Fuzzy Logic Control of Two-Stage Grid-Connected Photovoltaic System

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Abstract: In this paper, a two-stage grid-connected photovoltaic system is presented. The optimal performance of solar panels at varying temperatures and irradiance levels is achieved by the application of a fuzzy logic-based maximum power point tracking method. Space vector modulation is used to control the inverter; to achieve capacitor voltage balance, redundant switching states of a three level inverter are used. The grid side control regulates the power and the current injected to the grid, the conventional PI controllers are replaced by fuzzy PI. Simulations have been made using Simulink environment on MATLAB to validate the control of the proposed system.

Keywords: Photovoltaic generator, Fuzzy logic MPPT, three-level FC inverter, Simplified space vector modulation, Fuzzy logic-based regulator.

1. INTRODUCTION

In 2019, electricity contributed for about 19.7% of worldwide final energy consumption, a significant rise from 9.5% in 1973. In the same year, 2019, the global production of solar photovoltaic (PV) electricity was estimated to around 681 TWh [1]. Solar PV energy has emerged as an extremely promising option because to its numerous benefits, including its environmental friendliness, lack of pollution, safety features, silent operation, ease of installation, and very quick building times [2]. As a result, solar PV technology is widely used in a variety of industries, including grid-connected systems, PV pumps, and standalone systems [3- 4].

PV modules have nonlinear behavior as seen by current-voltage (I-V) and power-voltage (P-V) characteristic curves. These curves have a single maximum power point (MPP) that varies with environmental factors such as irradiance and temperature. To enhance the efficiency of PV systems, a maximum power point tracking (MPPT) algorithm must be integrated. The primary objective of MPPT is to consistently obtain the maximum power output from the PV panels, regardless of changing environmental conditions. This is accomplished by matching the operating point of the PV module (I-V) with the load characteristic [5].

The MPPT accomplishes this by regulating the voltage or current outputs of the PV panel, allowing the converter to operate at or near the MPP on the P-V characteristic curve [6], different MPPT methods have been proposed and practically implemented to optimize the PV output under uniform, and non-uniform solar irradiation conditions [7-9], of course each method has its advantages and disadvantages, these methods can be classified into:

- Classic techniques such as Hill Climbing (HC), Perturb and Observe (P&O) with fixed or variable step sizes, Incremental Conductance (INC), Short-Circuit Current (SCC), Open-Circuit Voltage (OCV), and Constant Voltage Tracking (CVT).
- Evolutionary techniques such as Kalman Filter (KF), Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Mine Blast Optimization (MBO), and Bat algorithm.

This work describes an intelligent control technique based on a fuzzy logic controller with MPPT system. The goal is to enhance the energy conversion efficiency of PV systems operating under varying environmental conditions. The proposed controller's performance is assessed on a PV grid-connected system. A three-level Flying Capacitor (FC) inverter structure is used with its space vector modulation control taking into account the balancing of the capacitor voltage.

The paper is organized as follows. Section 2 provides an overview and modeling of our system (the electrical model of photovoltaic cell and the converters), the MPPT based on fuzzy logic theory, inverter control with capacitors voltage balancing algorithm and grid side control. Section 3 presents the results and discussions of the global system simulation.

2. DESCRIPTION AND MODELING OF THE SYSTEM

A typical grid-connected PV system is depicted in "Fig. 1", the proposed system consists of a 100 kW PV array connected to a DC-DC boost converter. The MPPT method used in this paper, as previously indicated, is the fuzzy logic MPPT. The boost converter is connected to a three-phase three-level FC inverter, which is controlled using a space vector modulation with voltage capacitor balancing, a filter which is typically used at the output of the inverter to attenuate high-frequency harmonics, and step-up transformers, it is used to raise the inverter output voltage and adapt it to the distribution grid voltage.

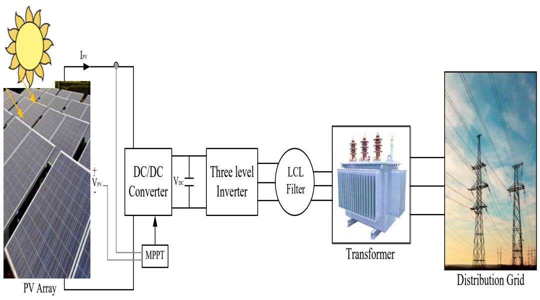

Fig. 1 Global diagram of the studied system.

