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Reactive Power Compensation and DC link Voltage Control using Fuzzy-PI with DSOGI-PLL on Grid-connected PV based D-STATCOM

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ABSTRACT- The large-scale integration of photovoltaic (PV) generation introduces critical challenges for power systems, including voltage stability issues and increasing requirements for reactive power compensation. To address these challenges, PV inverters can be operated as Distribution Static Synchronous Compensators (D-STATCOM) to simultaneously supply active power and provide ancillary reactive power support. This paper proposes a control strategy for grid-connected PV-based D-STATCOM systems that incorporates a Fuzzy-PI controller for DC-link voltage regulation and a Dual Second-Order Generalized Integrator Phase-Locked Loop (DSOGI-PLL) for accurate phase angle detection. The Fuzzy-PI controller improves DC-link voltage regulation by adaptively tuning PI controller parameters and surpasses the complexity in mathematics design of conventional PI controller with the robustness of fuzzy logic principles. Meanwhile, the DSOGI-PLL enhances synchronization performance under unbalanced or distorted grid conditions, ensuring reliable current control in the synchronous reference frame. Simulation studies conducted in MATLAB/Simulink demonstrate that the proposed approach achieves the following outcomes: stable active power delivery, superior DC-link voltage regulation (following neatly reference signal and stabilizing under grid voltage variations), and effective compensation of local demands and grid support of reactive power under voltage contingencies. These results highlight the feasibility and improved performance of integrating advanced control methods of which archivable by the proposed control model into PV-based D-STATCOM configurations for modern distribution networks.

Keywords: Grid-Connected PV, D-STATCOM, Fuzzy-PI Control, Reactive Power Compensation, DSOGI-PLL, Grid-Feeding Inverters.

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1. INTRODUCTION

The growing environmental crisis has intensified global attention on renewable energy, with photovoltaic (PV) systems gaining prominence due to their sustainability, zero emissions, and ease of deployment [1, 2]. Typically, PV systems interface with low-voltage distribution networks through power electronic converters, supplying local loads under high irradiance and relying on grid support during low irradiance periods.

However, the increasing penetration of power electronics and evolving load profiles have created operational challenges such as voltage distortion, phase imbalance, and reactive power fluctuations [1–3]. Conventional solutions using SVC, SVG, and STATCOM devices [7–10] demand significant capital investment. Recent studies have revealed that PV inverters share structural similarities with D-STATCOM, enabling their use in reactive power support at distribution terminals [2]. Thus, optimizing Voltage Source Converter (VSC) control for simultaneous active power generation and reactive power compensation has become a central research direction, requiring

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precise current detection, reference current synthesis, and stable DC-link voltage regulation [4].

Extensive work has addressed reactive power compensation methods. For instance, [5] investigates coordinated reactive power from multiple PV inverters, while [6] employs voltage-regulated back-to-back converters to mitigate fluctuations. Other studies discuss PV integration in weak grids [7], fuzzy logic-based MPPT [11], and advanced PLL methods such as DSOGI-PLL, which improve performance under unbalanced or distorted conditions [8–10]. Large-scale PV integration has also been associated with overvoltage and imbalance issues in distribution systems [11].

This paper proposes a PV-based D-STATCOM control architecture for reactive power compensation and DC-link voltage stabilization. The design incorporates a dual-loop strategy: a Fuzzy-PI controlled outer DC-link voltage loop, enhancing robustness without complex modeling, and an inner current control loop based on DSOGI-PLL for improved phase detection under disturbances. The proposed approach demonstrates superior performance in both voltage regulation and reactive power compensation, validated through comprehensive simulation studies.

The paper includes four sections. *Section 2* provides theoretical backgrounds and the proposed control system. Simulation scenarios and results discussion to validate the proposed model are then given in *section 3*. *Section 4* delivers conclusions of the proposed control system.

2. THEORETICAL BACKGROUNDS AND THE PROPOSED CONTROL SYSTEM

2.1. Grid connected PV based DSTATCOM

The general PV based VSC model shown in *figure 1* includes a voltage source converter to deliver DC power from PV system into power gird, a LCL filter for harmonic canceling and measuring instrument at point of common coupling (PCC) [1, 12, 13].

