Enhanced Grid Integration of Photovoltaic Systems Using Meerkat Algorithm-Tuned Fuzzy Logic Controller in Modular Multilevel Converters

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***Abstract*—Modular Multilevel Converters (MMCs) are widely adopted in medium- and high-voltage applications. To reduce system losses and costs, half-bridge converters are often preferred. However, their vulnerability under fault conditions limits their reliability. To overcome this, a full-bridge MMC is employed in this work, offering improved fault tolerance. With suitable arm voltage and circulating current control strategies, both power losses and harmonics are minimized. This study develops an 11-level MMC integrated with a grid-connected photovoltaic system, where the DC link is powered by a solar source. A fuzzy logic-based fractional-order PID (FOPID) controller ensures stable operation under different conditions. To further enhance control accuracy, the Meerkat Optimization Algorithm (MOA) is applied for optimal parameter tuning. Simulation results demonstrate superior performance, achieving a Total Harmonic Distortion (THD) of 0.26%, outperforming conventional controllers.**

***Index Terms*—Modular-multilevel converter, total harmonic distortion, Meerkat Optimization Algorithm, photovoltaic.**

I. INTRODUCTION

Problems, rising energy consumption and environmental issues with traditional fossil fuels [1]. Among several renewable sources, photovoltaic (PV) renewable energy systems are mostly used by the researchers because of its advantages and lower installation costs [2]. According to current studies, the development of grid-connected photovoltaic systems is the primary goal, since it exceeds 99% of the installed capacity of PV systems when compared to standalone systems [3]. Compared to stand-alone systems, grid-connected systems are less expensive and require less maintenance. To interconnect PV and grid, inverters are mostly used, it will convert DC power from PV to AC power [4, 5]. The Modular Multilevel Converter (MMC) is one of the sophisticated converters extensively used to increase conversion effectiveness of DC to AC converters [6]. The MMC is a modularly constructed multi-level converter. It operates redundantly and fault-based using modular components [7].

Prof. Marquardt first presented the modular multilevel converter (MMC) in a German patent in 2001 [8]. MMC is mostly used for medium and high voltage power applications, due to its benefits like low harmonics modular construction, loss reduction in switches, and adequate fault management [9]. MMC control may be divided into two categories: output current control and internal current control. Converters' active and reactive power is managed using output current control [10]. The converter's output is independent of the circulating current, and the output current is regulated to transmit electricity to the AC grid [11]. Uncontrolled MMC causes high circulating current and high voltage ripples. Therefore, the control system is essential to MMC operating at peak efficiency. Potential variations in each sub-modules arm and DC connection give rise to the circulating current issue in each arm of the MMC [12]. To achieve optimal performance, the MMC must solve some control challenges arising from its fundamental structure. Internal circulating

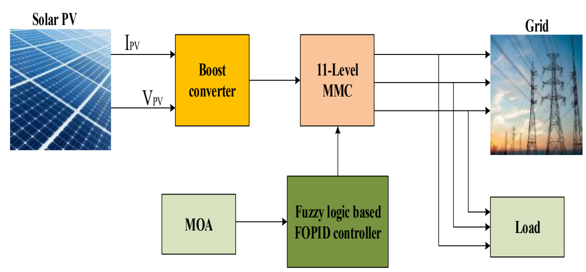
harmonic current in MMC, capacitor ripple voltage, component ratings, losses etc. are some of the issues [13]. Many research has been done to address this problem. Proportional integral and proportional resonant controller is used by author in [14] to enhance rms current. Generalized decoupled double synchronous reference frame-based control framework was used in [15] to reduce the capacitor ripple in MMC. Many researchers have now proposed a variety of topologies and control methodologies for the control objectives, including output voltage regulation, circulating current ripple injection or suppression, submodule capacitor voltage balancing and averaging etc. Still there are many lags in these area, therefore this paper proposed a novel control strategy to minimize the capacitor ripple voltage, losses, rms current etc. The major objective of this paper is;
To design an 11-level modular multi-level converter, integrated with grid-tied renewable energy sources.
This work proposes a Fuzzy Logic-based Fractional Order Proportional Integral Derivative (FOPID) controller to minimize capacitor ripple voltage and harmonics.

