Compensation of KVar and Controlling DC link Voltage using Fuzzy-based Grid-connected PV System with d-STATCOM

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***Abstract*- Substantial PV power generation connecting to grid will bring a lot of challenges, such as voltage constancy, KVar compensation, operational consistency and so on. In order to grasp neighbouring loads KVar compensation and improve controllability of PV system, it should use new switching devices and superior control Substantial PV power generation connecting to grid will bring a lot of challenges, such as voltage constancy, KVar compensation, operational consistency and so on. In order to grasp neighbouring loads KVar compensation and improve controllability of PV system, it should use new switching devices and superior control methodology of Voltage Source Converter(VSC). This paper focuses on control approach of VSC to realize neighbouring loads KVar compensation and become stable DC link voltage. To some extent, VSC can be used as d- STATCOM. This paper also developing SIC MOSFET, which can recognize higher switching frequency. The control approach of VSC (d-STATCOM) includes two parts: DC link voltage control and internal current loop control. By using Fuzzy-PI, DC link voltage can be smoother and stable. A parameter-self- adjustable Fuzzy-PI controller has simpler arrangement and superior robustness when fuzzy logic control and PI control are combined together suitably. Real power current of inner current loop is regulated by tracking output variables of DC link voltage, while KVar current is corrected by tracking neighbouring loads KVar consumption. The result shows grid-connected PV system with d-STATCOM can compensate neighbouring loads KVar, output real power stably and keep grid-connected voltage steady.**

Index Terms-- Grid-connected PV; d-STATCOM;VSC; Fuzzy-PI Control; KVar Compensation; SIC MOSFET; High Frequency Switching

INTRODUCTION

With the descent of the global environment, renewable energy, headed by PV power generation, has attracted worldwide concentration because of its advantages of environmentally clean, pollution-free and simple fitting[1]. In recent years, the distributed generation system of PV power generation is steadily developing from the island to the integrated grid, signifying that large-scale grid-connected PV will be the main mode of PV power generation[2]. PV power generation system is connected with low voltage distribution network through converter, realized to load power supply.

In larger light intensity, it can provide supply to nearby neighbouring loads . When the light intensity is low, neighbouring loads are supplied by power grid.
With the new changes of power grid and load, high tech electronic supplies and the new challenges of the infiltration of power electronics technology, a more number of inductive loads connected to large power grid, it may lead to power grid voltage distortion in the ending, 3-phase unbalance and impact KVar and other complicated conditions, which will have bad impacts on the distribution network[3-5].

In order to regulate the voltage of terminals of the grid, the usual method of KVar compensation, such as SVC, SVG and STATCOM, which increases cost of power equipment. With the result of research, the main structure of PV inverter and d-STATCOM is fully reliable, hence PV power generation system can be installed in the distribution network of terminals to provide KVar, therefore the Voltage Source Converter (VSC) of grid-connected PV is will place major role.

In order to the real power production and KVar compensation in the grid-connected PV system, the key is to detect neighbouring loads current and reference currents of active and reactive component of grid. The reactive component mainly reflects KVar requirement by neighbouring loads, and active component reflects the real power requirement by neighbouring loads. Also, DC link voltage of VSC is maintained constant to provide continuous output. A lot of researches on KVar compensation nowadays proposes a phase locked loop (PLL) to obtain the KVar compensation more accurately based on the discrete Fourier transform(DFT), but it is complicated in operation and necessity of the controller. Ref[7] uses residual power energy of multiple PV inverter to output KVar, which can provide voltage sustain for the line, the communication between each PV power supply is established, and the algorithm is solved according to the

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voltage regulate target, and the KVar necessary by each inverter is obtained and uses on-load tap transformers to regulate voltage variation caused by access of the distributed generation and also discusses PV distributed generation system with KVar compensation, current controlled SVPWM algorithm, weak grid and Fuzzy-logic based MPPT control.

In this paper, VSC (d-STATCOM) is introduced to compensate neighbouring loads KVar and regulate DC link voltage, which is better than the conventional SVC. The regulating approach consists of two loops: outer control loop of DC link voltage and inner current control loop. Fuzzy-PI control is introduced to regulate DC link voltage. A kind of nonlinear control algorithm does not need to establish a accurate mathematical model. The adaptive PI parameters can be attuned to make system has better strength. A method based on direct KVar 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 favourable to eliminate harmonics. The control approach proposed in this paper can efficiently improve system control performance, and the effectiveness is proved in results.

SYSTEM STRUCTURE

Grid-connected PV system is combined with number of series and parallel combinations of PV, MPPT module, VSC (d-STATCOM) module, neighbouring loads and distribution network. Fig. 1 shows the system structure.