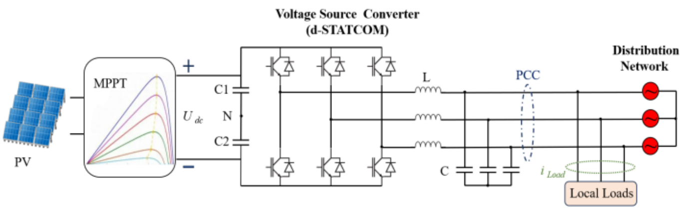

Figure 1. PV based grid-connected D-STATCOM system

According to system requirements, a VSC-based D-STATCOM can simultaneously provide local reactive power compensation while ensuring maximum PV power extraction. Thus, controlling the PV-based VSC in grid-supporting mode is preferable [12, 13]. In this mode, fast inner current control loops regulate grid-injected currents to track reference values derived from active and reactive power demands. Various methods exist for reference current implementation, including resonant controllers in the αβ frame, hysteresis, sliding-mode, or predictive control strategies [12, 13]. Among these, conventional PI controllers in the dq0 synchronous frame remain the most widely adopted solution.

Deriving the Clark-Park transformation *eq. (1)*, instantaneous components under control can be represented as dc values in an orthogonal dq frame, rotating synchronously at the detected grid fundamental frequency.

$$T_{abc\rightarrow\alpha\beta} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}, T_{\alpha\beta\rightarrow dq} = \begin{bmatrix} cos(\omega t) & sin(\omega t) \\ -sin(\omega t) & cos(\omega t) \end{bmatrix} \quad (1)$$

In this reference frame, two independent control loops are in charge of regulating the direct (*d*-axis) and quadrature (*q*-axis) components. In detail, according to [21], the system in *figure 1* is demonstrated in dq0 synchronous reference frame as follows;

$$V_{ds}^e = Ri_{ds}^e + L\frac{di_{ds}^e}{dt} - \omega_e Li_{qs}^e + e_{ds}^e$$
$$V_{qs}^e = Ri_{qs}^e + L\frac{di_{qs}^e}{dt} + \omega_e Li_{ds}^e + e_{qs}^e \quad (2)$$

where, V_d, V_q are d-axis and *q*-axis terminal voltage components of VSC system, i_d and i_q are *d*-axis and *q*-axis output current components, *e* stands for system voltage at PCC, *R* and *L* are resistance and inductance of connection line, *ω* is electrical angular frequency, respectively.

Since all the quantities in *eq. (2)* are DC after applying synchronous frame transformation. Then output three-phase voltages of the PV VSC system can be regulated by i_d and i_q current components. A block diagram of a typical AC PI regulator on the synchronous *dq* reference frame which can be applied to control VSC output voltages, is shown in *figure 2* including the feed-forward components described in *eq. (3)*. The feed forward *dq* frame voltage components (V_{dq}^{ff}) include the PCC *dq* frame voltages together with coupling terms due to the rotation of the reference frame such as $-\omega Li_q$ in the *d*-axis and ωLi_d in the *q*-axis are demonstrated as;

$$V_{ds-ff}^e = -\omega_e\hat{L}i_{qs}^e + \hat{e}_{ds}^e$$
$$V_{qs-ff}^e = \omega_e\hat{L}i_{ds}^e + \hat{e}_{qs}^e \quad (3)$$

Control of currents components are then deployed from [12, 13]. The d-axis current component (i_d) or the active power current component is regulated by the DC link voltage of the PV VSC system to harness the DC power. In addition, the output power of PV based RES highly depends on irradiation level and environment temperature of the PV panels [12-14, 15]. Therefore, MPPT control techniques is applied to adjust the DC output voltage of the PV string which then create the reference d-axis current. Among the vast effective MPPT control techniques, P&O shown to be the most popular.

On the other hand, *q*-axis current component in charge of regulating reactive power or voltage at its terminal by controlling

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the amount of reactive power injected into or absorbed from power system to follows the target reactive power generation or nominal voltage. The instantaneous active and reactive power components of a PV VSC system are calculated as follows [22];

$$P^* = U_{dc} I_{dc}^* = u_d i_d + u_q i_q$$
$$Q_l^* = u_d i_{lq} - u_q i_{ld} \quad (4)$$

Figure 2 shows the general control structure for PV based DSTATCOM in synchronous reference frame.