A. Photovoltaic Generator Model:

A PV generator comprises several interconnected panels, each of them consisting of a series of cells. Various mathematical models have been developed to describe the behavior and functioning of PV panels. These models differ in terms of the computation approach, the number of parameters involved and model accuracy of the [2, 4]. In this study, the PV panel is represented by a two diode model. This model incorporates a current source to simulate the luminous flux, while the losses are characterized by shunt and series resistors, as depicted in "Fig. 2" [4].

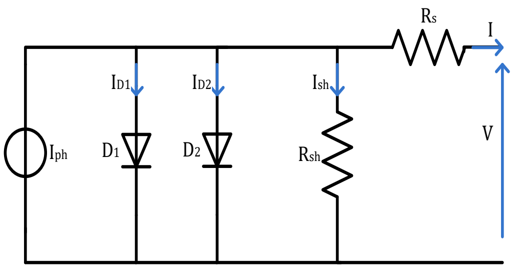

Fig. 2 Photovoltaic electrical model.

The solar cell's output current can be computed using the analogous circuit shown above:

$$I = I_{ph} - (I_{D1} + I_{D2}) - I_{sh} \tag{1}$$

With:

$$I_{D1} = I_1 \times \left[e^{\frac{q*(v+Rs*I)}{A*K*T}} - 1\right] \tag{2}$$

$$I_{D2} = I_2 \times \left[e^{\frac{q*(v+Rs*I)}{A*K*T}} - 1\right] \tag{3}$$

$$I_{sh} = \left(\frac{V+R_S*I}{R_{sh}}\right) \tag{4}$$

B. Boost Converter Model:

PV panels' voltages fluctuate in response to solar irradiation levels. To improve the control of energy generated by these panels, the integration of a DC-DC converter becomes necessary; the DC-DC converter is positioned between the PV panel and the inverter, with the purpose of increasing the voltage and maximizing power extraction from the panels; for this specific study, a boost DC-DC converter has been selected. "Fig. 3" gives us the boost converter's circuit, and its operational concept is as follows:

$$V_{dc} = \frac{V_{PV}}{1-\alpha} \tag{5}$$

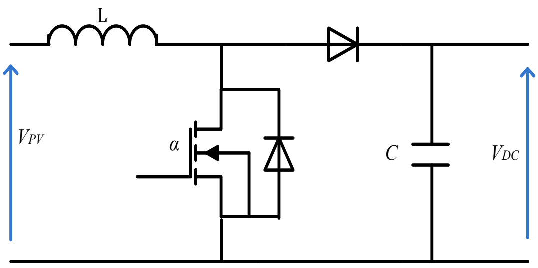

Fig. 3 Circuit of the Boost converter.

C. Three-level FC Inverter:

The fundamental concept of a multilevel inverter is to generate a sinusoidal voltage waveform from multiple voltage levels, which are typically generated from capacitor voltage sources [10, 11]. In this regard, the FC converter acts as an alternate multilevel inverter employed in this study. MEYNARD and FOCH introduced the FC converter in 1992 [12].

The circuit diagram of a three-phase, three-level FC inverter is depicted in "Fig. 4". In this configuration, each of the three inverter phases is coupled to a shared DC bus. The DC bus is divided into three levels by two capacitors. As a result, the voltage across each capacitor is E/2, with E being the total voltage across the DC bus.

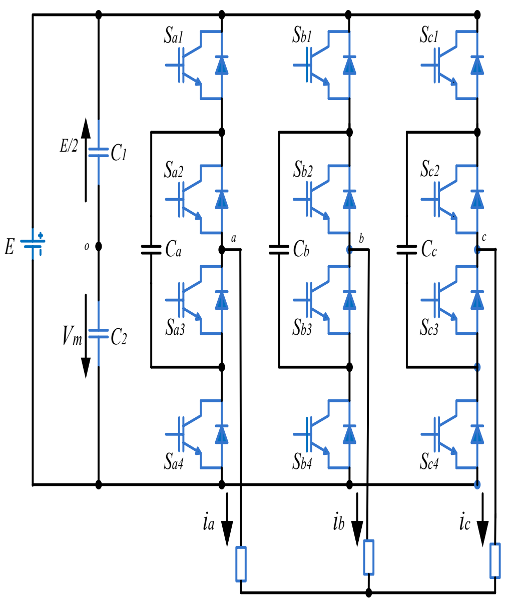

Fig. 4 Three levels Flying Capacitor inverter circuit.