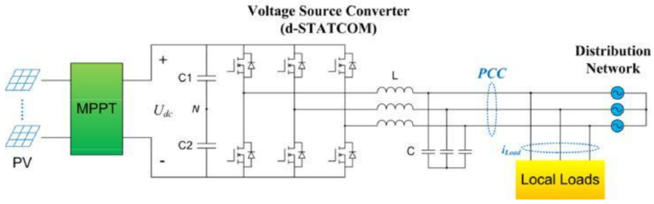

Figure 1. System structure

The main reason of grid-connected PV system is to transmit real power of PV array to grid. While, according to needs, VSC (d-STATCOM) can grasp KVar compensation of neighbouring loads, which means power factor of distribution network is near to unity power factor. This is what distribution provider needs. On the other hand, DC link voltage of VSC (d-STATCOM) and voltage at PCC should remain steady under any condition.

For PV array, the system produce a maximum of 10.7kW at 1000W/m^2 of sun radiation. The PV array having seven parallel strings and each string has five series-connected modules. Each module consist of ninety six cells. In simulation model, PV array modules are modelled accurately, which is nearer to actual conditions.

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

For VSC (d-STATCOM), Six-armed-H-bridge converter structure is used. It is also seen as a Three-level NPC (Neutral Point Clamped) converter. The system adds on neighbouring loads KVar 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 KVar or voltage at its terminal by controlling the amount of KVar 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 real 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 neighbouring 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.

PROPOSED CONTROL APPROACH

Fig. 2 shows VSC control approach of VSC controller.

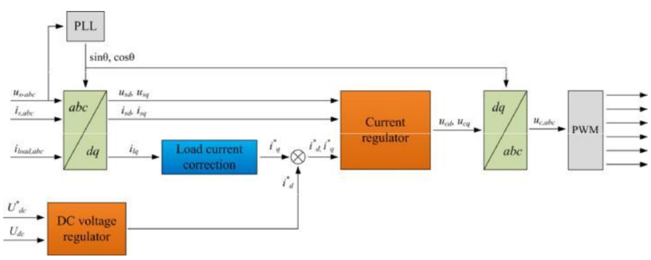

Figure 2. VSC control approach

As mentioned before, VSC controller needs voltage and current data on PCC ($u_{s,abc}$ & $i_{s,abc}$), current data of neighbouring 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 steady DC link voltage in the locality of reference value. While, due to DC output voltage of PV is nonlinear, it does not recover 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 recover grid-connected performance. The DC link voltage control diagram with Fuzzy-PI algorithm is shown at Fig. 3.

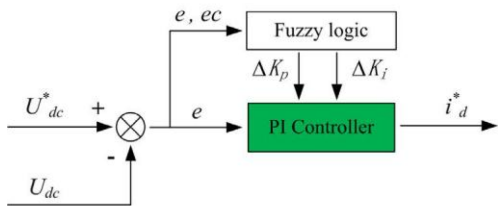

Figure 3. DC link voltage control diagram with Fuzzy-PI

Unlike traditional PI control algorithm, Fuzzy-PI control algorithm uses fuzzy logic to regulate 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 compassion, and better strength. Membership functions of *e* and *ec* are shown as Fig. 4.

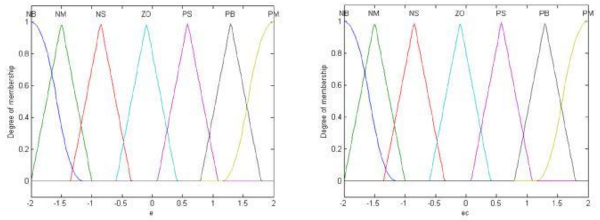

Figure 4.membership functions of *e* and *ec*

According to PI controller debugging familiarity, 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 real power injected by VSC (d-STATCOM) from PV to grid is given by:

$$P^* = U_{dc} I_{dc}^* = U_d i_d + U_q i_q \quad (1)$$

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

$$Q^* = U_d\, i_{id} - U_q\, i_{id} \quad (2)$$

where, *ud* and *uq* 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 neighbouring loads current.

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

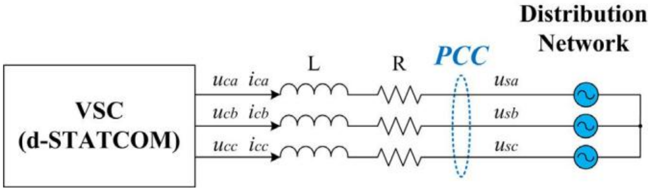

Figure 5. Simplified connection of VSC (d-STATCOM) to Distribution Network

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 KVar control approach can be proposed. The control diagram of active and reactive current is shown in Fig. 6.

