Reactive Power Compensation and DC link Voltage Control using Fuzzy-PI on Grid-connected PV System with d-STATCOM

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***Abstract*— Massive PV power generation connecting to grid will bring many challenges, such as voltage stability, reactive power compensation, operational reliability and so on. In order to realize local loads reactive power compensation and improve controllability of PV system, it should use novel switching devices and advanced control methodology of Voltage Source Converter(VSC). This paper focuses on control strategy of VSC to realize local loads reactive power compensation and stabilize DC link voltage. To some extent, VSC can be used as d-STATCOM. This paper also introduces SiC MOSFET, which can realize higher switching frequency. The control strategy of VSC (d-STATCOM) includes two parts: DC link voltage control and inner current loop control. By using Fuzzy-PI, DC link voltage can be made smoother and stabler. A parameter-self-adjustable Fuzzy-PI controller has simpler structure and higher robustness when fuzzy logic control and PI control are combined together appropriately. Active power current of inner current loop is controlled by tracking output variables of DC link voltage, while reactive power current is corrected by tracking local loads reactive power consumption. The simulation result shows grid-connected PV system with d-STATCOM can compensate local loads reactive power, output active power stably and keep grid-connected voltage steady.**

***Index Terms*-- Grid-connected PV; d-STATCOM; Fuzzy-PI Control; Reactive Power Compensation; High Frequency Switching**

I. Introduction

With the deterioration of the global environment, renewable energy, headed by photovoltaic power generation, has attracted worldwide attention because of its advantages of environmentally clean, pollution-free and simple installation[1]. In recent years, the distributed generation system of photovoltaic power generation is gradually developing from the island to the integrated grid, indicating that large-scale grid-connected PV will be the main mode of photovoltaic power generation[2]. Photovoltaic power generation system is connected with low voltage distribution network through converter, realized to load power supply. In larger light intensity, it can provide electricity to nearby local loads. When the light intensity is small, local loads are supplied by power grid.

With the new changes of power grid and load, high tech electronic products and the new challenges of the penetration of power electronics technology, a large number of non-resistive loads connected to large power grid, it may lead to power grid voltage distortion in the ending, three-phase imbalance and impact reactive power and other adverse conditions, which will have bad impacts on the distribution network[3-5]. In order to improve the voltage stability of terminals of the grid, the traditional method of reactive power compensation is using reactive power compensation device to compensate the reactive power, such as SVC, SVG and STATCOM, which increases additional investment of power equipment. With the finding of research, the main structure of photovoltaic inverter and d-STATCOM is fully consistent, hence photovoltaic power generation system can be equipped in the distribution network of terminals to provide reactive power, therefore the research of Voltage Source Converter (VSC) of grid-connected PV is the key.

In order to realize the active power generation and reactive power compensation in the grid-connected PV system, the key is to detect local loads current and synthesize reference currents of active and reactive component of grid. The reactive component mainly reflects reactive power requirement by local loads, and active component reflects the active power requirement by local loads. Also, DC link voltage of VSC is maintained constantly to provide continuous output power. There have been a lot of researches on reactive power compensation nowadays. Ref[6] proposes a phase locked loop (PLL) to obtain the reactive power compensation more precisely based on the discrete Fourier transform, but it is complicated in operation and has high requirement of the controller. Ref[7] uses residual power energy of multiple PV inverter to output reactive power, which can provide voltage support for the line, the communication between each photovoltaic power supply is established, and the algorithm is

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solved according to the voltage control target, and the reactive power required by each inverter is obtained. Ref[8] uses on-load voltage-regulating transformers to regulate voltage fluctuation caused by access of the distributed generation. Ref[9-12] also discusses photovoltaic distributed generation system with reactive power compensation, current-controlled SVPWM algorithm, weak grid and Fuzzy-logic based MPPT control.