The specific switching states for the three-level FC converter are illustrated in Table 1.

Table 1 Switch sates of the three-level FC converter.

State	S_{x1}	S_{x2}	S_{x3}	S_{x4}
N	0	0	1	1
O_1	1	0	1	0
O_2	0	1	0	1
P	1	1	0	0

D. MPPT With Fuzzy Logic Control:

The objective of MPPT is to optimize the power output from a PV generator [2]. The proposed fuzzy controller for MPPT has two inputs: the error E(k) and the change of error CE(k) of the PV panels current. The fuzzy controller's output is the variation in the duty cycle dD(k). Based on this, we derive a new duty cycle variation.

The linguistic inputs of the fuzzy MPPT controller consist of five fuzzy sets each, resulting in a total of twenty-five rules. These rules can be found in Table 2.

Table 2 Rules generated for the fuzzy MPPT.

CE(k) / E(k)	*NB*	*NS*	*ZE*	*PS*	*PB*
NB	NB	NS	NS	ZE	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	ZE	PS	PS	PB

"Fig. 5" depicts the fuzzy logic MPPT inputs CE(k) and E(k), as well as the output dD(k) membership functions. Inputs are error and error variation of the current from the PV generator and the output of our MPPT is the variation of duty cycle.

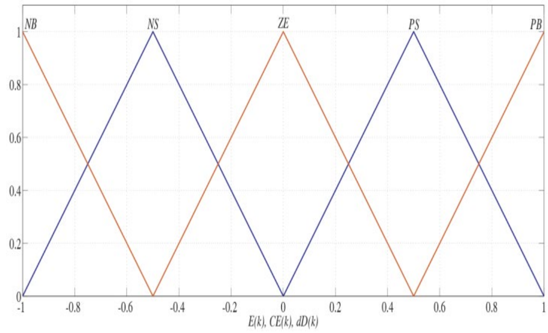

Fig. 5 Inputs (*CE(k)*) and (*E(k)*), and output (*dD(k)*) membership functions of fuzzy logic *MPPT.*

E. SVPWM Technique for Three-level Inverter:

Space Vector Pulse Width Modulation (SVPWM) is a popular control approach for multilevel inverters. It uses control system variables to express switching vectors as points in the complex (α, β) space. SVPWM schemes outperform Sinusoidal Pulse Width Modulation (SPWM) schemes in terms of harmonic elimination and fundamental voltage ratios [13, 14]. Additionally, SVPWM techniques achieve a maximum peak output voltage that is approximately 15% higher than modulation techniques based on triangular carrier waves [15, 16]. The three-level FC inverter shown in "Fig. 6" has 27 possible switching states; each phase leg of the inverter consists of four switching devices that can be in one of three unique switching states designated as +, 0, and - to represent positive, zero, and negative switching sequences, respectively.

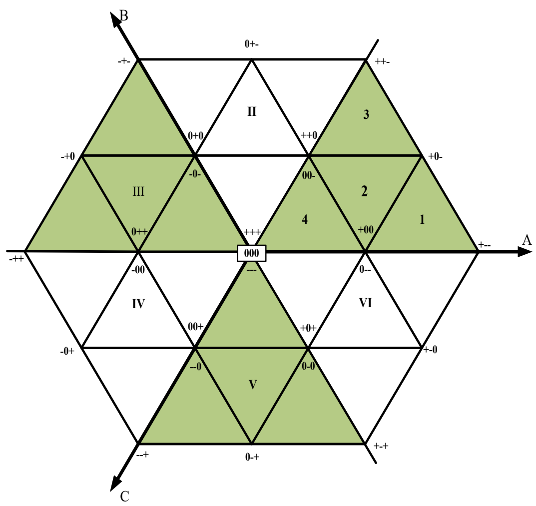

Fig. 6 Three-level space vector diagram.