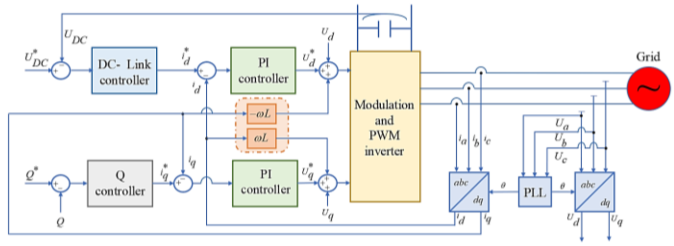


Figure 2. General control structure of a VSC system in synchronous reference frame

2.2. Fuzzy-PI controller

Basically, a fuzzy logic system (FLS) has four stages: Fuzzifier, rule base, inference engine and defuzzifier. Fuzzy controller operates on crisp inputs and gives crisp output, whereas processing is done on fuzzy variables. By defining the rules of the inference engine between the membership functions of inputs and knowledge base of designer to give adaptive outputs values [4,16-20].

Unlike traditional PI control algorithm, Fuzzy-PI control algorithm uses fuzzy logic to adjust proportional coefficient (K_p) and integral coefficient (K_i) of PI controller. Fuzzy logic gets control target error (ER) and error variation rate (DE) as input variables and uses these inputs to adjust control coefficients (K_p & K_i) of PI controller. *Figure 3* demonstrates a general Fuzzy-PI controller.

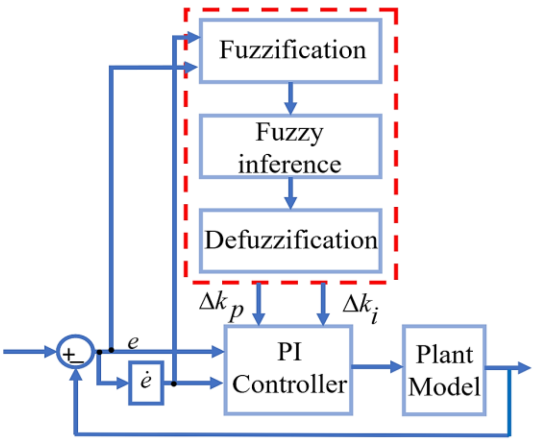
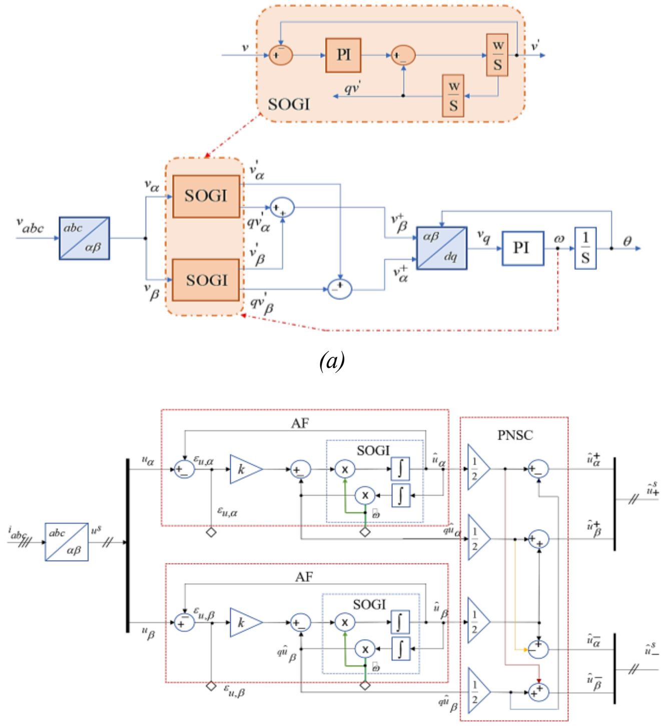


Figure 3. A general Fuzzy-PI controller model

2.3. DSOGI-PLL phase angle detection for three-phase inverter interfaced RES

Phase detecting is crucial when applying PI controller for three-phase VSC system working in grid-feeding mode, usually PLL is employed [12]. However, unbalanced voltage conditions will affect the phase angle calculation which results in low performance of control output quantities [8, 9]. Therefore, DSOGI is applied to determine positive and negative of fundamental components of three-phase voltage, isolated to the unbalanced components. DSOGI consists of two SOGI-QSG, the positive components then fed to PLL to obtain more precise phase angle for synchronous transformation [8]. *Figure 4(a)* and *4(b)* represent the block diagrams of DSOGI-PLL and DSOGI, with mathematical description of SOGI model is shown in *eq. (5)*.



