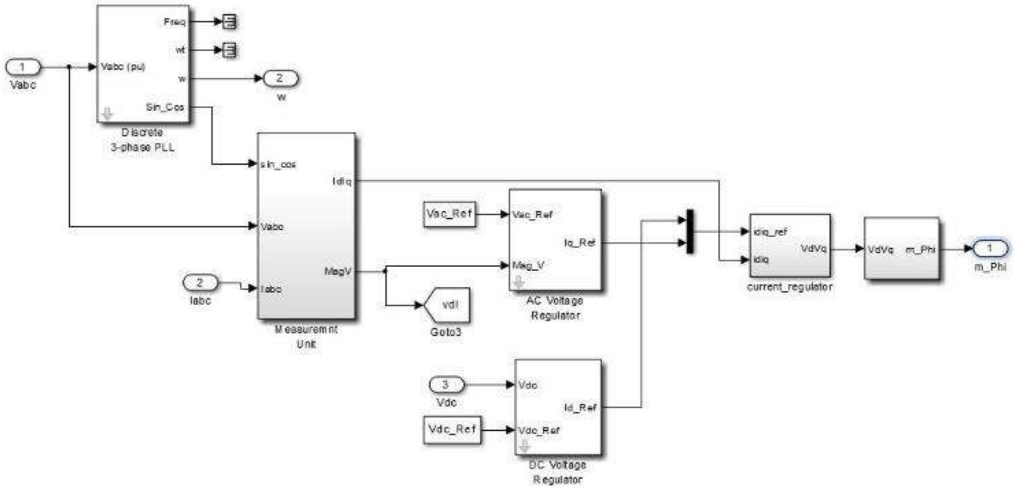

Fig 9: Simulink Model of Double Loop Controller

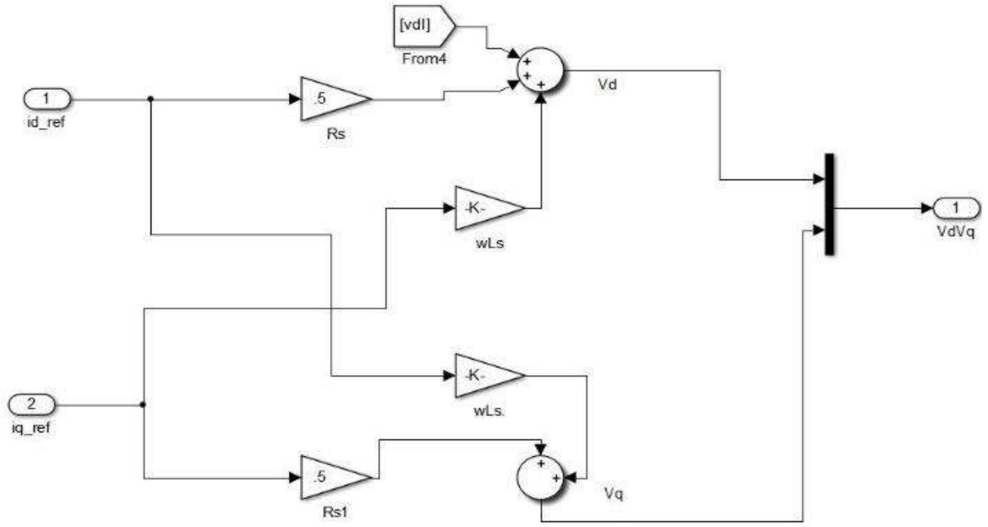

Fig 10: Simulink Model of DOV Control Strategy

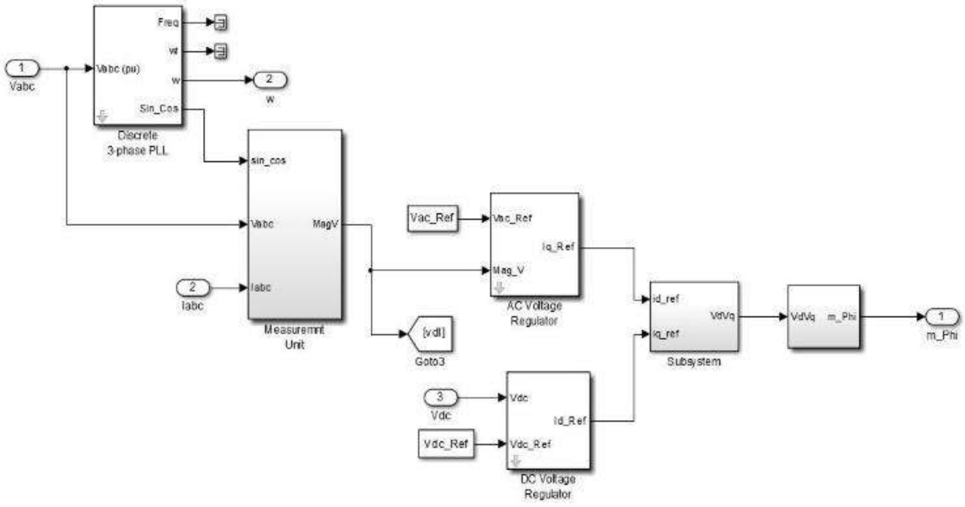

Fig 11: Simulink Model of DOV Controller

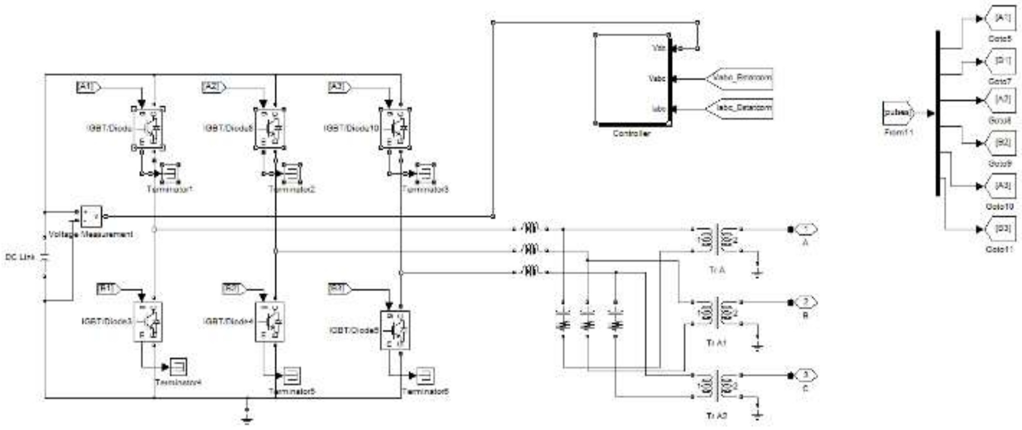

Fig 12: Simulink Model of DOV-Fuzzy-PI Control Strategy

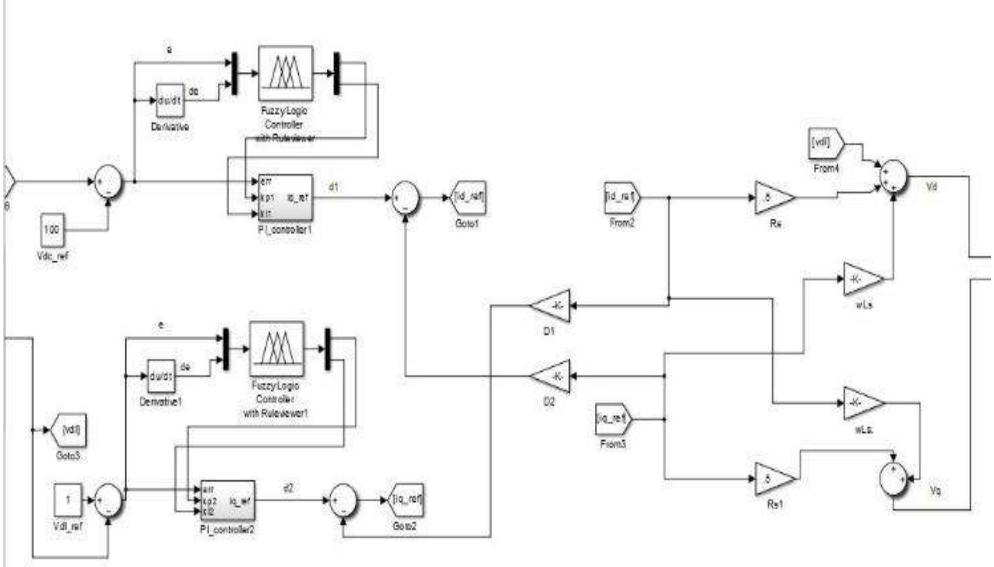

Fig 13: Simulink Model of DOV-Fuzzy-PI Controller

B. Results

Case 1: In this case, the production of a voltage drop at the PCC is realized by switching a reactive power (inductive) load at *t* = 0.2 s, while a swell at the PCC is obtained by disconnecting the given load at *t* = 0.4 s. Fig-14,15&16. Shows the response curves of V_{PCC} with the three control strategies. From Fig.16, it is obvious that there are less overshoot and shorter settling time in the response curves of V_{PCC} with the fuzzy-PI-based DOV control strategy than those with the typical double-loop control strategy & DOV control strategy; a further merit of this control strategy is its capability to regulate the dc-link voltage and maintain the voltages at the PCC.

