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Mitigation of transformer-energizing inrush current using grid-connected photovoltaic system

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ABSTRACT

This paper presents a novel technique for suppressing the transformer-energizing inrush current. This technique is based on existing of a Photovoltaic (PV) generation system. Large magnitude inrush current can occur with certain combination of point of wave energization and residual core flux. The PV system is exploited to produce a magnetic flux in the core of the energized transformer in a negative direction of that produced by the main grid during grid-off. In this paper, the wave-energizing instant is optimally chosen and hence the amount of the residual flux existing in the core is controlled to be ready to sink the energizing effect. The impact of existing of PV system that connected to 280 kV, 60 Hz grid is studied at different energizing instances, different power ratings and different solar irradiances. The method is illustrated by simulation results and validated by harmonic analysis. The optimum energizing instances are explored at different working circumstances. The results at transient and steady states verify that the proposed technique enables the minimization of the inrush current by optimized grid-switching instance.

Introduction

Connection of the transformer to the distribution grid results in an inrush current flow in the primary winding, which results in strong magnetic fields and misplacement of the windings. Consequently, insulation properties are deteriorated. Similar effects also occur during disconnection since the magnetizing current is forced to stop flowing, and frequent connection/disconnection hence reduces transformer reliability and lifetime [1].

Heretofore, several approaches have been proposed to lessen the phenomenon of the magnetizing inrush current [2–10]. Ref. [2] has studied the effects of residual flux for optimal closing instant to minimize inrush current. In [3], authors used a grounding resistor connected at a transformer neutral point for inrush current reduction. Ref. [4] has reduced the inrush current by using series compensator. In Ref. [5], authors introduced a systematic switching study to minimize the inrush current without residual flux estimation. The authors in [6] used the conventional superconducting fault current limiter to reduce the inrush current. Also in [7], a voltage compensation-type inrush current limiter was presented, in which the presented limiter can automatically insert high impedance to restrain the sudden change in line current. The work in [8] presented an inrush current reduction strategy, which sets the residual flux of a single-phase transformer to a large magnitude and specific polarity in a method described as “preflux” and then energizes the transformer at a specified system voltage angle based on the flux polarity. Refs. [9,10] have presented a flux compensation technique combined with a transformer switching control for the uninterruptible power supply (UPS) to avoid inrush current when a transformer is switched on. A series choke has been used to limit the inrush current in [10].

The above methods for reduction of inrush current require bulky additional components the design of which has to be adapted to the specific transformer requirements which are either unavailable at all the transformers or have high cost. A recent innovation in power systems is the connection of many PV strings for generating energy. These PV systems can be exploited to improve the performance of the system’s components. This paper proposes a method in which the PV system is used to reduce the inrush current.

In the studied system, boost DC–DC converter with a maximum power point tracker (MPPT) controller is used to force the PV to operate at its maximum operating point. In [11], many MPPT methods have been reported for solar PV generators. MPPT by the incremental conductance method plus an integral regulator is adopted in this paper [12,13]. Control and grid synchronization

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for distributed power generation systems was reviewed in [14]. Single-phase vector control for single-phase voltage source converter (VSC) is developed to maintain the DC-link voltage and independent active and reactive power flow [15]. In this paper, A single-phase vector controller that controls the line current for unity power factor is adopted [14,15]. In-quadrature signal generation in the design of phase-locked loops (PLLs) applied to synchronize with single-phase grids presented in [16] is also considered in this work. Method presented in Refs. [17,18] are used to apply the dq transformation to single-phase systems based on a time shift to generate the imaginary component.

The magnitude of the inrush current peak depends on: (a) the magnitude of applied voltage at the instant of energizing, (b) the magnitude and polarity of the residual flux existing in the core of the transformer, and (c) characteristics of the load connected to the transformer. In this paper, the second pint is the key beyond decreasing the inrush current.

Transformer saturation behavior is researched with the existence of PV farm and compared to the only grid case. Harmonic analysis is carried out using windowed Fast Fourier Transform (FFT) in order to see how the inrush current departs from the standard sine waveform. Investigation of the proposed idea is presented at different energizing instances, different solar irradiances, and different power ratings of the PV string. Transient and steady state performances of the system are illustrated at different power plants and different energizing times.