In this paper, VSC (d-STATCOM) is introduced to compensate local loads reactive power and stabilize DC link voltage, which is better than the traditional SVC. The control strategy consists of two parts: outer control loop of DC link voltage and inner current control loop. Fuzzy-PI control is introduced to stabilize DC link voltage. A kind of nonlinear control algorithm does not need to establish a precise mathematical model. The adaptive PI parameters can be adjusted to make system has better robustness. A method based on instantaneous reactive power theory is adopted in the inner current control loop. SiC MOSFET is also introduced in this paper. Because of its switching frequency can be as high as 100kHz, it is conducive to eliminate harmonics. The control strategy proposed in this paper can effectively improve system control performance, and the effectiveness is proved in simulation results.

II. SYSTEM STRUCTURE

Grid-connected PV system is combined with PV array, MPPT module, VSC (d-STATCOM) module, local loads and distribution network. Fig. 1 shows the system structure.

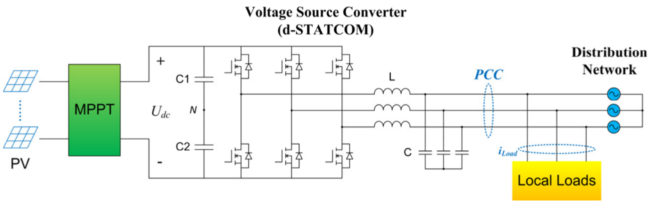

Figure 1. System structure

The main function of grid-connected PV system is to transmit active power of PV array to grid. While, according to requirements, VSC (d-STATCOM) can realize reactive power compensation of local loads, which means power factor of distribution network is close to unity power factor. This is what distribution supplier needs. On the other hand, DC link voltage of VSC (d-STATCOM) and voltage at PCC should remain stable under any circumstance.

For PV array, the system delivers a maximum of 10.7kW at 1000W/m^2 of sun irradiance. The PV array consist of 7 parallel strings and each string has 5 series-connected modules. There are 96 cells of each module. In simulation model, PV array modules are modeled precisely, which is closer to actual conditions.

For MPPT, the boost converter boosts DC voltage from approximate 270V to 600V. MPPT is used in this converter which automatically varies the duty cycle in order to generate the required voltage to extract maximum power.

For VSC (d-STATCOM), 6-armed-H-bridge converter structure is used. It is also seen as a 3-level NPC (Neutral Point Clamped) converter. The system adds on local loads reactive power compensation function to VSC, so that VSC can be considered as d-STATCOM.

d-STATCOM (distribution - STATic synchronous COMpensator) is a kind of shunt device to distribution network of FACTS (Flexible AC Transmission Systems). It uses power electronics to control power flow and improve transient stability on distribution network. d-STATCOM regulates reactive power or voltage at its terminal by controlling the amount of reactive power injected into or absorbed from power system.

VSC (d-STATCOM) regulates DC bus voltage at about 600V and keeps unity power factor of distribution network. Due to DC bus connected to PV array, VSC (d-STATCOM) doesn't need to provide active power to DC capacitors in order to maintain DC voltage.

Nowadays, SiC MOSFET is widely used in VSC (d-STATCOM) as switching devices, which improves switching frequency up to 100kHz. The high switching frequency means the transformer from VSC to grid can be removed, and just a set of appropriate LC filter can perform low pass filtering.

SiC (Silicon Carbide) is a semiconductor in research and early mass-production providing advantages for fast, high-temperature and/or high-voltage devices. The first devices available were Schottky diodes, followed by junction-gate FETs and MOSFETs for high-power switching. Due to multifold lower switching losses com-pared to Si IGBTs, SiC MOSFET based power converters can be operated at higher switching frequencies. Therefore, the size of the passive filter elements in the circuit can be greatly reduced.

VSC (d-STATCOM) controller needs the voltage and current data on PCC, current data of local loads and DC link voltage data of VSC. The simulation results on later part shows that only these limited V/I data can perform all functions of this system.

III. PROPOSED CONTROL STRATEGY

Fig. 2 shows VSC control strategy of VSC controller.