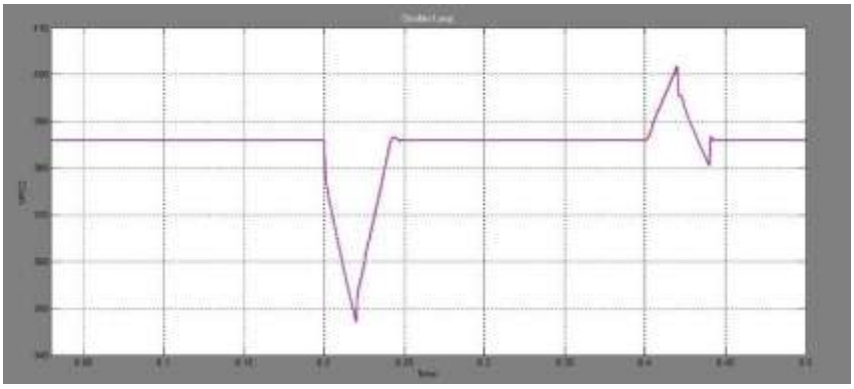

Fig 14: Voltage Output of Double-loop Control Strategy at PCC

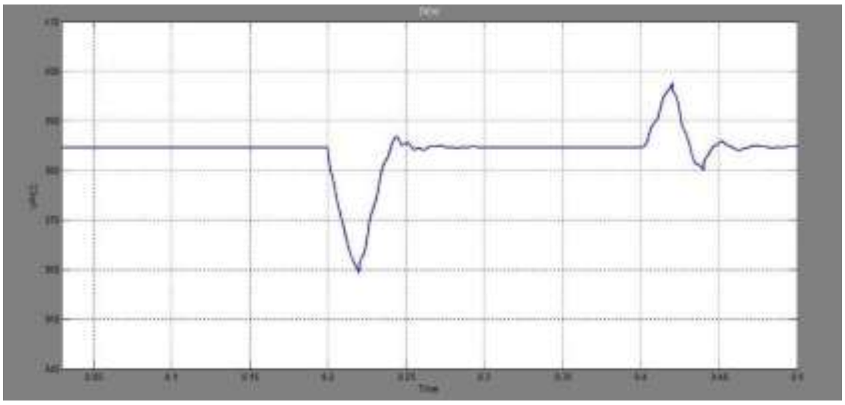

Fig 15: Voltage Output of Direct Output Voltage (DOV) Control Strategy at PCC

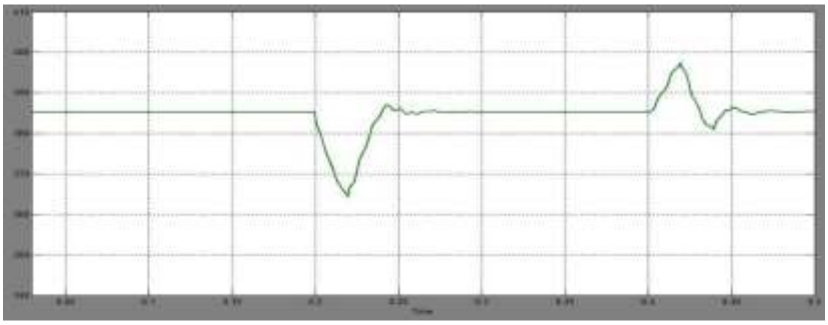

Fig 16: Voltage Output of Fuzzy-PI-Based Direct Output Voltage Control Strategy at PCC

VI. Conclusion

Two control strategy for STATCOM are used, first is conventional double loop and second is DOV. Fuzzy-PI- based DOV control strategy for the STATCOM with a two-level inverter utilized in utility distribution systems is presented. Based on power balancing principal, the DOV control strategy not only reduces the active and reactive current control loops of the conventional double-loop control strategy but regulate the dc-link voltage and maintain the voltages at the PCC. The simulation results firstly show the feasibility of the proposed fuzzy- PI-based DOV control strategy.

Table-III Test System parameters

AC source (Grid Voltage)	25KV
Transformer (load side)	25KV/600V
Grid Resistance	0.0625 Ω
Grid Inductance	0.16 mh
Grid Frequency	60 Hz
Load Resistance	3.6 Ω
Load Inductance	4 mh

Table- IV Controller parameters

V_{ac} Regulator gains	K_p=10	K_i=2
V_{dc} Regulator gains	K_p=8	K_i=0.8
Current Regulator gains	K_p=0.8	K_i=200

Table-V STATCOM Parameters

DC Capacitor	10,000 µF
Internal Resistance	$1\times10^{-3}\Omega$
Snubber Resistance	$1\times10^{5}\Omega$
Kind of PWM	Carrier wave PWM
DC link voltageV_{dc}	800V
Connecting Resistance	0.05 Ω
Connecting Inductance	1mh
Switching Frequency	10kHz

Table-VI Parameters of LC filter

Filter Inductance	0.1mh
Filter Capacitance	30µf
Coupling Transformer	400/200V
Transformer Rating	300KVA

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