The zero voltage vectors have three switching states: (0 0 0, + + +, - - -); the vectors in “Fig. 6” are divided into three groups: small vectors, medium vectors, and large vectors, as shown in “Fig. 7”.

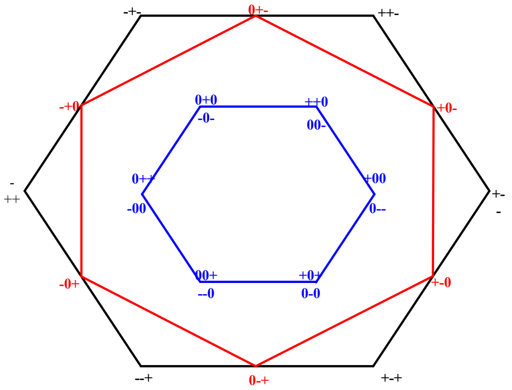

Fig. 7 Hexagon small, middle and large vectors.

In this study, two capacitors, C_1 and C_2, are balanced using redundant states. Redundant states, such as (+ 0 0) and (0 - -), are employed to balance the capacitors. In the state (+ 0 0), capacitor C_1 discharges while C_2 charges, whereas in the state (0 - -), capacitor C_1 charges and C_2 discharges. The balancing procedure differs based on how the converter operates. Table 3 illustrates how the use of redundant states can affect the neutral point in both an inverter and a rectifier.

Table 3 Effect of redundant states on the capacitors voltage.

Redundant states	***Capacitor’s voltage***	
	Inverter	***Rectifier***
(0 - -) (0 0 -) ***(- 0 -) (- 0 0)*** ***(- - 0) (0 – 0)***	V_{c1} ↑ and V_{c2} ↓	V_{c1} ↓ and V_{c2} ↑
(+ 0 0) (+ + 0) ***(0 + 0) (0 + +)*** ***(0 0 +) (+ 0 +)***	V_{c1} ↓ and V_{c2} ↑	V_{c1} ↑ and V_{c2} ↓

F. Grid Side Control:

In our system, sinusoidal currents must be injected at frequencies that match those of the electrical grid. This synchronization is essential to facilitate the generation of active power from the PV generator, which is subsequently fed into the grid. The active and reactive powers are given using components of grid voltage current ($V_{gd}, i_{gd}, V_{gq}$and i_{gq}) by [17, 18]:

$$\begin{cases} P_g = V_{gd} i_{gd} + V_{gq} i_{gq} \\ Q_g = V_{gd} i_{gq} - V_{gq} i_{gd} \end{cases} \quad (6)$$

By controlling $i_{dg}$and i_{dg}, references for active and reactive power can be obtained (P_{gref}, Q_{gref}):

$$\begin{cases} i_{gd\,ref} = \dfrac{P_{gref}.V_{gd} - Q_{gref}.V_{gq}}{V_{dg}^2 + V_{qg}^2} \\ i_{gq\,ref} = \dfrac{P_{gref}.V_{gq} + Q_{gref}.V_{gd}}{V_{gd}^2 + V_{gq}^2} \end{cases} \quad (7)$$

“Fig. 8” shows us the diagram of the grid side control.

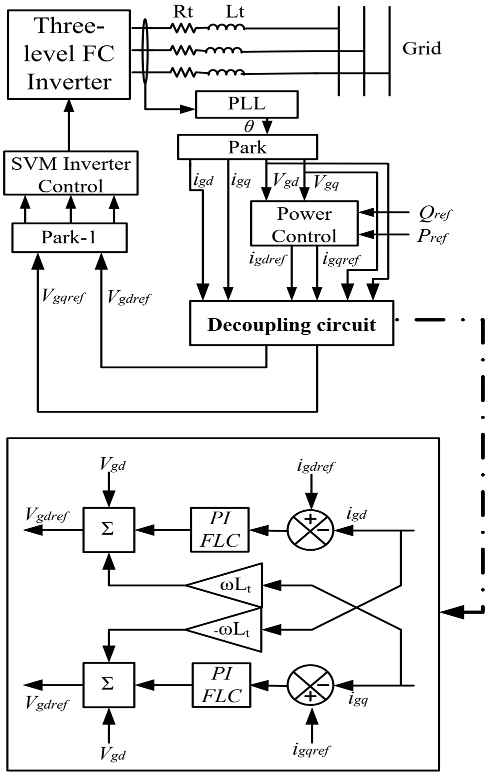

Fig. 8 Diagram of the grid side control.

