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Smart fuzzy logic control of photovoltaic system: case study Kingdom of Saudi Arabia

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ABSTRACT

Robust controls of photovoltaic (PV) system applications that include modular multilevel inverter (MMI) for interfacing stand-alone and grid-connected operating modes are investigated in this paper to overcome interfacing problems of two-level and three-level inverters. The MMI provides high-quality voltage, current, and power signals without additional filters, which reduces complexity and cost of interface circuits. A new control method of active and reactive power has been introduced for PV systems to get maximum power point (MPP) in various climatic circumstances. The steady-state and dynamic performances of MMI are investigated using MATLAB/Simulink. A fuzzy logic control is proposed to track the MPP utilizing the perturb and observe (P&O) technique. A fair comparison between fuzzy logic control and proportional integral (PI) control was conducted using MATLAB/Simulink. The fuzzy logic controller for obtaining MPPT by P&O method is proposed to get fast and accurate results. The obtained results obvioused that the fuzzy logic controller is quick accessing MPP than PI controller. A simple LC filter can achieve minimum harmonics provided by total harmonic distortion (THD) of MMI within IEEE limit. The PV system for stand-alone and grid-connected modes is being tested under climatic conditions in the city of Tabuk, Kingdom of Saudi Arabia (KSA).

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1. INTRODUCTION

High economic growth, population and urban growth in the Kingdom of Saudi Arabia (KSA) has led to an exponential growth in demand for electricity. Electricity demand in KSA is expected to increase by more than 6% per year. The production of electricity to cover the load is often provided by traditional methods of producing crude oil, heavy oil and gas throughout the country. Electricity consumed in the KSA has significant carbon effects due to the burning of fossil fuels. In 2017, KSA's carbon dioxide emissions increased to 1.75% of global emissions [1].

Since traditional methods of electricity generation will adversely affect human health and alternative generation method should be used to save the environment and health, as well as to support the peak hours traditional generation. The geographical location of the KSA is in the sunbelt making the KSA one high solar energy producer. The serious competition of solar energy with conventional generation for indirect fossil fuels costs [2]. The average energy generated by sunlight hitting KSA is 2200 kWh/m2, so It is worth trying to produce clean electric power in the country from directly sunlight by photovoltaic (PV) cells.

The performance of a PV system is affected by climatic aspects such as irradiation and temperature. But the PV generator is an important source of renewable energy because of its fuel cost characteristics, favorable environment, low maintenance costs and quiet operation. The use of renewable energy in the KSA is essential in remote places as well as connecting to the national power grid, which can help by contributing to the peak demand needed in the summer [3].

Many researches show that PV energy will be an important renewable energy resource for future power plants. One of the main characteristics of solar energy is that it can be easily converted into electrical energy. This is the advantage of the quiet operation of PV systems compared to other renewable energy sources. In stand-alone and grid-connected PV systems, an electronic power interface is required to obtain AC power. The multi-level inverter (MLI) is importantly used in industrial branch and scientific research because of its features such as low dv/dt coil output voltage and low common mode voltage. Due to the low distortion and harmonics of the MLI output voltage, the complexity and filter's cost, as well as the electromagnetic interference (EMI) level, will be decreased. In this regard, the development of new structures with low cost, high reliability and efficient management processes should be considered. Multilevel modular inverter (MMI) was introduced as opposed to conventional inverters in grid-connected mode. In the MMI structure, several blocks are connected in series on each leg, and the corresponding AC output signal can be generated by switching the blocks.

The MLI serves two purposes: minimal voltage source as well as minimal switch components. An asymmetric cascaded multilevel inverter (ACMLI) is capable to obtain the specific DC voltage by selecting the DC voltage level value and using it by mathematically adding or subtracting from the DC voltage. This system used modulation of multi-carrier sine-wave technology to control the inverter. The scheme has many applications in the integration of renewable energy sources (RES) in a distributed grid, electric vehicles (EV), and suppression of harmonics [4]. A major challenge in the MMI structure used in compensating and switching applications is balancing the upper and lower arms. The PV system using the MMI topology in grid-connected mode using MATLAB/Simulink was described in [5]. The MMI structure has lower power electronics if it is compared with the current topology of the multi-level inverter to generate a sine wave signal and achieve the required voltage profile with minimum harmonics distortion. A new control method for MMI can be used to connect the PV system directly to the main grid. An integration of MPC and traditional feedback control is proposed to control the MMI architecture in PV grid-connected mode [6]. A summary of the different problems of MLI in reducing the number of switches is given so that a new scheme of MLI will be provided [7]. PV system using MMI topology base block architecture on grid-connected mode can be able to convert DC power of PV system to a home or utility load AC power in MATLAB/Simulink presented in [8].