(a)

(b)

Figure 4. (a) General model of double second-order generalized integrator phase lock loop (DSOGI-PLL); (b) detail model of a DSOGI

$$D(s) = \frac{v'}{v}(s) = \frac{k\omega' s}{s^2 + k\omega' s + \omega'^2}$$
$$Q(s) = \frac{qv'}{v}(s) = \frac{k\omega'^2}{s^2 + k\omega' s + \omega'^2} \quad (5)$$

2.4. The proposed control model

This paper proposed a control model that includes a Fuzzy-PI to control the DC link voltage together with DSOGI-PLL for angle detection in current control loop in a PV-based D-STATCOM system operating in grid feeding mode. The PV DSTATCOM grid-connected system following the proposed control model is shown in *figure 5*.

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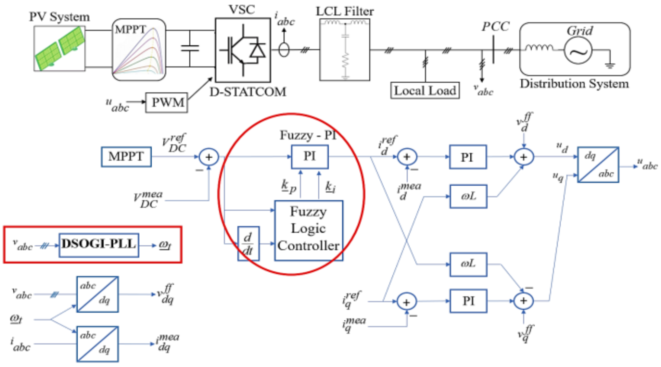
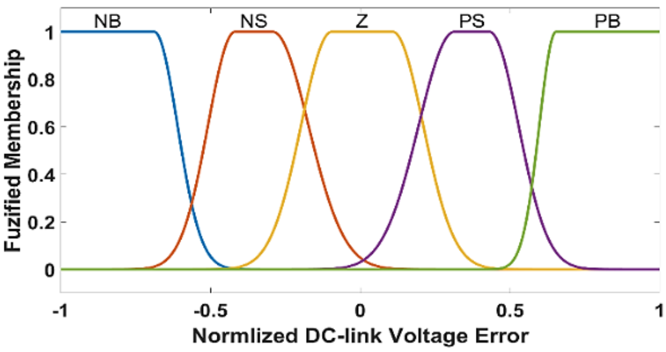
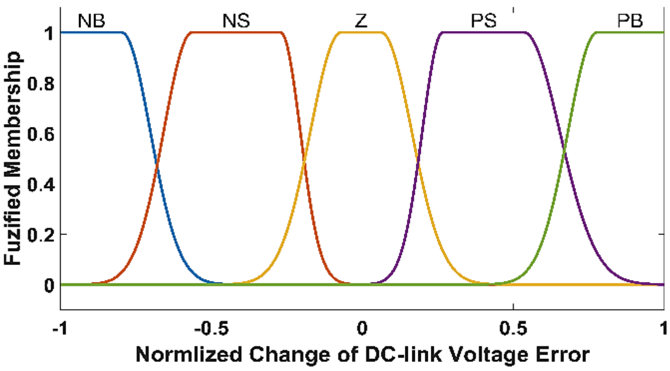


Figure 5. PV based grid-connected D-STATCOM system under simulation

The proposed control system employs a Fuzzy-PI DC-link voltage controller combined with the P&O MPPT technique. The controller takes the voltage error (ER) and its change (CER) as inputs, with corresponding membership functions shown in *fig. 6(a)–6(b)*, while the outputs are proportional (K_p) and integral (K_i) gains of the PI controller, defined by membership functions in *fig. 6(c)–6(d)*. Input linguistic variables include NB, NS, Z, PS, and PB (negative big to positive big), whereas output variables ES, MS, S, MB, and EB represent extreme small to extreme big values. The fuzzy inference engine applies rule bases (*tables 1–2*) to map inputs to outputs. In general, when ER is large, K_p is set high and K_i low to ensure rapid response without overshoot, while for medium ER values, K_p is reduced and K_i increased to minimize steady-state error.



