Research of Hierarchical Control Strategy for Photovoltaic & Battery Storage System

Qian Sun  
*Electric Power Research Institute of State Grid Henan Electric Power Company, Zhengzhou, Henan, China*

Qi Lei*  
*State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, Hubei, China*

Baofu Guo  
*XJ Group Corporation, Xuchang, Henan, China*

Jianwei Ma  
*Electric Power Research Institute of State Grid Henan Electric Power Company, Zhengzhou, Henan, China*

Chang Ye & Shihong Miao  
*State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan, Hubei, China*

**ABSTRACT:** According to the complementarity of photovoltaic and battery generation, the structure of photovoltaic and hierarchical storage system and its typical control methods are described in this paper, considering the demand of load side and distribution grid, hierarchical control strategy including primary control and secondary control is discussed, the model of converters and the control loop are presented in detail. The overall structure of hierarchical control composed by P-Q control and voltage-phase droop control is brief and cost-less. A simulation of the basic part in hierarchical control strategy under PSCAD/EMTDC environment is also included in this paper. The evaluation of hierarchical control strategy shows that photovoltaic and hierarchical storage system is practical for the application of distributed generators.

**Keywords:** hierarchical control; photovoltaic; battery storage; P-Q control

1 INTRODUCTION

As the issues of environmental pollution and depletion of fossil energy become extremely serious these years, clean energy generation and synchronization technology has been the focus of energy science researching and quickly attracted a wide range of global attention. As a mature technology, photovoltaic generation has superior properties such as low-cost and easy-deploying, the connection of small PV units with power ratings less than a few tens of kilowatts to low voltage networks potentially increases the permeability of clean energy generation [1], [2].

For distributed photovoltaic (PV) array units installed in the load side, the maximum power output of each unit is definitely restricted and will be affected by external factors such as light intensity, temperature etc. These limitations caused great challenges for generation-load coordinate dispatching and power system stability [3]. In order to minimize the volatility of PV unit output, distributed storage devices are used as a supplementary method to form the Distributed PV-Storage Joint Generation mechanism, which brings more flexibility in power consumption.

Considering the reliability of distributed grid, a certain capacity of the redundant power supply is very
necessary in emergency control. Centralized Storage System composed by large scale of battery series along with DC-DC converters is the common practice to accomplish the dispatching requirements.

Due to the complementary features of distributed PV units, low density battery storage and centralized storage, the hierarchical storage architecture for high permeability PV application is shown in Figure 1. It comprises a low voltage (LV) network, AC loads, one centralized storage system and two distributed joint generation systems. Each distributed generator (battery series and PV array) are coupled with a DC-DC converter controlled by typical strategy, DC voltage buses are connected to LV network by DC-AC converters which provide a variety of control objectives including reactive and active power control, voltage control, frequency control etc. Considering the overall control strategy of distribution network complemented by PV and battery storage, control schemes are discussed based on supervisory and communication structure with a central controller in [4] and [5], distributed control based on multi-agent system is shown in [6]-[8], and the traditional autonomous converter modeling has been introduced in [9]-[11].

Figure 1. PV and hierarchical storage application.

Based on the practical application architecture of the PV & hierarchical storage system, the work described in this paper regards the hierarchical classification of control strategy, which can be classified as the primary control and the secondary control. Primary control manages the converter energy interface with typical P-Q, MPPT methods and constant DC voltage control, secondary control is responsible for the voltage and frequency level of the AC bus, which can response to the changing from the load side. With the application of hierarchical control, the utilization ratio and stability of distributed photovoltaic generation will be increased. Besides, the total cost of clean energy deployment will be reduced as this structure needs less supervisory and communication facilities.