The conventional PI controllers are replaced by fuzzy PI and rules used for this part are given in Table 4. The inputs are error and error variation of i_{gd} and i_{gq} current, and outputs are V_{gd} and V_{gq} respectively.

Table 4 Rules generated for the fuzzy PI controllers.

Δ e_n / e_n	***NB***	***NS***	***ZE***	***PS***	***PB***
NB	NB	NS	NS	ZE	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	ZE	PS	PS	PB

3. RESULTS AND DISCUSSION

Global photovoltaic grid-connected system of “Fig. 1” is simulated using MATLAB-SIMULINK, variable temperature and irradiance are taken as shown in “Fig. 9”.

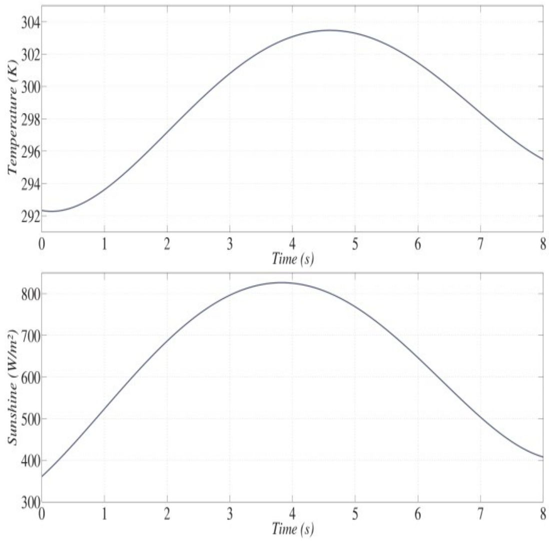

Fig. 9 Variations of irradiance and temperature.

“Fig. 10” shows the power generated by photovoltaic panels it has the same look as sunshine which demonstrates the effectiveness of our MPPT controller.

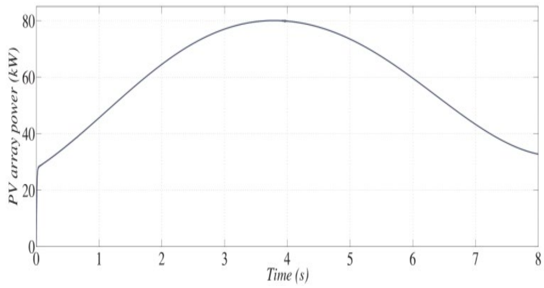

Fig. 10 Power generated by photovoltaic panels.

“Fig. 11” shows us the DC bus Voltage, It is maintained at a value of 1000V which corresponds to the input voltage of our three-level FC inverter.

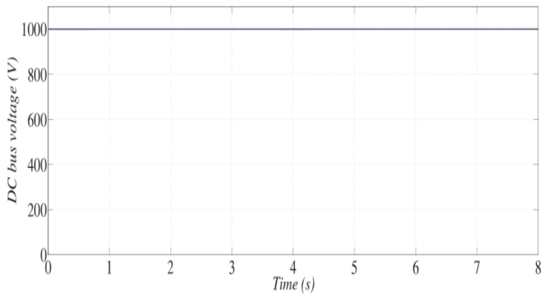

Fig. 11 DC bus voltage.

“Fig. 12” shows us the voltage of the two capacities which split the DC bus, its value oscillates between 500V ± 0.4% which shows the effectiveness of our capacitor voltage balancing algorithm.

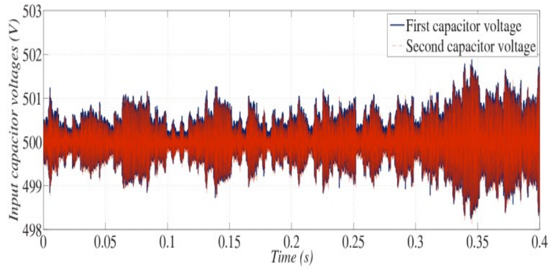

Fig. 12 DC bus voltage.