(a)



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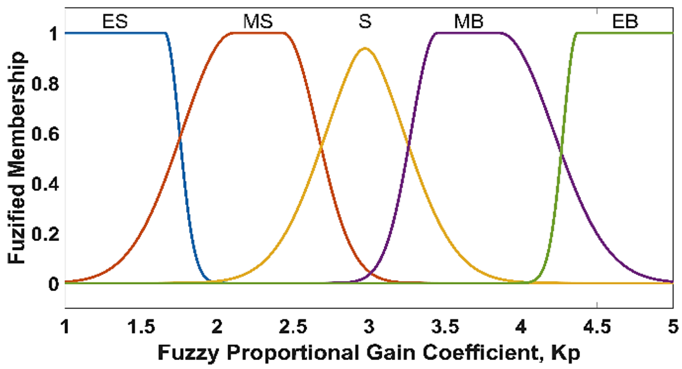
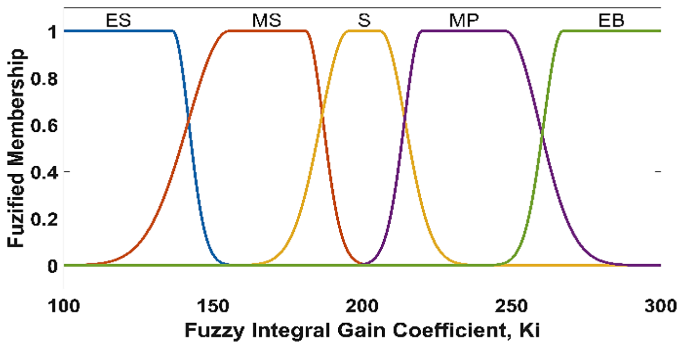


(c)



(d)

Figure 6. Optimized membership functions of Inputs: (a) DC link voltage error (b) Change of DC link voltage error, and Outputs: (c) Fuzzy-PI Proportional Gain (d) Fuzzy-PI Integral Gain

Table 1. Fuzzy Rules of KP

KP		ER				
		NB	**NS**	**Z**	**PS**	**PB**
DE	NB	EB	EB	MB	S	S
	NS	EB	MB	S	S	MS
	Z	MB	S	S	S	MS
	PS	S	S	S	MS	ES
	PB	S	S	MB	MS	ES

Table 2. Fuzzy Rules of KI

KI		ER				
		NB	**NS**	**Z**	**PS**	**PB**
DE	NB	ES	ES	MS	S	S
	NS	ES	MS	S	S	S
	Z	MS	S	S	S	MB
	PS	S	S	S	MB	EB
	PB	S	S	MP	EB	EB

The design of input–output membership functions and rule bases in fuzzy controllers relies on the designer's experience and experimental knowledge. Fuzzy logic control thus offers mathematical independence and flexibility, which are advantageous in practical applications. In addition, the proposed model integrates a DSOGI-PLL for phase angle detection. Compared with conventional PLLs, DSOGI-PLL provides more

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accurate estimation under unbalanced voltage conditions, enabling improved synchronous frame transformation in the current control loop. The instantaneous PCC voltage is used to generate the phase angle for dq0 transformation of three-phase currents, while orthogonal components v_d^{ff} and v_q^{ff} derived from DSOGI-PLL are applied as feedforward signals. The corresponding gain coefficients of the DSOGI-PLL are summarized in *table 3* (Appendix).

3. SIMULATION RESULTS AND DISCUSSION

Figure 7 shows the PV DSTATCOM grid connected simulation model under investigated and *figure 8* demonstrates the proposed control system. Simulations are carried under MATLAB/Simulink flatform.