2 ANALYSIS OF PRIMARY CONTROL

2.1 Control scheme of the DC-DC converter

Considering the practical application of distributed joint generation, battery series and PV arrays are usually connected to the AC bus through a two-step converter topology, which comprises a DC-DC converter and a DC-AC converter, comparing with the single DC-AC converter structure, two-step converter can contribute more flexibility and cost less control loop, namely, generation control and synchronization control can be decoupled to form the independent objective for each converter. The DC-DC converters are paralleled beside the DC bus and through the common DC-AC converter. The unidirectional DC-DC converter controls the PV array to approach the Maximum Power Point Tracking (MPPT); the bidirectional DC-DC converter maintain the DC bus voltage level to support the DC-AC converter [12].

As for the specific scheme of distributed joint generation controlling, the DC-DC converters connected with battery series are bidirectional which can work at boost and buck mode [13], changing between the charging and discharging status, as is shown in Figure 2. When T1 is driven by switch signal and T2 is off, converter is operating at buck mode and battery series are charging, if T1 is off and T2 has the input, the circuit is working at the boost mode and battery series are discharging.

For each thyristor used in the circuit, the switch signal is dominated by charge or discharge status and the setting value at terminal point. The calculating process is proposed in this paper, the state of charge (SOC) is used to generate the Brk_sig signal as described in equation (1) followed.

\[
\begin{align*}
\text{SOC} & \geq \text{SOC}_{\text{max}} & \text{Brk}_-\text{sig} &= 0\text{(charge)} \\
\text{SOC} & \leq \text{SOC}_{\text{min}} & \text{Brk}_-\text{sig} &= 1\text{(discharge)}
\end{align*}
\]

Where SOC represents the charging level of the battery, this process can be finished inside the battery series. If the SOC level is between the minimum value and the maximum value, the status of Brk_sig will be decided by the switch matrix. The switch matrix regards the value of Brk_sig, Vbatt and Ibatt, using the function in (2) to choose the right switch signal generated by the comparator of previous step, \(\alpha\) and \(\beta\) are manufacturing parameter related to battery type, which can be adjusted. SOC signal restricts the depth of discharging while the control signal can decide the speed of charging or discharging.
Voltage and current measured from the output side of battery series are fed to the block as input, two first order low pass filters are used to filter out the high frequency harmonics from these signals. The frequency, initial phase and duty cycle of the output wave provided by triangle generator can all be adjusted, thus creating a square wave with an amplitude of 0 or 1, then the square wave is fed into the level comparator along with the output of PI controller to generate the switch signal.

As for DC-DC converters connected with battery series in the centralized storage system, the control scheme has the similar structure as discussed in distributed joint generation. The DC-DC converter connected with PV array is used for MPPT control. This is achieved by creating a reference voltage (Vmppt) and then supplied to a PI controller which creates switching signals that force the voltage across the PV array to follow the reference voltage. The control scheme of MPPT is shown in Figure 3. The low pass filter, triangle generator and the comparator are the same as in Figure 2.

![Image](image.png)

Figure 3. Control scheme of DC-DC converter of PV.

MPPT control block that uses the Incremental Conductance Tracking Algorithm is introduced in (3), which is based on the slope of the PV array power curve [14]. The Maximum Power Point can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV).

\[
\begin{align*}
\Delta I & = I_{\text{ref}} - I_{\text{out}} \leq \alpha V_{\text{ref}} \quad \text{control} = 0 \\
\Delta I & = I_{\text{ref}} - I_{\text{out}} \geq \beta I_{\text{ref}} \quad \text{control} = 1
\end{align*}
\]

(2)

The control scheme discussed in Figure 2 and Figure 3 both indicate the concept of local control, which means the purpose of each DC-DC converter is pre-determined, the input parameters can be measured within the DC bus, thus getting rid of the influence from the secondary control, and reducing the complexity of supervisory and communication structure.

