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Influence of solar photovoltaic array on operation of grid-interactive fifteen-level modular multilevel converter with emphasis on power quality

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ABSTRACT

This paper unveils an operational impact of variable Solar Photovoltaic (SPV) array into 15-level single-stage Modular Multilevel Converter (MMC) thyristorized operated system. A MMC system is developed in which the working of three sub-system modules has been coordinated at a Point of Common Coupling (PCC). In addition, each of 15-level sub-system has been operated at a Resistance Inductance (RL) and a SPV array load. Furthermore, the investigation of DC power inversion into AC power has been elaborated by varying the switching angles of thyristors from 100° to 180°for an individual module. The operation of MMC system has been coordinated with Dynamic Voltage Restorer (DVR), where its performance has been estimated during grid faults under unity power factor conditions. Especially, the investigation on Power Quality (PQ) has been highlighted at PCC by operating with proportional integral and fuzzy logic controlled DVR. It has been verified that response with fuzzy logic DVR scheme is able to control the unbalanced conditions, under steady-state and transient conditions effectively. The effectiveness of the proposed controller is demonstrated by using standard IEEE-519/1547, which stipulates that harmonic level in utility injected current by any SPV source cannot exceed 5%. Therefore, a reduction in harmonics and DC offset is ensured satisfactorily, among all variables at PCC according to IEEE-519/1547 standard at fundamental frequency.

1. Introduction

Nowadays, the fossil fuel has been the main energy supplier for worldwide economy. This, however, has caused many environmental problems such as global warming and air pollution. Therefore, with regard to worldwide trend of green energy, the solar power technology [1,2] is envisaged to become one of the most promising type of energy resources [3]. At present, the number of Solar Photovoltaic (SPV) installations have seen an exponential growth [4], mainly due to the government and utility companies supporting green energy [5]. The deep integration of any renewable energy resource mainly depends on inexpensive technological improvement of global emissions and precise controlling techniques for Power Quality (PQ) [6,7].

The SPV systems with Pulse Width Modulation (PWM) controlled [8,9] inverters generate a square waveform with large harmonic content [10]. To overcome this, multilevel inverters offer sinusoidal waveform with reduced harmonic content and lower electromagnetic interference. As mentioned in references [11–14], the multilevel inverters exhibit lower switching frequency than standard PWM inverters thus, demonstrate the reduced switching losses. The modular type of multilevel converter has strong potential to replace cascaded type multilevel converter, especially in medium voltage applications [15]. Currently, intensive research is going in Modular Multilevel Converter (MMC) systems owing to their potential for medium power applications. MMC generates low harmonic at output voltage, thus eliminating filtering requirements. Moreover, it also allows avoiding interfacing transformer [16] thus, extending higher number of output levels easily. Although, the study of MMC systems is investigated with many applications, but this study has not been carried with single-stage SPV configuration. Therefore, this paper presents the analytic study on SPV grid-interactive power conversion system, coordinating with single-stage 15-level MMC system.

For a three-phase grid connected SPV system, a mathematical model based on a hybrid fuzzy-neural [17] and a 9-rule fuzzy logic control [18] has been proposed. It has been demonstrated that the fuzzy-neural control provides faster convergence speed and good dynamic operation around maximum power point. The control schemes implemented are proposed to regulate the DC bus voltage and reactive output power in rotating *dq*-reference frame [19–21]. The operation of a hybrid cascaded type multilevel inverter topology having three leg and H-bridge cells, has been investigated in [22]. In addition, it has been reported that maximum steps are produced in output voltage, with minimum number of required switching capacitors [23,24]. Various advantages of multilevel inverter systems which are: low power dissipation during switching, reduced harmonic distortion and electromagnetic interference; have been reported in [25]. It is their inherent ability that these inverters are capable to generate power of high quality from SPV systems and provide flexible functionality with improved PQ. The suitability of multilevel inverter for single-phase grid interaction is analyzed in [26]. The presence of several DC sources on DC side of inverter makes such inverters attractive for SPV applications.

A single-phase five-level [27], three-phase five-level [28] grid-connected SPV inverter and a multilevel H-bridge inverter [29] including battery energy storage is proposed in the literature. Total Harmonic Distortion (THD) is controlled through a digital type proportional integral current control type algorithm. This algorithm maintains the current injected into the grid sinusoidal with reduced harmonic distortion content. Additionally, the THD in voltage for a multilevel H-bridge inverter which includes battery as energy storage source, is found to be less than 6%.

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Furthermore, to decrease the cost on account of increasing switching devices and transformers, an efficient multilevel inverter switching pattern is proposed in [30]. It is equipped with two cascaded type transformers having a series connected secondary winding. In this system, the switching losses are further reduced by implementing a hybrid PWM type control [31]. In order to divide the power among the various converter modules, the proposed design is implemented for two different systems: one for a 10 kW-1,32 kV generation and another one for a 1 MW-13.2 kV medium voltage generation system. A prototype single-phase cascaded H-bridge inverter has been built in [32], which can configure to work as 5-, 7- or 9-level inverter according to the number of activated levels. The targeted 3rd, 5th and 7th harmonic have been eliminated with non-equal DC voltage sources, using particle swarm optimization. A five-level diode clamped inverter has been connected to grid by a traditional three-phase transformer through a space vector modulation as grid interface [33]. The THD analysis has been reported for inverter output voltage-15.61%, and grid current-1.98%. A single-phase multilevel inverter configuration that conjoins three series connected full bridge inverters and a single half bridge inverter for SPV system is proposed in [34]. Theoretical calculation of power losses and THD of output voltage-9.85% without using passive filters and 3.91% with filter inductance, is reported. A three-phase single stage grid interactive inverter with adaptive fuzzy-logic type Maximum Power Point Tracking (MPPT) capability is reported in [35]. The level of THD for the inverter output current is in the limits of international standards (< 5%), and the efficiencies of MPPT algorithm and total system are measured as 98.78% and 93.12%, respectively. An experimental validation to prove low current THD factor is reported [36] by developing a single-phase cascaded multilevel inverter delivering power from two SPV strings.