To fine-tune the control parameters of the proposed controller, this work incorporates the Meerkat Optimization Algorithm (MOA).

The remaining sections are arranged as follows: Section 2 describes the existing works related to power quality enhancement techniques in MMC. The proposed methodology with its system description is explained in section 3. The results are provided in section 4, and the conclusion is given in section 5.

II. METHOD

The use of multilevel inverters in medium voltage renewable energy generation processes has been increased by recent advancements in this technology. This research suggests a novel control strategy for a grid integrated solar photovoltaic (PV) system based on modular multilevel converter (MMC). Control method is proposed to suppress the circulating current's magnitude, capacitor ripple voltage, component ratings, losses and rms value of arm current. In this work 11 level modular multi-level converter is designed along with grid tied renewable sources. The DC supply of the system is fed by using solar connected power generating system. A novel control strategy is adopted to provide a balanced operation of the converter under different conditions. Fuzzy logic based fractional order proportional integral derivative (FOPID) controller is proposed in this work. The fuzzy part gathers the data based on the error and error derivative, this will enhance the performance of the MMC. Furthermore, to optimize the control parameters for the proposed controller Meerkat optimization algorithm (MOA) is included in this work. This MOA algorithm will optimally tune the gain parameters by considering constrained problems with diverse search spaces. Figure 1 represent the block diagram for propose



A. Modelling of Solar PV
A solar cell functions as the key element in a photovoltaic (PV) system. A PV panel or PV module is formed by connecting multiple solar cells in series [22]. The PV arrays are formed by connecting these modules both in series and in parallel configurations. The PV array has been modeled by only a single diode within the PV cell. The solar PV is modelled and expressed as;

$$I = I_{PV} - I_d - I_{SH}$$

B. 11 level modular multi-level converter
The model consists of three phases, with each phase having two arms, resulting in a total of six arms [23]. In each arm, there are N series-connected FBSMs, along with an arm inductor and an arm resistor. In carrier-based modulation for MMC, the upper and lower voltage references are supplied by two sinusoidal references that are out of phase with each other. The number of output voltage levels is determined by the angular separation between the carrier sets of the upper and lower arms. When there

is a 180-degree phase difference between these carrier sets, it generates N+1 voltage levels. Conversely, when the carrier sets are in phase, it results in 2N+1 voltage levels. This 2N+1 voltage level generation is employed in the output voltage control of MMC. The connection between the DC link voltage and the output voltage of a single phase is expressed as;