2.2 Control scheme of the DC-AC converter

Based on pulse width modulation (PWM) technology of voltage source inverter (VSI), various of DC-AC converter control methods including P-Q control, V-f control, virtual generator etc. have been discussed in [15] and [16]. P-Q control is easy to realize and can be fixed at a certain active or reactive power output level, V-f control can help maintain the voltage and frequency level of the AC bus. As the primary control the primary control method in this paper aims at separated control with less communication line between converters and buses, on the other hand, the PV arrays of distributed joint generation are working at MPPT mode to generate the maximum power, it’s natural to restrict the DC-AC converter connected to distributed joint generation under P-Q control. The typical P-Q control block is shown in Fig. 4. It comprises the expected P-Q input, V-I dual loop and the instruction voltage output. The overall process is based on double loop decoupling under park transformation.

![Image](image.png)

Figure 4. V-I dual loop of P-Q Control.

Where \( P_{\text{ref}} \) and \( Q_{\text{ref}} \) are the pre-loaded parameters, the specific values are calculated according to the number and rated-power of PV arrays. \( \omega \) represents the grid frequency, \( U_a \) and \( U_q \) are voltage at points of common connection (PCC) under \( dq0 \) axis.

![Image](image.png)

Figure 5. Diagram of negative sequence compensation

When the three phase voltages are unbalanced, in order to compensate the negative sequence component of the PCC voltage, there will be both positive sequence component and negative sequence component in the DC-AC converter’s output current and voltage. The process shown in Figure 4 is only for three phase balanced occasion. Based on the duality of positive sequence and negative sequence, if the \( dq \) component of negative sequence are feed to the V-I dual loop, the output voltage command \( e_{abc}^p \) will be \( e_{abc}^N \) which represents the negative sequence voltage tuning signal, the compensation process is shown in Figure 5, two notch filters are used to extract the negative sequence voltage of AC bus. The sum of \( e_{abc}^p \) and \( e_{abc}^N \) will be taken as the final voltage tuning signal, after triangle-carrier modulation, the driven signal of thyristors
can compensate the impact of three phase unbalance, thus maintain the three phase symmetry at PCC.

\[ V_{\text{controlled oscillator}} \rightarrow \text{phase detector} \rightarrow \text{loop filter} \rightarrow \text{abc/dq0} \rightarrow U_{\text{primary control}} \]

Figure 6. Process of hardware-software combined PLL.

Usually the DC-AC converter control strategy is presented under the dq0 synchronous rotating coordinate system, park transformation needs the phase of voltage as reference, then the phase locked loop (PLL) is used to measure the voltage phase, however, the precision of hardware based PLL is decreased when three-phase unbalance occurs, thus the software PLL method is proposed. When the distribution grid is operating at normal state, the q axis voltage after park transformation remains zero, so it’s obvious that keeping the q axis voltage as zero will cause the output voltage of DC-AC converter to track the phase of the grid while reducing the impact of three-phase unbalance. The software and hardware combined PLL process is shown in Figure 6. Firstly, phase selector choose the hardware PLL output \( \theta_h \) to feed the abc/dq0 transformation, \( U_q \) is fed back to the software PLL and then \( \theta_s \) will be the new reference of abc/dq0, this mechanism will react every time when the grid voltage reaches a new status.

3 ANÁLYSIS OF SECONDARY CONTROL

Considering the application of hierarchical storage distribution grid with high permeability PV generators, the primary control strategy discussed above has the following features: 1) the target of primary control is largely relevant with the distributed joint generation, including DC-DC converters and DC-AC converters; 2) the objective of primary control are all fixed or pre-setted, namely, the P-Q values of DC-AC converter control are defined according to the manufacturing parameters of distributed joint generation, the DC bus voltage value are setted based on the number of battery units in each series; 3) the process and parameters of primary control are mostly separated, which means the changing of distribution grid operating status and the commands from distributers have less impact on primary control strategy.

Comparing with primary control, secondary control is designed to react with the voltage or frequency fluctuation, and have the ability to maintain the voltage and frequency level if load variation occurs. The main target of secondary control is the converters inside centralized storage system and the parameters of control block should be adjustable.