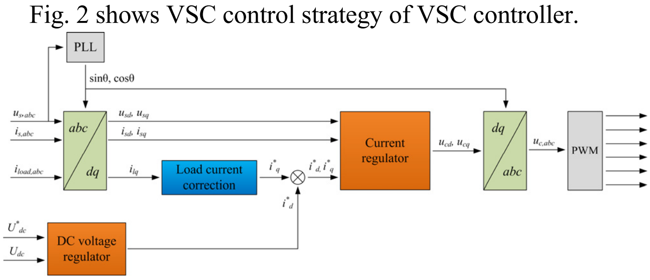

Figure 2. VSC control strategy

As mentioned before, VSC controller needs voltage and current data on PCC ($u_{s,abc}$ & $i_{s,abc}$), current data of local loads ($i_{load,abc}$), and DC link voltage data of VSC (U_{dc}).

There are two control loops in VSC controller: an external DC voltage control loop and an internal AC current control loop. The outer loop is to regulate DC link voltage to reference value (U^*_{dc}) and the inner loop is to regulate AC current to reference value (i^*_d, i^*_q).

A. DC link voltage control using Fuzzy-PI

Linear control algorithm, such as PI, can stabilize DC link voltage in the vicinity of reference value. While, due to DC output voltage of PV is nonlinear, it does not improve output voltage vibration. Accordingly, Fuzzy-PI control algorithm is more suitable to control DC link voltage of VSC. It will make system get a good dynamic performance and indirectly improve grid-connected performance. The DC link voltage control diagram with Fuzzy-PI algorithm is shown at Fig. 3.

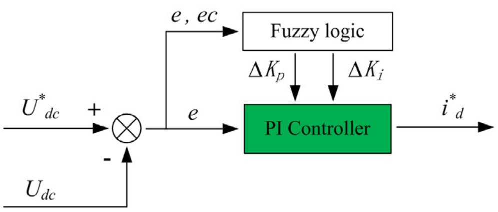

Figure 3. DC link voltage control diagram with Fuzzy-PI

Unlike traditional PI control algorithm, Fuzzy-PI control algorithm uses fuzzy logic to adjust proportional coefficient (*Kp*) and integral coefficient (*Ki*) of PI controller.

Fuzzy logic gets DC link voltage error (*e*) and error variation rate (*ec*) as input variables, and uses these inputs to adjust control coefficients (*Kp & Ki*) of PI controller.

The universe of discourse of four variables (*e*, *ec*, *Kp* and *Ki*) are divided into seven grades, respectively {"NB", "NM", "NS", "ZO", "PS", "PM", and "PB"}. Membership functions adopts closed triangle shape so that the system has higher resolution, better sensitivity, and better robustness. Membership functions of *e* and *ec* are shown as Fig. 4.

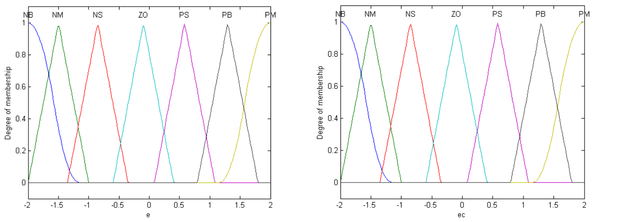

Figure 4. membership functions of *e* and *ec*

According to PI controller debugging experience, when the absolute value of *e* is large, *Kp* should be a large value to make system has good tracking performance. At the same time, to avoid system overshooting, *Ki* should be limited, usually used the zero value. When the absolute value of *e* is small, to get a good system steady performance, *Kp* and *Ki* should be large values. When the absolute value of *e* is medium, to get a small overshooting, *Kp* should be a small value and *Ki* should be a medium value. Fuzzy rules of *Kp* and *Ki* are shown as Table I and Table II.