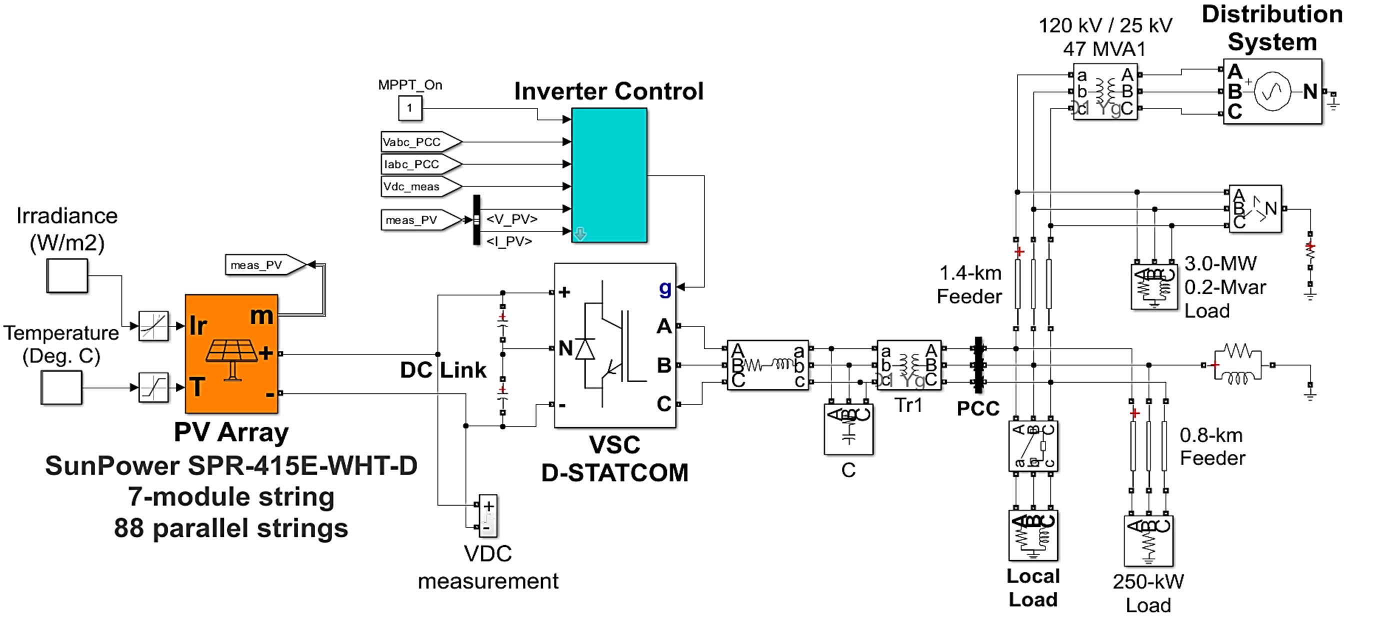

Figure 7. Simulation diagram of a PV grid connected DSTATCOM with the proposed control system