3.1 Modeling of voltage and frequency control

There are three typical DC-AC converter control methods: P-Q control, droop control and V/f control. V/f control can keep the output voltage amplitude and frequency as expected, but the output power should be large proportion of the connected grid and is easy to generate circulating current. Droop control is designed to imitate the feature between P-f and Q-U of traditional generators, which can take part in the voltage and frequency control of distribution grid. The DC-AC converters under primary control can not directly adjust the voltage and frequency as they are dominated by certain P-Q value. So the DC-AC converter connected with centralized storage system should be controlled by droop method, these converters can help sustain the voltage and frequency level, thus realizing the goal of secondary control [17].

The specific details of DC-AC converter connected to centralized storage system is shown in Figure 7, \( U_{dc} \) is the dc voltage output of DC-DC converter, \( U_i \angle \delta_i \) is the voltage at the connection, \( ZL \theta \) stands for the impedance of the distribution line. The output power can be calculated as equation (4).

\[
P = \left( \frac{U_i}{Z} \cos \delta - \frac{U_{dc}}{Z} \right) \cos \theta + \left( \frac{U_i}{Z} \sin \delta \right) \sin \theta
\]

(4)

In low voltage distribution network, line impedance is mainly resistive, \( \theta \) is nearly zero, \( \delta \) is very small, \( \sin \delta \approx \delta \) can be used to simplify (4) as (5):

\[
P = \frac{U_i(U_i - U_{dc})}{R} \cos \delta
\]

(5)

\[
Q = \frac{U_i U_{dc}}{R} \sin \delta
\]

It’s easy to find out that voltage amplitude and phase are affected by \( P \) and \( Q \) separately, by introducing the method of negative feedback and voltage oriented control, the rule of voltage-phase droop control is shown in (6).

\[
\delta^* = f_0 + a(Q - Q_o)
\]

\[
U^* = U_o - b(P - P_o)
\]

(6)

3.2 Structure of voltage-phase droop control

The overall scheme of voltage-phase control is shown
in Figure 8. It comprises the P-Q computation process, droop control, reference voltage computation and V-I dual loop. The transformation between abc axis and dq0 axis can also use the negative sequence compensation method described in Figure 5 and Figure 6.

$$P = (u_{d}i_{d} + u_{q}i_{q}) \cdot \omega / (s + \omega)$$

$$Q = (u_{q}i_{d} - u_{d}i_{q}) \cdot \omega / (s + \omega)$$

(7)

Droop control is designed based on equation (6). $U_{odref}$ and $\delta_{odref}$ are the output voltage reference of DC-AC converters when disconnected from PCC. a and b are the droop ratio related to voltage amplitude and voltage phase. $f^*$ is the frequency of the distribution grid. The output $\theta$ is also used as a reference to restrict the $U_{eq}$ at zero point, as is shown in Figure 9.

$$P = \frac{U_{odref} + u_{eq}}{\alpha} \cdot \omega$$

$$Q = \frac{Q_{odref} + \delta_{odref} + \delta}{f^*} \cdot \sum k_{s} \cdot \sum \theta$$

(8)

Figure 9. Structure of droop control.

The voltage-current dual loop is shown in Figure 10. The inside loop is designed to track current which considered shunt effect in the parallel capacitor, the current loop has to respond rapidly, so the time constant should be small while the proportional coefficient can be larger to reduce the tracking time when designing the PI controller. The outside loop is used to track voltage, the voltage lost on the inductance of distribution line is included.

4. SIMULATION AND ANALYSIS

4.1 Simulation parameters

According to the primary control and secondary control strategy, the simulation platform under the PSCAD/EMTDC environment was developed in order to evaluate the behavior of the control structure. A test network was built based on a micro grid in Henan Finance & Taxation School, and the single-line diagram developed in PSCAD is shown in Figure 11. The structure shows the connection between two distributed joint generations, one centralized storage system, transformers, and the distribution network, which is represented by a three phase voltage source. The high voltage side and low voltage side of transformer is 10kV/380V, the local AC loads are represented by fixed resistors which is basically for lighting, the capacity of local loads is 90kW, in order to sustain the power supply in a complete charging-discharging cycle, the battery capacity of centralized storage system is 400kWh considering the efficiency factor.