$$M = \frac{2v_m}{v_{DC}}$$

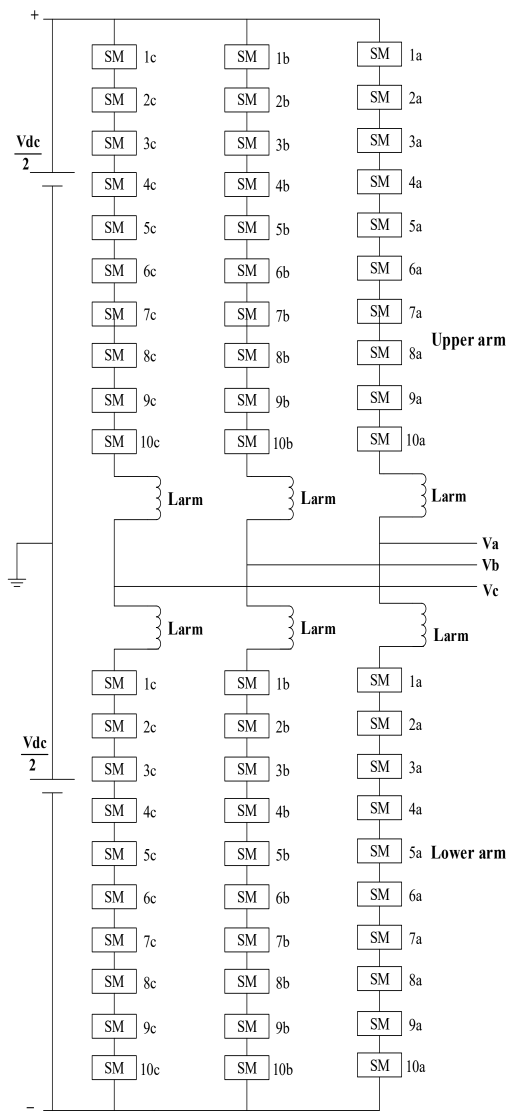


Figure 2: Three phase 11-level MMC topology

The differential power term circulates only within the MMC's arm and does not contribute to the output power. Thus, reducing this term significantly ecreases capacitor ripple. By the integration of both differential and common terms within the arm power, the variation of energy is acquired in each arm and is expressed as;

Proposed control strategy

In this work, fuzzy based FOPID controller is utilized to enhance the performance of 11-level MMC. This method will reduce the capacitor ripple voltage, differential current and component ratings. Thus proposed method enhance the reliability and efficiency of the system. The gain parameters of proposed controller is tuned using MOA algorithm.

III. RESULTS AND DISCUSSION

The proposed method is implemented in Matlab/Simulink tool. The performance of this proposed method is evaluated by comparing the results with existing methods. Figure 6 represent the Simulink block for the proposed method.

The SI unit for magnetic field strength H is A/m. However, if you wish to use units of T, either refer to magnetic flux density B or magnetic field strength symbolized as µ0H. Use the center dot to separate compound units, e.g., —A·m².

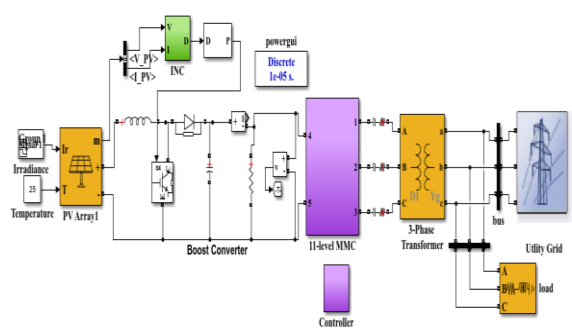


Figure 3: Simulink block for the proposed method.

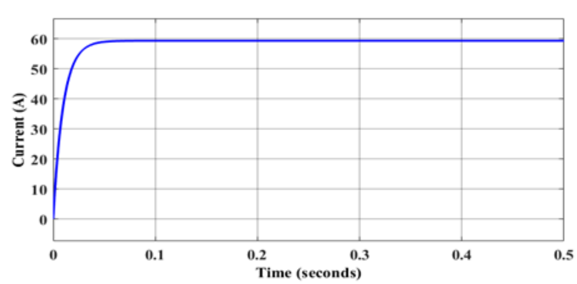


Figure 4: Analysis of PV array current

Figure 4 illustrates analysis of PV array current constant irradiance of 1000 W/m² and a temperature of 25°C are applied as the input conditions. Under these conditions, the current is gradually increased from 0 to 60A. Figure 7(b) illustrates the voltage, which is progressively increased from 0 to 230V. Finally, Figure 7(c) depicts the power, which is ramped up from 0 to 125,000W.

IV. CONCLUSION

This research work includes the development and design of an 11 level modular multi-level converter with grid tied renewable sources. A novel control scheme has been implemented to maintain balanced operation of the converter across various conditions. This paper introduces a FOPID controller and employs MOA to optimize its control parameters. The proposed approach aims to minimize capacitor ripple voltage, losses, component ratings and harmonics. In this paper, the MATLAB/SIMULINK is carried-out for evaluating the proposed method. The experimental results demonstrated that the proposed technique achieved a THD of 0.26%. The performance was assessed under both linear and non-linear load conditions. Consequently, the results confirmed that the proposed technique offers superior performance and high effectiveness. For future research, we will broaden this study by implementing a hybrid approach. This expansion will aim to enhance the effectiveness and adaptability of the proposed technique, potentially improving its performance across a wider range of conditions and applications.

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