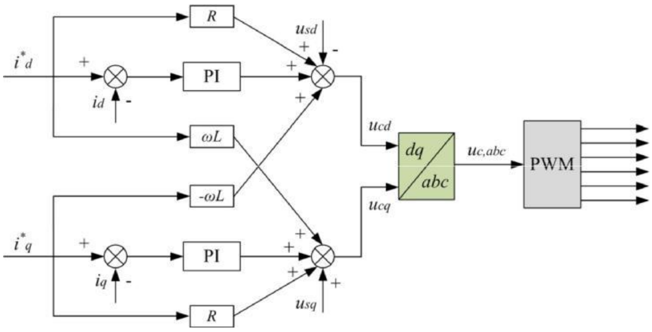

Figure 6. Control diagram of active and reactive current control

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

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

IV. SIMULATION RESULTS

The proposed grid-connected PV system shown in Fig.1 is simulated in this part, which contains without transformer VSC structure. The main task of the simulation is to appraise the performance of proposed control approach in injecting the energy produced by PV array and the KVar compensation of neighbouring 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 real power is shown in Fig. 7:

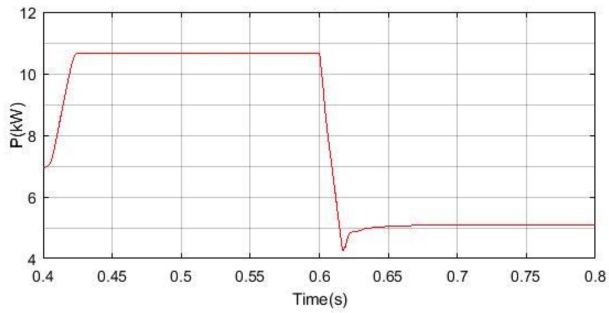

Figure 7. PV output real power

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

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

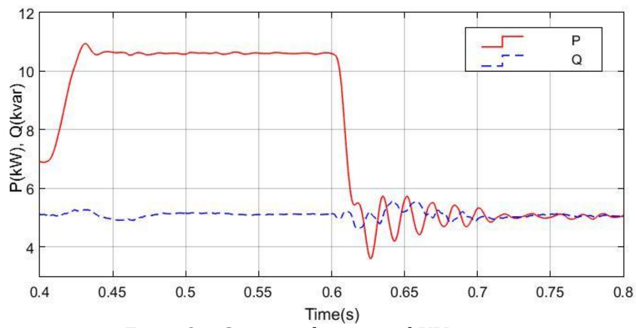

Figure 8. Output real power and KVar

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

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

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

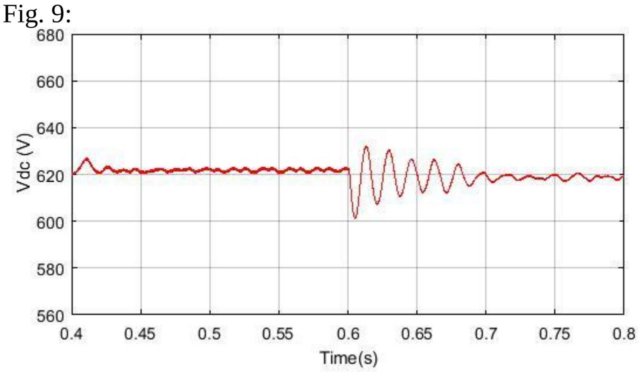

Figure 9 Dc link voltages of VSC

From 0.4s to 0.6s, DC link voltage keeps stable. 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:

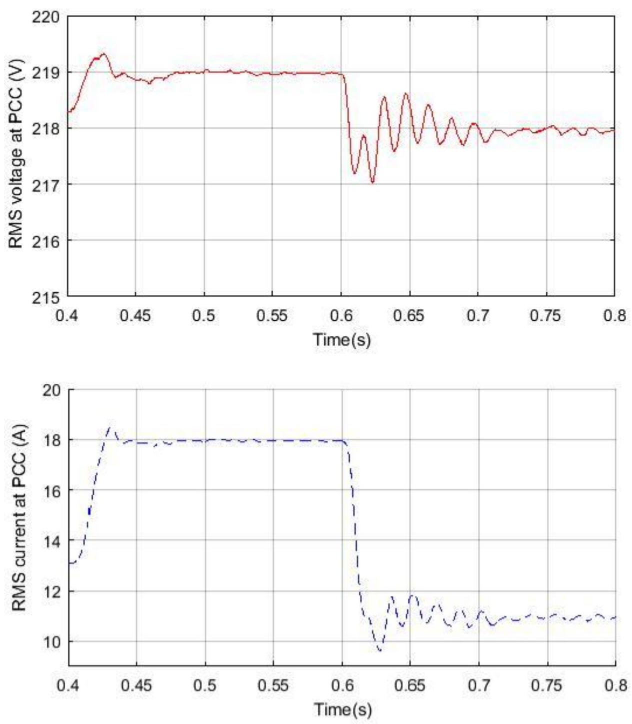

Figure 10. RMS voltage and current at PCC

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.

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 approach for neighbouring loads KVar 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 real power with different solar irradiance, realize KVar compensation for neighbouring 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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