TABLE I. FUZZY RULES OF *KP*

		e						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	**PB**	**PB**	**PM**	**PM**	**PS**	**PS**	**ZO**
	NM	**PB**	**PB**	**PM**	**PM**	**PS**	**ZO**	**ZO**
	NS	**PM**	**PM**	**PM**	**PS**	**ZO**	**NS**	**NM**
	ZO	**PM**	**PS**	**PS**	**ZO**	**NS**	**NM**	**NM**
	PS	**PS**	**PS**	**ZO**	**NS**	**NS**	**NM**	**NM**
	PM	**PS**	**ZO**	**NS**	**PM**	**NM**	**NM**	**NB**
	PB	**ZO**	**NS**	**NM**	**PM**	**NM**	**NM**	**NB**

TABLE II. FUZZY RULES OF *KI*

		e						
		NB	NM	NS	ZO	PS	PM	PB
ec	NB	**NB**	**NB**	**NB**	**NM**	**NM**	**ZO**	**ZO**
	NM	**NB**	**NB**	**NM**	**NM**	**NS**	**ZO**	**ZO**
	NS	**NM**	**NM**	**NS**	**NS**	**ZO**	**PS**	**PS**
	ZO	**NM**	**NS**	**NS**	**ZO**	**PS**	**PS**	**PM**
	PS	**NS**	**NS**	**ZO**	**PS**	**PS**	**PM**	**PM**
	PM	**ZO**	**ZO**	**PS**	**PS**	**PM**	**PB**	**PB**
	PB	**ZO**	**ZO**	**PS**	**PM**	**PB**	**PB**	**PB**

B. *AC current regulation algorithm*

The active power injected by VSC (d-STATCOM) from PV to grid is given by:

$$P^* = U_{dc} I_{dc}^* = u_d i_d + u_q i_q \tag{1}$$

According to p-q theory, the instantaneous load reactive power is given by:

$$Q_l^* = u_d i_{lq} - u_q i_{ld} \tag{2}$$

where, u_d and u_q are the d-q components of PCC voltage in the synchronously rotating frame, by Park transformation. i_{ld} and i_{lq} are the d-q components of local loads current.

Fig. 5 shows the simplified connection of VSC (d-STATCOM) to distribution network.

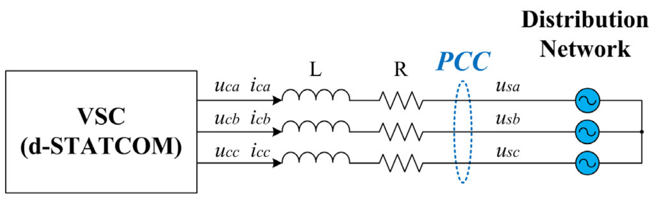

Figure 5. Simplified connection of VSC (d-STATCOM) to Distribution Network

In Fig. 5, *L* and *R* are equivalent inductance and resistance from VSC (d-STATCOM) to grid. According to Fig. 5, the voltage equation in time domain is shown as below:

$$\begin{bmatrix} u_{ca} \\ u_{cb} \\ u_{cc} \end{bmatrix} - \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} + R\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} \tag{3}$$

Through Park transformation, the d-q components of 3-phase voltage and current can be gotten. Then, equation (3) is converted under dq0 coordinate system as below:

$$L\frac{d}{dt}\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} + \begin{bmatrix} R & -\omega L \\ \omega L & R \end{bmatrix}\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} = \begin{bmatrix} u_{cd} - u_{sd} \\ u_{cq} - u_{sq} \end{bmatrix} \tag{4}$$

According equation (4), active and reactive power control strategy can be proposed. The control diagram of active and reactive current is shown in Fig. 6.

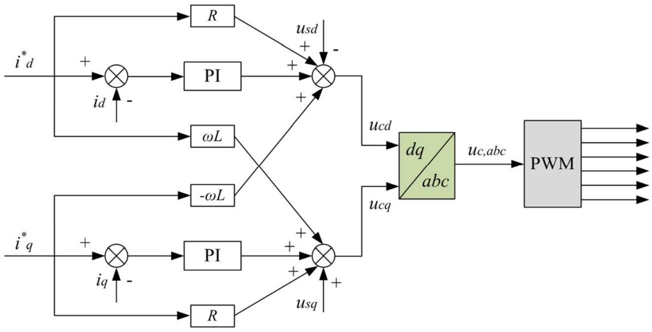

Figure 6. Control diagram of active and reactive current control

Additionally, i^*_d and i^*_q should contain current data information from local loads current, if VSC (d-STATCOM) performs local reactive power compensation. Otherwise, the voltage at PCC won't be stable. This is the main reason why VSC controller should acquire local loads current.