Grid-connected photovoltaic system

The configuration of the studied single-phase grid-connected PV system is shown in Fig. 1. It consists of PV farm, DC–DC boost converter, DC link capacitor, single-phase VSC and its controller, LCL filter, step-up coupling transformer for interfacing with the grid, and load connected to the grid through a saturable transformer. The test switch is connected in the grid side. The PV arrays are connected to a DC–DC boost converter for step up the PV voltage to the level of the allowable maximum line voltage using MPPT controller. The MPPT controller is achieved through a current estimator of the PV array, and generates the reference voltage for the DC–DC boost converter. The single-phase VSC with LCL filter converts a DC input voltage into an AC voltage by means of appropriate switch signals to make the output current in phase with utility voltage and unity power factor.

PV array

The studied PV array is a model of a 10-MW array of the model uses 330 SunPower modules (SPR-305). The array consists of 6600 strings of 5 series-connected modules connected in parallel ($6600 * 5 * 305.2$ W = 10 MW). The module characteristics are extracted from NREL system advisor model [19]. Table 1 lists the maximum ratings of grid-connected PV system components.

DC–DC boost converter with MPPT controller

This converter boosts the DC voltage from 273.5 V to 500 V. This converter uses a MPPT system, which automatically varies the duty cycle in order to generate the required voltage to extract maximum power. The MPPT controller that uses the incremental conductance technique optimizes switching duty cycle. At the maximum power point, the ratio of change in power to change in voltage is equal to zero as:

$$\frac{dP}{dV} = 0 \tag{1}$$

Expanding (1) and using it as error signal, Eq. (2) is obtained

$$\frac{dI}{dV} + \frac{I}{V} = error \tag{2}$$

The integral regulator is then used to minimize that error. The output of this regulator is the correction of the duty cycles.

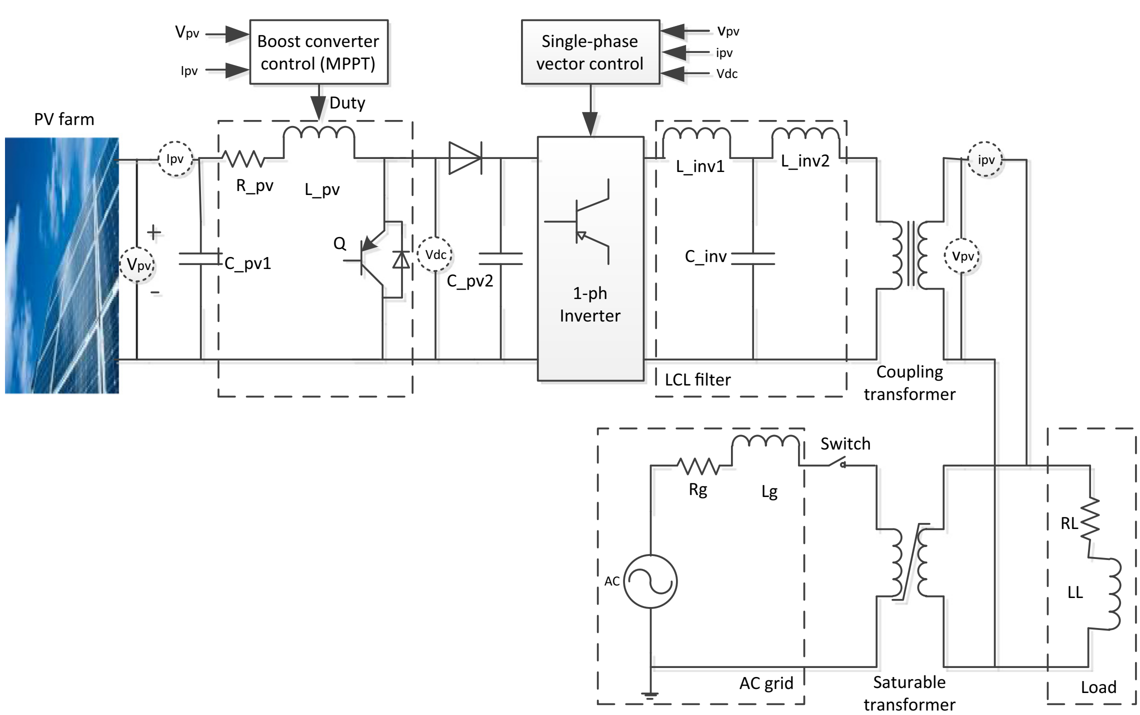

Fig. 1. Configuration of single-phase grid-connected photovoltaic system.