Dynamic Performance Evaluation of PV Integration

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Abstract. Topics on adaptability of Grid-connected photovoltaic systems (GCPVS) under sag conditions has been proposed. A basic low-voltage-ride-through (LVRT) strategy widely used in engineering practice is taken in this paper and manages to ride through different sag conditions. The role of hardware protection has been discussed in detail. By simulation validated that the proposed GCPVS have strong adaptability

1. Introduction

With the promotion of renewable energy policy among different countries, Grid-connected photovoltaic systems become a major type of power equipment as it provides power supplement in both LV and MV power network. Grid codes has been proposed to ensure that GCPVS can stay connected during voltage sag according to grid voltage conditions [1].

Different topics on improving the LVRT ability of GCPVS have been discussed. Researches on improving the performance of the current controller has been made to maximize the dynamic responses during and after the fault [2], however the computation complexities has not been reduced which makes them less practical. Power balance is vital in maintaining the operation of GCPVS. In [3] an interleaved boost converter is proposed to increase power conversion efficiency and multiple modes are constructed for the limitation of PV array and improve the post-fault dynamic response of a photovoltaic system. Authors of [4] discussed on the asymmetrical control strategies to stabilize DC voltage and a none-MPPT mode for boost converter to lower PV power. PV inherent characteristics such as voltage and power droop is embed into boost converter control in [5].

In this paper, both single-stage and two-stage GCPVS are investigated for the evaluation of PV adaptability under sag conditions. A 500-kW GCPVS model is carried out in simulation section. Different test conditions are simulated to verify the adaptability of GCPVS in MV network. Assistant methods such as improvement in control strategies and addition of hardware protection is present in the paper to build a simulation model close to engineering practical.
2. Modelling and proposed control strategies during faults

2.1. System description
Two-stage and single-stage systems are both widely used in power generation systems [6]. During normal grid condition, MPPT is online to ensure the maximum power extraction from PV array. Single-stage GCPVS generate DC referenced voltage and outer voltage controller plays the role to maintain DC voltage at MPP. With boost converter online, DC voltage could operate at a fixed operation point and expand the operation range by means of adjustment of duty cycle. INC-Cond MPPT method [7] is used to generate the reference voltage in both cases.

![Figure 1. LVRT Requirement in grid codes of China [2]](image1)

2.2. Response characteristics and concerns about GCPVS under sag conditions
As grid faults occurs, GCPVSs experience sag events and voltage signals are detected almost instantaneously. Symmetrical and asymmetric fault will bring down PS component. The response characteristics of GCPVS during symmetrical sags are discussed separately in this section. Power balance between is maintained during normal voltage condition with the DC-voltage control online, the output power from PV array is fully transferred to PCC and DC voltage operates at a fixed value.

Array output power $P_{pv}$ and inverter active power $P_{g}$ satisfy an equilibrium equation.

![Figure 2. Dual Current-loop Control Structure](image2)
According to the instantaneous power theory, \( P_g \) can be expressed in the form

\[
P_g = \frac{3}{2} \left( u_d i_d + u_q i_q \right)
\]  

During Symmetrical voltage sag, PS d-component of the voltage falls and q-component is keep zero. Equation (1) can be rewritten as

\[
\Delta P = P_{pv} - \frac{3}{2} u_d i_d = \frac{1}{2} C \frac{dU_{dc}^2}{dt}
\]  

To maintain the power balance, the active power injected \( P_{pv} \) is kept constant, d-component of the current \( i_d \) increase as the voltage \( u_d \) decrease. AC over-current protection would trigger if the current exceeds the protection set-point. With the current limit online, \( P_g \) is finally restricted as \( u_q \) reduced, the unbalanced active power \( \Delta P \) rises. The accumulated energy brought by \( \Delta P \) into DC-link capacitor push up DC voltage.

In a two-stage system, MPPT controller is decoupled with the GSC control system. As the result if no additional control strategy is added to the boost converter controller, MPPT stays in operating mode and \( P_{pv} \) delivers the maximum power regardless of the GSC controller, \( \Delta P \) is never mitigated in whole circumstance. Extra protection circuit is vital to avoid overvoltage on the DC-bus. Several simple strategies [3][7] has been proposed such as the implement of crowbar and short-circuit/open-circuit of the PV array. Yet considering the engineering practice, a brake-chopper employed in wind turbines [8] is added to the DC bus to limit DC voltage within appropriate range. Hysteresis control is presented against overvoltage. The protection parameter is listed in Table 1.