This paper aims to describe the modeling and control of a SPV array supported 15-level three module in single-stage configuration. The operation of MMC is evaluated for three-phase grid interactive system during grid faults. The impact of Dynamic Voltage Restorer (DVR) [37–39] is analyzed during the faulted conditions. The operation of DVR has been controlled through Proportional Integral (PI) and Fuzzy Logic Control (FLC). Moreover, the thyristor of each MMC module is operated in continuous-current conduction mode at unity power factor. Since the SPV array is non-linear in nature [1], the real and reactive output power are derived under stochastically changing environmental conditions for three modules of MMC system. It is envisaged that reactive power requirement of Resistance Inductance Capacitance (*RLC)* load is achieved by each of three modules, and hence its compensation is achieved. In addition, the simulation of FLC-DVR is found to be satisfactory to eliminate unbalanced swell and sag for variables at Point of Common Coupling (PCC) [40]. Using Fast Fourier Transform (FFT) [41,42] technique, the calculated values of THD for load current and utility current are estimated to be 1.98% and 1.95%, respectively, which conforms the correctness of implemented proposed system according to IEEE-519/1547 standard [43].

2. Computational system model

The simulation scheme of 15-level MMC system fed SPV array is depicted in Fig. 1. A MMC system is an arrangement of three multilevel converter modules, which are connected to a three-phase electric grid at PCC through an Inductance-Capacitance-Inductance (*LCL)* filter. Each module of MMC system is operated at a Resistance Inductance-*RL* and an experimental validated SPV array. Further, the three SPV arrays are operated under different levels of solar radiation levels: 600 W/m^2, 800 W/m^2 and 1000 W/m^2, and different cell temperatures: 10 °C, 20 °C and

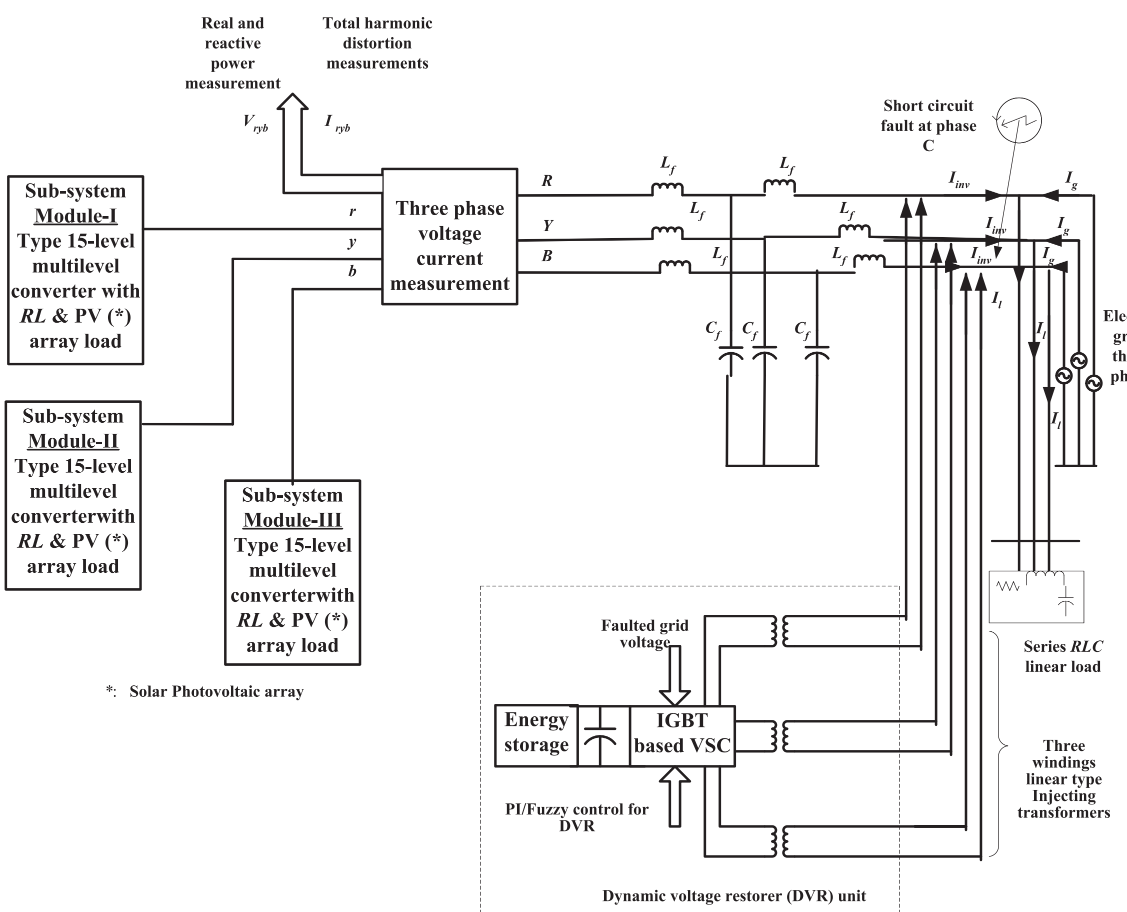

Fig. 1. Block diagram of single-stage three-phase grid-interactive 15-level MMC modules fed *RL* and SPV arrays.