“Fig. 13” shows us the output voltage of the FC inverter and its spectral analysis; the output voltage has a staircase shape with several levels which relates to a sinusoid compared to a classic two -level inverter and the THD of our signal is 27.52% , value which is acceptable.

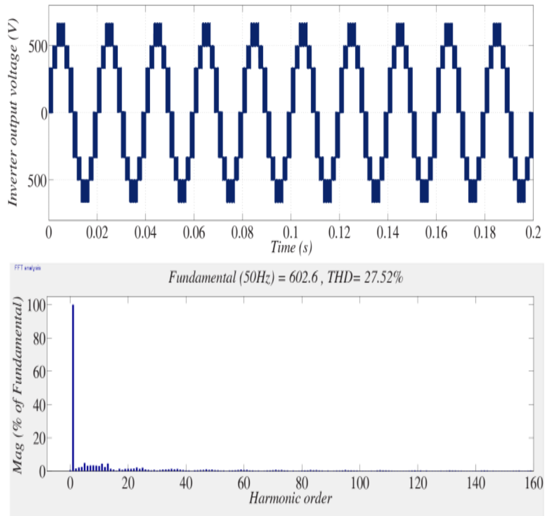

Fig. 13 Output voltage of the FC inverter and its spectral analysis.

“Fig. 14” shows us a zoom of current injected to the grid and its spectral analysis; the THD of our signal is 0.37%, value which is very acceptable.

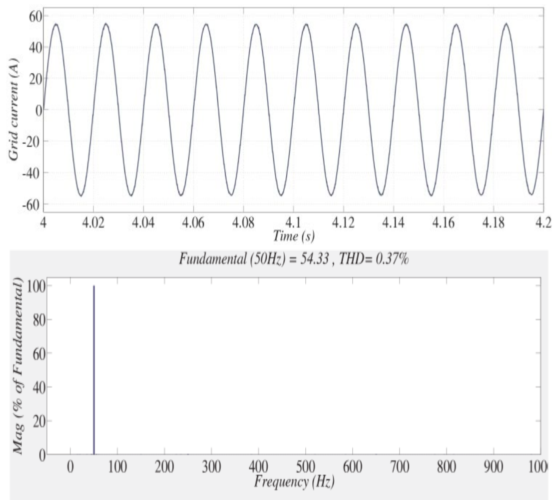

Fig. 14 Current injected to the grid and its spectral analysis.

"Fig. 15" shows us the active and reactive power injected to the grid, we note that the active and reactive power injected to the grid follow well their reference which shows the robustness of our grid side control.

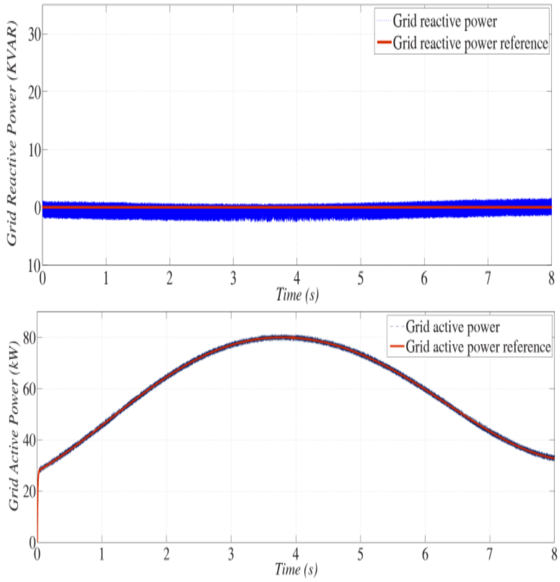

Fig. 15 Active and reactive power injected to the grid.

4. CONCLUSION

This paper presents a three phase three levels FC inverter for photovoltaic grid-connected system. The configuration for the proposed system was designed first and simulated using MATLAB/simulink, the results of simulation shows the robustness and the effectiveness of the control algorithms proposed.

The proposed control scheme features several advantages such as the generation of high-quality voltage, the capacity to operate at a lower switching frequency than a two-level.

The FLC can provide more efficient than the conventional controller for nonlinear systems.

The inverter can be easily expanded by increasing the levels. Thus, number of the output levels is increased and the inverter generates higher-quality output voltage.

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