| Symbol | Parameter description | Value |
|--------|-----------------------|-------|
| \( R_{br} \) | Brake Resistance | 0.6Ω |
| \( U_{br} \) | Brake chopper relay voltage | 550V |

3. Simulation scenarios and results

![Figure 3. Schematic Diagram of the Test Circuit](image)

In this section, simulation test on the adaptability of GCPVS during sag conditions. Fig. 3 shows schematic diagram of the test circuit. Grid faults are simulated at Bus3 close to main grid. Protections on DC and AC side are considered online as a judgement of adaptability. The models are built with Matlab/Simulink software. The two-stage model is equipped with a boost converter to extract maximum power from the array while a brake-chopper to consume redundant energy. DC voltage is
set to 500V in normal conditions. The single-stage model operates at 547V in standard test conditions (STC). Key parameters of the GSCare listed in Table 2. Boost converter switching frequency is set to 5000Hz, the MPPT controller parameter is set to 0.001/5. Test conditions is carried out in reference to LVRT curve in the grid code GB/T 19964-2012, as Table 3 illustrated.

### Table 2. Key Parameter of the GSC

| Symbol  | Parameter description       | Value         |
|---------|-----------------------------|---------------|
| $P_b$   | GSC rated power            | 500KVA        |
| $U_{dc}$ | DC-voltage operating range | 400-820V      |
| $C_{dc}$ | DC-link capacitance        | 30mF          |
| $U_g$   | Grid line voltage          | 270$\sqrt{2}$V |
| $f_g$   | Grid frequency             | 50Hz          |
| $L_g$   | AC L filter inductance     | 0.08mH        |
| $f_{sw}$ | Inverter switching frequency | 19.5Hz       |
| $U_{dc\_ref}$ | DC voltage set point     | 500V/547V     |
| $K_{pu}$, $K_{iu}$ | Voltage controller parameter | 5/600       |
| $K_{pi}$, $K_{iu}$ | Current controller parameter | 0.35/25      |

### Table 3. Sag Case of the Adaptability Test

| Sag case | Sag Amplitude (pu) | Duration (ms) | Fault occurrence (s) | Fault clearance (s) |
|----------|--------------------|---------------|----------------------|---------------------|
| 1        | 0.015              | 150           | 0.1                  | 0.25                |
| 2        | 0.2                | 625           | 0.1                  | 0.725               |
| 3        | 0.5                | 1250          | 0.1                  | 1.35                |

Two-stage system under STC(Irradiance:1000W/m2/Temperature: 25 °C PV Output power 1.008p.u.) is tested in sag case 1. Simulation result is illustrated in Fig.4 a). ZVRT(zero voltage ride through) is firstly carried to testify the adaptability of two-stage GCPVS in extreme cases. A three-phase to ground fault occurs at 0.1s and lasts for 150ms. During the voltage sag, the injected power from inverter Falls to near 0 while MPPT keeps online to generate full power from PV array. The unbalanced power pull DC voltage up to 1.1p.u, brake chopper switches to discharge the overplus right after. DC voltage is kept close to 1.1 p.u. Reactive current is injected into grid yet voltage component is close to 0. The consequent power is not obvious. The GCPVS stays grid-connected and operates correctly during the whole period and overcurrent/overvoltage is avoided.
Two-stage system under STC is tested in sag case 2 and 3. Simulation result is illustrated in Fig. 4 b) and c). It is obvious sag condition in the two cases is less severe than scenario 1. The brake chopper helps the system ride through the fault. Reactive current is generated according to the reactive current curve in Fig. 1. While the current limitation is accomplished following Eqn. \[ I_d = \sqrt{1.1^2 - I_q^2}. \] In sag case 2, the q-component of the current is set to 1.05 p.u., and corresponding d-component of the current is set to 0.328 p.u.; The active and reactive power is 0.066 p.u. and 0.21 p.u.; In sag case 3, the q-component of the current is set to 0.6 p.u., and corresponding d-component of the current is set to 0.922 p.u.; The active and reactive power is 0.461 p.u. and 0.3 p.u. During the period, the peak current is limited within 1.2 p.u., LVRT requirement is met. GSC injects the peak reactive power when the sag amplitude is 0.45 p.u. 0.304 p.u. can be injected into grid. Grid voltage support can be significant in such cases.

4. Conclusion

In this paper, adaptability of GCPVS under sags is tested. Both single-stage and double stage system is modeled and simulated using Matlab/Simulink tool. LVRT requirement is considered and discussions upon the dynamic response is made and verified in the simulation section. Simulation results prove the strong adaptability of the GCPVS, as it derates the output current and avoids overvoltage problem, finally promote the grid voltage support ability.

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