On the other hand, local loads current acquisition is flexible. VSC (d-STATCOM) only compensates reactive power for the local loads those are easy to acquire current data. Others will be compensated by grid or other local reactive power compensation devices. This is fully in accordance with the principle of local reactive power compensation.

IV. Simulation Results

The proposed grid-connected PV system shown in Fig.1 is simulated in this part, which contains a transformerless VSC structure. The main task of the simulation is to evaluate the performance of proposed control strategy in injecting the energy generated by PV array and the reactive power compensation of local loads.

The total simulation time is 0.8s. Since MPPT works from 0.4s, so each figure of simulation results is from 0.4s to 0.8s. Solar irradiance changes from $1000W/m^2$ to $500W/m^2$ at 0.6s, and temperature is set to constant (25°C).

The control system uses a sample time of 100us for voltage and current controllers as well as for the PLL synchronization unit. Pulse generators of boost and VSC converters use a fast sample time of 1us in order to get an appropriate resolution of PWM waveforms. Switching frequency of MOSFET is set to 45kHz. Local load is set to 8kW and 5.937kvar.

The PV output active power is shown in Fig. 7:

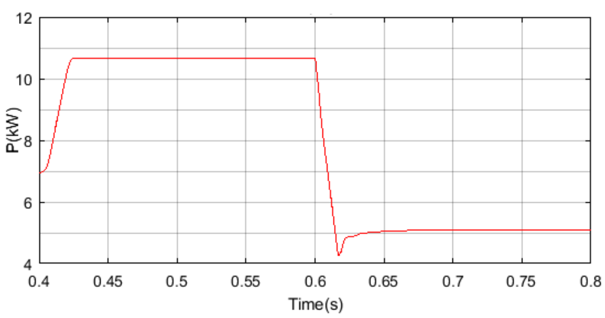

Figure 7. PV output active power

As mentioned before, PV arrays has a maximum of 10.7kW at $1000W/m^2$. At 0.6s, solar irradiance drops half, so PV output active power drops to 5kW. On the other hand, Fig. 7 shows that the curve of PV output active power is smooth when system becomes steady, which means PV arrays model and MPPT works very well.

The output active power and reactive power of VSC (d-STATCOM) is shown in Fig. 8:

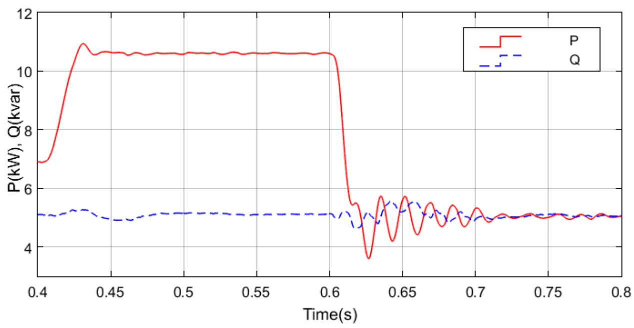

Figure 8. Output active power and reactive power

In Fig. 8, solid line stands for active power and dash line stands for reactive power. From 0.4s to 0.6s, because of maximum sun irradiance, VSC outputs maximum active power. On one hand, it meets the active power requirement of local load (8kW). On the other hand, extra active power is sent to grid. Also in this period, VSC almost meets the reactive power requirement of local load (5.937kvar), which proves local load reactive power compensation control strategy is effective.

From 0.6s to 0.8s, because of sun irradiance dropping, VSC outputs half of maximum active power, which is lower than local load needs. While, the output reactive power is slightly effected. It is also seen that the system needs more than 0.1s to be steady, which is a bit longer than expect in general.