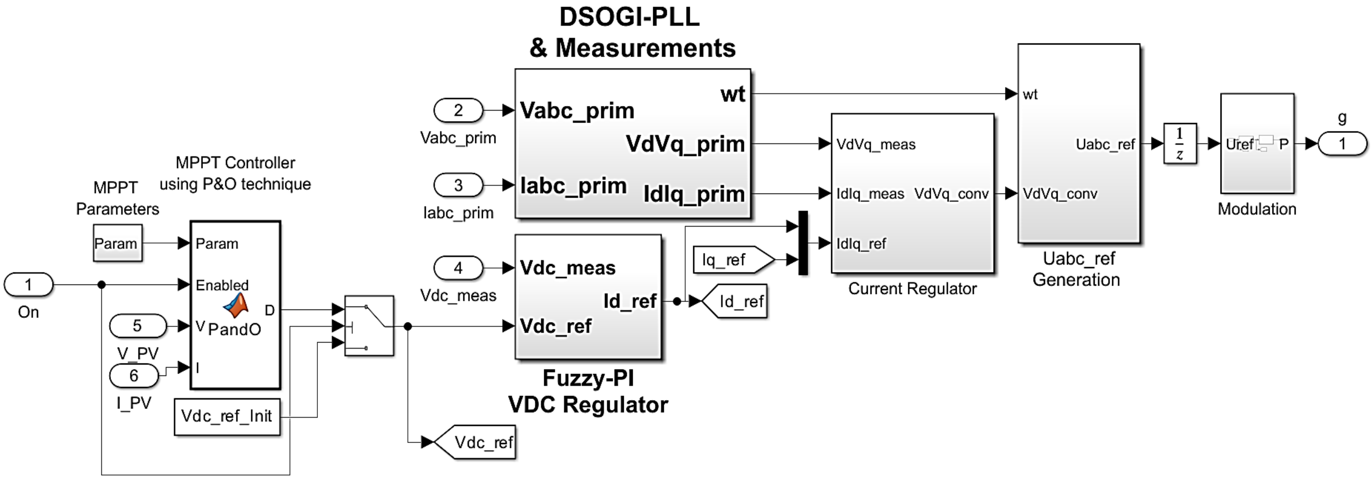

Figure 8. Simulation block diagram of the proposed control system

As shown in *figure 7*, the PV DSTATCOM system includes three main parts: the PV modules convert irradiation energy into DC power, VSC (DSTATCOM) system transfers DC to AC power with the capability in reactive power compensation and connecting to Distribution System via an LCL filter. The general system simulation parameters are given in *table 3* in Appendix.

The proposed control model is validated under different operating scenarios as follows:

- Firstly, irradiation level is reduced to 20% within 0.6s begins at 0.4s follows the increasing environmental temperature at 1.1s;
- Then at 1.2s a 100kW local load at the PCC is connected;
- Finally, power grid voltage variation is immersed under 0.5s period begins at 1.7s. The whole simulation period lasts for 2s.

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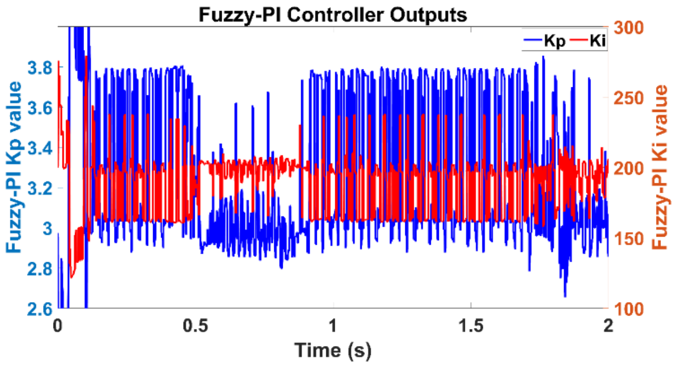


Figure 9. Fuzzy Proportional (K_p) and Integral (K_i) gain values

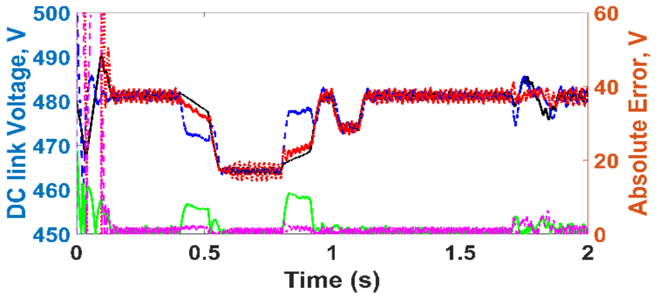
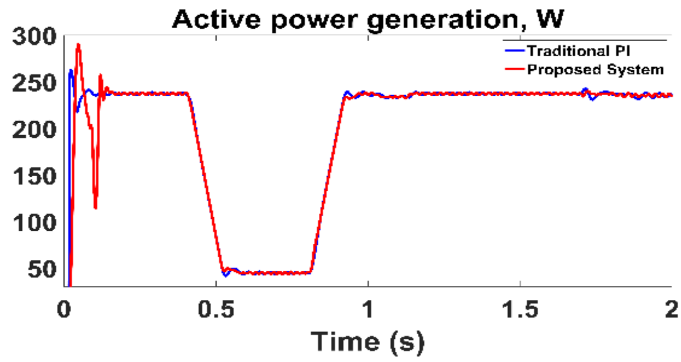