4.2 Results and analysis

The DC-DC converter connected with PV array is controlled by MPPT method, the actual output voltage $V_{pv}$ and MPPT reference voltage $V_{mppt}$ is shown in Figure 12, the initial reference irradiation is 1200W/m², the reference temperature is 20°C, at $t=2s$, the irradiation dropped to 1000W/m² at $t=4s$ and the temperature increased to 50°C at the same time. The $V_{mppt}$ fluctuates with the changing of environmental parameters while $V_{pv}$ can track the average value of $V_{mppt}$ with limited fluctuation, thus proving the ability of achieving maximum power output. The DC bus voltage and PV array power output is shown in Figure 13, $P_{pv}$ droppped at $t=2s$ and $t=4s$ due to the same reason, the new output level can be sustained after each transient process, as the DC-DC converter connected with battery series in distributed joint generation is controlled under constant DC voltage control, the DC bus voltage $V_{dc}$ is set to 0.7kV. At $t=2s$ and $t=4s$, $V_{dc}$ can cross the PV array power drop by changing the discharging speed of battery series, the waveform of $V_{dc}$ shows the DC bus can provide a
robust DC side voltage support for DC-AC converter. Figure 14 shows the active and react power output of distributed joint generation and centralized storage system, which are operated by primary control and secondary control separately, at t=0.5s, the DC-AC converter in distributed joint generation was given a $P_{ref}$ of 30kW, at t=2s, $P_{ref}$ was reduced to 8kW and $Q_{ref}$ was reduced to 16kW (inductive) from zero, at t=3s, $Q_{ref}$ was changed to 16kW (capacitive), it was shown that the actual power output of DC-AC converter in distributed joint generation can follow the changing of $P_{ref}$ and $Q_{ref}$. The upper part of Figure 14 indicates the power output of DC-AC converter in centralized storage system and the distribution grid, and it’s obvious that when the P-Q output of distributed joint generation changes, the output of secondary control can compensate the power variation.

Figure 12. Voltage of PV array under MPPT control.

Figure 13. DC bus voltage and PV array power output.

Figure 14. P-Q output of primary and secondary control.

Figure 15 and Figure 16 demonstrates the dynamic features of centralized storage system under voltage-phase control. Figure 15 shows that the voltage of AC bus is changed according to the active power output variation of centralized storage system, when active power output increases, AC bus voltage will drop and vice versa, the result verified the voltage droop feature of battery series. The relationship between frequency on AC bus and reactive power output of centralized storage system is shown in Figure 16, it’s obvious that frequency will alternate to the new operating status as active power output changes, which presents the positive correlation discussed in equation (6), during the fluctuation of reactive power, the maximum difference of frequency is small and the center frequency is clamped to power frequency which is 50Hz in the simulation. The relationship of P-U and Q-f shows that secondary control strategy based on voltage-phase droop control can take advantage of centralized storage system’s droop feature to react with the changing of power output of other distributed generation.

Figure 15. P and AC bus voltage by voltage-phase control.

Figure 16. Q and frequency under voltage-phase control.

5 CONCLUSIONS

This paper purposes the structure of photovoltaic and hierarchical storage system and describes the typical control methods, hierarchical control strategy comprises primary control and secondary control, primary control is conducted to achieve PV array MPPT control, DC bus voltage control and DC-AC converter P-Q control, secondary control is designed to control...
the DC-AC converter connected with centralized storage system by the improved voltage-phase control. In summary, primary control services the distributed PV arrays and low capacity battery series, the purpose is to minimize the volatility of PV unit and getting the maximum power output. While secondary control services the centralized storage system, achieving the ability to track the voltage and frequency of AC bus. The operating targets of primary control and secondary control are separate and independent, thus reducing the investment of communication and supervisory systems between central controller and distributed equipment.