The DC link voltage of VSC (d-STATCOM) is shown in Fig. 9:

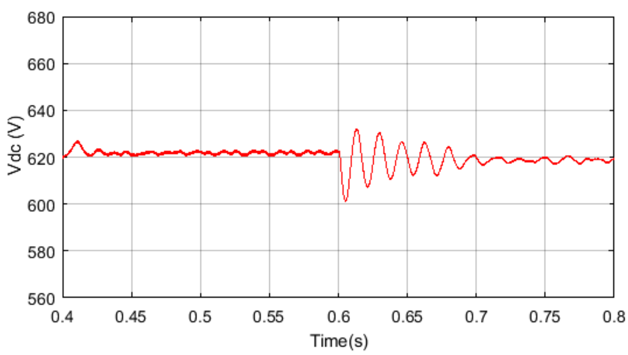

Figure 9. DC link voltage of VSC (d-STATCOM)

From 0.4s to 0.6s, DC link voltage keeps steady. While, since solar irradiance drops at 0.6s, DC link voltage fluctuates increasingly. By spending 0.1s, Fuzzy-PI control algorithm stabilize this fluctuation. It is acceptable but control performance should be improved.

The RMS voltage and current at PCC is shown in Fig. 10:

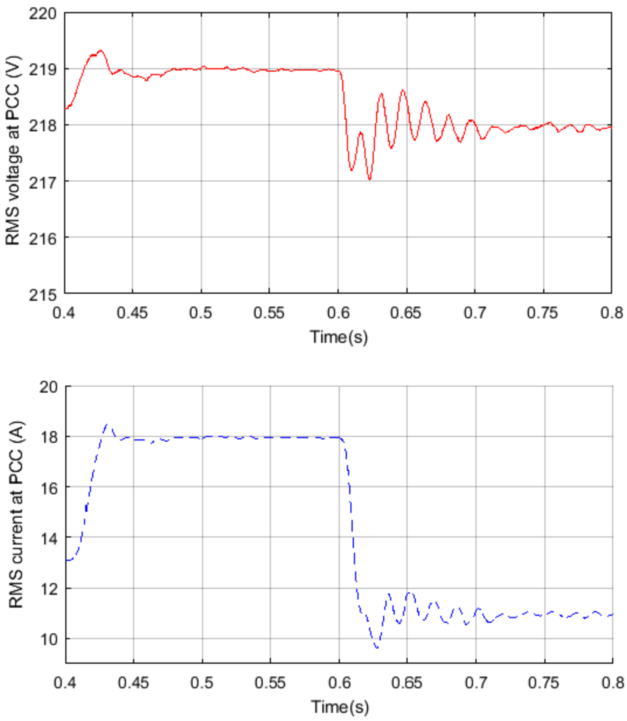

Figure 10. RMS voltage and current at PCC

Solid line stands for voltage (phase to ground) and dash line stands for current. Phase to phase voltage is set to 380V so phase to ground voltage equals to 219.4V (380/1.732 = 219.4). When solar irradiance keeps at maximum, voltage at PCC keeps at rated voltage. When solar irradiance drops, voltage at PCC also drops a bit. Also, there is a transient process when system changes from one balanced state to another.

By the way, the curves of three-phase voltage are very smooth, while current are not. Similarly, when solar irradiance keeps at maximum, current can keep smooth. When solar irradiance drops, current can't. Since there is no more disturbance except solar irradiance, control algorithm should be improved in future.

V. CONCLUSION

Grid-connected PV generation is a kind of important renewable distributed generation. This paper presents a grid-connected PV simulation system with d-STATCOM. A kind of control strategy for local loads reactive power compensation and Fuzzy-PI algorithm for DC link voltage control are proposed. The simulation results show that grid-connected PV system with d-STATCOM can output different active power with different solar irradiance, realize reactive power compensation for local loads and keep grid-connected voltage steady. This work is willing to contribute to the development of renewable energy power generation and smart grid.

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