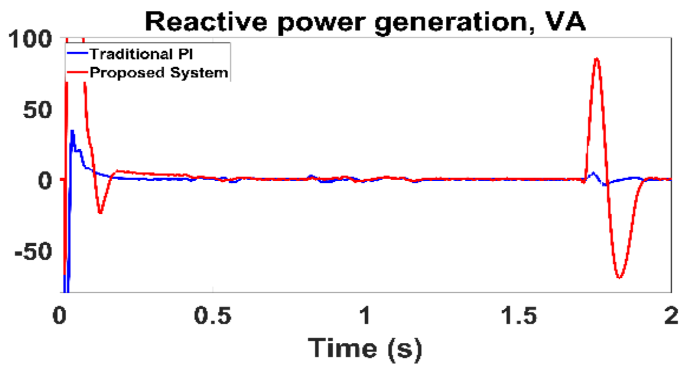
Figure 10. DC link voltage responses and absolute errors between the reference signal, the conventional, and proposed control model

Figure 9 illustrates the proportional (K_p) and integral (K_i) gains generated by the fuzzy logic controller for DC-link voltage regulation. These adaptive gains vary with system contingencies to fulfill the intended design objectives which improve dynamic DC link voltage regulation and support reactive power generation. *Figure 10* compares the DC-link voltage response with absolute errors between MPPT reference signal, output responses of the conventional PI regulator and the proposed control model. DC-link voltage response of the proposed model (red line) more accurately tracks the MPPT reference (black line) as compared to the conventional PI regulator (blue line), as shown in *figure 10*. More specific, the traditional PI regulator endures voltage deviations up to 10 V (or approximate 2%, as shown in green line) during irradiance changing periods (0.4–0.6 s and 0.8–1.0 s), that contrasts to extremely small absolute error values of the proposed model, as in *figure 10* with magenta line. Enduring a grid voltage disturbance at 1.7s, both methods stabilize DC-link voltage around 480 V, but the proposed model shows a superior adaptability with nearly no changing as compared to the traditional PI model.

Figures 11(a) and *11(b)* present active and reactive power at the PCC. While active power responses are similar for both models under irradiation reducing and power grid voltage variation contingencies, as shown in *figure 11(a)*. However, significant differences are observed in reactive power generation as in *figure 11(b)*. During the grid voltage variation occurred at 1.7s, the proposed controller adjusts reactive power generation from +80VAR to -60VAR (red line) to support system voltage, whereas the conventional PI appears no changes, as shown in blue line as in *figure 11(b)*. With validated simulation results shown in *figure 10* to *figure 11*, the proposed adaptive Fuzzy-PI with DSOGI-PLL control strategy has fulfilled designing targets in which enhancing DC-link voltage and reactive power support of the PV based D-STATCOM system.



(a)



(b)

Figure 11. Simulation results between the traditional PI and proposed control system of (a) Active power generation and (b) Reactive power generation

4. CONCLUSION

This paper proposed a control model that derived a Fuzzy-PI regulator to stabilize DC link voltage and a DSOGI-PLL for angle detection in current control loop of the PV based DSTATCOM system. Employing the Fuzzy-PI controller not only shows better DC link voltage regulation under various contingencies but also inherits degree of freedom in mathematical burden as in designing the PI controller. Furthermore, together with deriving DSOGI-PLL for phase angle detection, the proposed control system delivers better output response in reactive power generation follows voltage contingency while regulating DC link voltage under transient events. The positive outcomes of the proposed control model have been validated through simulation results under different operating scenarios where DC link voltage control is improved and reactive power regulation capability is fulfilled of the PV based DSTATCOM system.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix:

Table 3. Simulation parameters

Name	Value
Inverter nominal 3-phase power (VA), P_{nom}	250e3
Nominal inverter primary line-to-line voltage (V^{rms}), V_{nom_prim}	25e3
Nominal inverter Secondary line-to-line voltage (V_{rms}), V_{nom_sec}	250
Nominal DC link voltage (V), V_{nom_dc}	480
System frequency (Hz), Fnom	60
Sampling time (s), T_s	1u
Current regulator Proportional gain, K_{pc}	0.3
Current regulator Integral gain, K_{ic}	20
Switching frequency (Hz), F_c	5k
Inverter filter capacitor (μF), C_f	127.55
Inverter choke inductance (μH), L_f	100
Feed-forward impedance (Ω), R_{ff}	0.21
SOGI-QSG Gain, K	2
DSOGI-PLL Proportional Gain, K_p	50
DSOGI-PLL Integral Gain, K_i	150

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