Based on the overall structure of hierarchical control and the typical model of PV arrays and battery series, a simulation of the photovoltaic & hierarchical storage system under PSCAD/EMTDC is demonstrated. The control strategy and evaluation shows that photovoltaic along with hierarchical storage system is an practical way for distributed generators application.

ACKNOWLEDGEMENT

This paper is sponsored by 2015 Science-Tech Project ‘Research and application of energy storage technology in distributed photovoltaic power generation with high permeability’ of STATE GRID Corporation of China (GN: SGHADK00PJJS1500060).

REFERENCES

[1] Hatzigioryou N, Asano H, Iravani R, et al. 2007. Microgrids. Power & Energy Magazine IEEE, 5(4): 78-94.
[2] Pepermans G, Asen J, Haeseldonckx D, et al. 2005. Distributed generation: definition, benefits and issues. Energy Policy, 33(6): 787-798.
[3] Wang C, Wang S. 2008. Study on some key problems related to distributed generation systems. Automation of Electric Power Systems.
[4] Chamorro H R, Ramos G. 2011. Microgrid central fuzzy controller for active and reactive power flow using instantaneous power measurements. Power and Energy Conference at Illinois (PECII), 2011 IEEE, pp: 1-6.
[5] Belfkira R, Zhang L, Barakat G. 2011. Optimal sizing study of hybrid wind/PV/diesel power generation unit. Solar Energy, 85(1): 100–110.
[6] Wang Z, Yang R, Wang L. 2011. Intelligent multi-agent control for integrated building and micro-grid systems. Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES, pp: 1-7.
[7] Sujiñ A, Agarwal S K, Kumar R. 2014. Centralized Multi-Agent implementation for securing critical loads in PV Based micro grid. Journal of Modern Power Systems & Clean Energy, 2(1): 77-86.
[8] Dimeas A L, Hatzigioryou N D. 2005. Operation of a multi-agent system for microgrid control. Power Systems IEEE Transactions on, 20(3): 1447-1455.
[9] Barker C D, Whitehouse R. 2010. Autonomous converter control in a multi-terminal HVDC system. AC and DC Power Transmission, 2010. ACDC. 9th IET International Conference on, IET, pp: 1-5.
[10] De Brabandere K, Bolsens B, V D K J, et al. 2007. A voltage and frequency droop control method for parallel inverters. Power Electronics, IEEE Transactions on, 22(4): 1107-1115.
[11] Lee B K, Ehsami M. 2001. A simplified functional simulation model for three-phase voltage-source inverter using switching function concept. IEEE Transactions on Industrial Electronics, 48(2): 309-321.
[12] Duryea S, Islam S, Lawrance W. 2001. A battery management system for stand-alone photovoltaic energy systems. IEEE Industry Applications Magazine, 7(3): 67-72.
[13] Zhang F H, Zhu C H, Yan Y G. 2005. The controlled model of bi-directional DC-DC converter. Proceedings of the CSEE 2005.
[14] Rajapakse A D, Muthumuni D. Simulation tools for photovoltaic system grid integration studies. Electrical Power & Energy Conference (EPEC), 2009 IEEE, pp: 1-5.
[15] Vasquez J C, Guerrero J M, Luna A, et al. 2009. Adaptive droop control applied to voltage-source inverters operating in grid-connected and islanded modes. Industrial Electronics IEEE Transactions on, 56(10): 4088-4096.
[16] Mou X, Daqiang B I, Ren X. 2010. Study on control strategies of a low voltage microgrid. Automation of Electric Power Systems, 34(19): 91-96.
[17] Blaabjerg F, Teodorescu R, Liserre M, et al. 2006. Overview of control and grid synchronization for distributed power generation systems. IEEE Transactions on Industrial Electronics, 53(5): 1398-1409.