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Fault analysis of solar photovoltaic penetrated distribution systems including overcurrent relays in presence of fluctuations

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ABSTRACT

Intermittence from solar photovoltaic (PV) source can deteriorate overcurrent relays (OCRs) response to fault. This paper proposes a method for fault analysis with OCRs consideration to discuss relays faults currents fluctuations in time against PV fluctuations. The simulated PV fluctuations are short time dynamic high and low irradiations fluctuations and PV connection and disconnection based PV-dominated feeders. Two distribution systems (DSs) based accurate PV systems are modeled separately with and without Battery Energy Storage System (BESS) for the purpose of proposed method. Series and parallels PV modules are arranged to model accurate 6.5 kV PV farm power. Two level three-phase voltage source inverter (VSI), DC-DC boost converter and LCL filter are applied for each PV system. Precise detailed control strategies are implemented in PSCAD software. This paper proposed method complies with congestion which is frequently avoided in literature. The results discussions based proposed method clarified PV fluctuations scenarios impacts on OCRs dynamic fault currents profiles in presence and absence of BESS and clearly revealed and argued related important findings. In addition, OCRs performance is shortly analyzed based particle swarm optimization (PSO) algorithm efficiently coded in Matlab. The obtained results could be very profitable to power system relaying operators to handle protection challenges with PV power fluctuations.

1. Introduction

Attention is needed towards PV fluctuations to conveniently address relay malfunctions in electrical power system. Therefore, DSs fault analysis involving OCRs against PV fluctuations scenarios such as dynamic irradiation fluctuations and PV connection and disconnection is worth investigating, and this paper focuses on that aspect using a new approach.

Mitigating PV fluctuations impact on DS protection is much needed. Namely, research articles, standards [1,2] and books [3,4] are progressively contributing to that goal. Renewable generation impact on protection systems [5,6]; fault current limiters to sustain OCRs with different distributed generators (DGs) [7]; renewable energy and various energy storage systems [8–13]; low voltage ride through (LVRT) capability [10,14,16]; fault current contribution from large PV systems [17]; innovative control strategies [8–11,18–20]; smoothing PV power output fluctuations [8,21]; power system frequency restoration [22]; mitigating temporary over-voltages [23] and PV grid connected systems performance and fault analysis [12,19,24–29] are some of the promising works achieved.

Moreover, the authors in [26,27] discussed, fault analysis on distribution feeders with high penetration of PV systems; accommodating high PV penetration on distribution feeders, respectively, where in [26], a method is proposed to estimate OCR operating time in PV-dominated distribution feeder. In [30], a numerical comparison of the effects of different types of DG units on OC protection systems in MV distribution grids is proposed. In [31], a new protective method for grid connected dispersed PV systems is developed to detect short circuit fault in distribution line. Procedures for fault location and isolation to solve protection selectivity problems in MV distribution networks with dispersed generation is carried out in [32]. A method for evaluation of OC protection in unbalanced DSs is available in [33].

In this paper based PV-dominated distribution feeders, we investigate OCRs maximum faults currents fluctuations analysis against short time fault while considering solar radiation fluctuations and PVs connection and disconnection in time. A method is proposed to address OCRs dynamic faults currents profiles analysis in time. In addition, other relevant aspects are carried out to highlight important findings.

Complex and accurate DSs models with and without BESS are employed in this paper to investigate fault analysis against dynamic high and low irradiation fluctuation making use of OCRs in a technically simple and special manner not proposed before. OCRs fault currents

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profiles in time are clearly analyzed based comparison in an interesting way. Few relays are implemented to ease analysis when taking into account of all the relays in time based distinct PV fluctuations scenarios. Three lines to ground (3L-G) symmetrical fault which is a severe fault in power system is applied. Usually, inaccurate models are developed, which this work overcomes as it mainly uses self-built power conversion facilities and control strategies. In fact, it is obvious that, the more accurate the system the better the results precision. The control strategies are dq current control and voltage mode PQ control based synchronous rotating frame control strategy; Incremental Conductance (IC) maximum power point tracking (MPPT); phase locked loop (PLL); pulse width modulation (PWM); sinusoidal pulse width modulation (SPWM) and BESS control. OCRs performance is analyzed based PSO algorithm as case study.

The remainder of this paper is organized as follows. Section 2 exposes PV systems modeling with control strategies details and relevant explanations including emphasizing this work goal. In Section 3, PV penetrated DSs models are explained to show this paper modeling quality. Section 4 argues solar radiation fluctuation impact on PV system performance in distinct manners to highlight important findings with descriptive figures. Section 5 provides the proposed simulation method details. Section 6 gives PSCAD simulations results and provides convincing discussions and comments. Section 7 presents relays performance analysis based PSO algorithm. All the results are provided in form of Tables and figures. Section 8 concludes this paper.

2. PV systems modeling description

The PV systems with and without BESS in Figs. 1 and 2, respectively, apply to this paper proposed fault analysis method.

Figs. 1 and 2 similarly show 6.5 kV PV farm, DC-DC boost converter, two level VSI, LCL filter, IC MPPT with PWM, voltage mode PQ control, dq current control leading to SPWM, direct and inverse park transformations, PLL, and 100 MVA grid linked to two delta-star transformers. However, Fig. 1 shows BESS with buck-boost converter interface. The PV farm voltage and current are v_{pv} and i_{pv} respectively, whereas other appearing variables are defined further.

2.1. Synchronous rotating frame control strategy

The relationship between natural (*abc*) and rotating (*dq0*) frames of injected grid current (i_{abc}) formulated based park transformation is in (1). The three-phase voltage (v_{abc}) is in (2). θ is the grid voltage phase angle; v_m the phase maximum voltage, whereas i_d, i_q, and i_0 are direct, quadrature, and zero components currents, respectively. Usually, i_0 is neglected.

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{2/3} \times \begin{bmatrix} \cos(\theta) & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin(\theta) & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

$$v_{abc} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = v_m \times \begin{bmatrix} \cos(\theta) \\ \cos(\theta - 2\pi/3) \\ \cos(\theta + 2\pi/3) \end{bmatrix} \tag{2}$$

The grid active power (P) and reactive power (Q) follow (3) when v_q is not null, and (4) if $v_q = 0$ due to PLL which assures θ synchronization. PLL is a negative feedback control, with details available in [4].

$$\begin{cases} P = v_d i_d + v_q i_q \\ Q = v_d i_q + v_q i_d \end{cases} \tag{3}$$

$$\begin{cases} P = v_d i_d \\ Q = v_d i_q \end{cases} \tag{4}$$

where v_d and v_q are direct and quadrature voltages components, respectively.The dq current control in rotating reference frame takes dq-frame voltages (v_{dq}), currents (i_{dq}) and dq-frame reference currents (i^*_{dq}) from voltage mode PQ control to produce dq-frame reference voltages (v^*_{dq}). Voltage mode PQ control is outer control loop whereas dq current control is inner control loop. Joined both control loops constitutes synchronous rotating frame structure.

2.2. Voltage mode PQ control

DC bus voltage (v_{dc}) and reactive power (Q) PI controls are in (5).

$$\begin{cases} i^*_d = (K_{pd1} + K_{id1} \times \frac{1}{s})(v^*_{dc} - v_{dc}) \\ i^*_q = -(K_{pq2} + K_{iq2} \times \frac{1}{s})(Q^*_{dc} - Q) \end{cases} \tag{5}$$

where K_p and K_i are proportional and integral gains of the controllers (PI1 and PI2), whereas v^*_{dc} and Q^* are v_{dc} and Q references, respectively. The variable i^*_d also determines active power (P) control. In other words, voltage mode PQ control assures DC bus voltage control, active power control and reactive power control. Precisely, the control loop outputs i^*_d for both DC bus voltage control and active power control, and generates i^*_q for reactive power control.

2.3. Boost converter and VSI control

Fig. 3 shows boost converter PWM control. The state of difference between PV farm voltage (v_{pv}) and IC MPPT output voltage (v_{MPPT}) in (6) decides control signal of switch T_1 through PI 3 regulation based signals comparator. The signal is 0 when (v_{MPPT}) is greater than (v_{pv}) and 1 else.

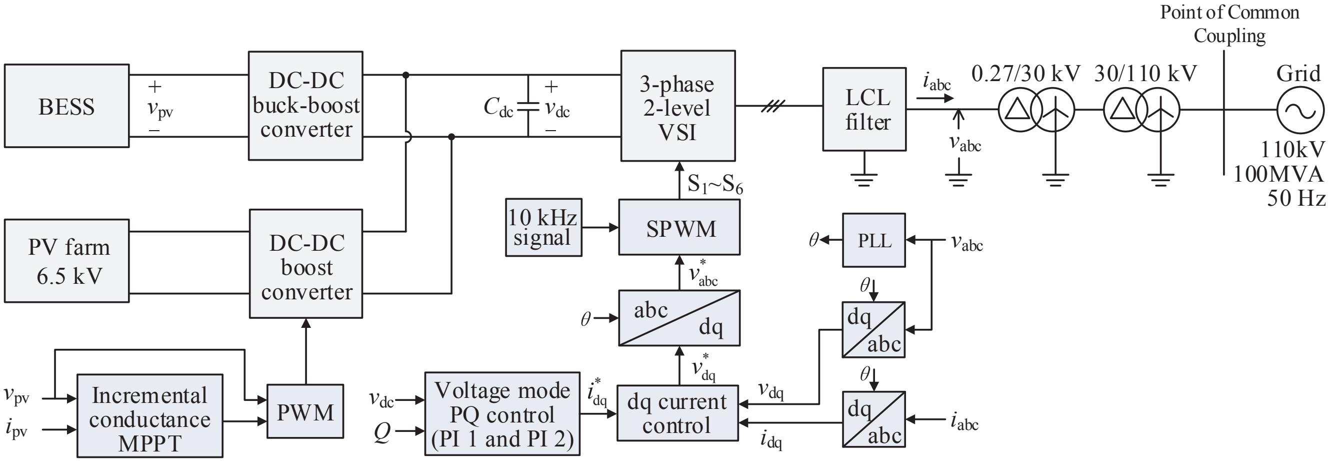

Fig. 1. Modeled PV system with BESS.