A nonlinear dynamic model of MMI was developed in [9]. Positive-sequence and negative-sequence symmetrical voltage and current elements are included in this model, and a robust adaptive current controller has been developed for the GC-MMI that includes sliding mode and fuzzy controllers. Modeling and control of MMI are carried out to integrate grid-connected PV system. Designing a proper MMI is critical in faulty conditions to ensure converter stability and adequate dynamic performance. Intelligent demonstration of a hybrid wind and PV system by implementing fuzzy logic in the steps necessary to exploit the efficiency of RES. The output power is converted by quadratic boost converters (QBC) and MLI to effectively maintain power quality and grid stability [10]. This scheme structure was formed by investigating the old scheme to avoid unbalance problems like unbalanced voltage and power quality issues. Design and implementation of MMI for controlling an induction motor (IM) using intelligent methods for marine pumps presented in [11]. Sudheer and Kumar [12] investigated a new type of MMI that uses a transformer with three windings. This transformer does not need isolation reactors. A multi-level switching modulation scheme has been introduced, using the concept of multi-carrier pulse-width modulation.

The important challenge is to synchronize the PV system with the power grid. PI controller can be used to provide sufficient performance, but it gives bad transient conditions. Therefore, develop and implement a fuzzy logic control with PI control to solve the transient problem by suppressing the gain of the controller which depends on the system operationIt is recommended to implement MMI for connecting renewable energy sources in autonomous and/or grid-connected modes of operation as it provides high-quality signals of power, voltage and current without complex filters which lead to a reduction in the cost and structure of interconnect circuits [14]. A new MMI model has been proposed to control the active and reactive power of PV arrays at the maximum power point (MPP) in various climatic conditions. A new design methodology for a smart PV system on grid mode with energy storage to feed laying hen breeding centers. To achieve this goal, a reliable size combination was developed according to the data flow pattern using a deterministic method design for the PV system. After that, the "Homer" program tested design economics. Optimization production and consumption of energy using fuzzy logic control. The optimization load energy can be obtained using mist regulator, which controls the indoor weather of the livestock house [15].

The grid-connected large-scale PV system has set new issues related to stability problems and control of the network and PV system with the stored device. The PV system is designed for 8 kW with a storage battery, and this battery is connected to the network in AC or DC modes with the ability to change control signals for MPPT monitoring using built of dynamic model into household PV systems [16]. The new adaptive control unit is adjusted for optimum performance using two different optimization methods: invasive weed and harmonic detection. The robustness test is implemented to test the strength of the system to various random modes of irradiation and cell temperature without disturbing tracking of the point of maximum power [17]. A detailed analysis of chaos control and nonlinear dynamics in SEPIC DC-DC solar PV system to reduce fluctuations close to MPP is presented in [18]. To track the point of true maximum power and zero oscillations close to the MPP, the output voltage must ensure the operation of the first period. Abdullah *et al.* [19], neural network (NN)-based MPPT technology was implemented in a PV system. A comparison between two control methods by developing an independent photovoltaic system connected to a DC booster chopper using perturb and observe (P&O) MPPT and developing an MPPT using ANN for the same system. The operation of the PV system has been enhanced by controlling MPPT by ANN controller as the MPP oscillations have been reduced.

Das *et al.* [20], connecting PV with MMI system to the power grid for improved power quality (PQ) is presented. With modular design and high-performance signals MMI. This system has significant applications in medium and high powers. The reference current is generated using the spotted hyena optimization (SHO) approach, as well as adjusting the parameter value of PI control of the MMI. This SHO technology operates under various load power conditions that can be compared with traditional particle swarm optimization (PSO) and firefly optimization (FO) methods. Incremental connection (INC) technology based on MPPT was used for maximum power consumption. In addition, in addition, MMIs assist the system by compensating for overloads from unbalanced loads as well as ensuring good performance of the output waveform with minimum switching frequency.

Global maximum power point tracking (GMPPT) is defined as extracting MPPs from PV arrays in real time as environmental conditions change. A problem with GMPPT is poor tracking speed and efficiency in commercial. A new rectangular wave of power comparison (RPC) based GMPPT method was established that uses a basic relationship between shading factor, voltage of shunt diode and GMPP [21]. The best performance can be achieved when using MPPT, which is a challenge due to the complexity of MPPT PV system design during the day due to fluctuations in solar radiation. Napole *et al.* [22] describes a new MPPT technology depend on estimating reference voltage with fuzzy logic controller (FLC) for maximizing power from PV array. This structure has been executed in the dSpace 1,104 panel of peimar SG340P PV panel in commercial sector. The structure output has been compared with those of conventional slip mode controller (SMC) I/O method, and the results showed advancement of the developed technique.

In order to reduce the interfacing problems between two-level and three-level inverters used in the PV system, we have proposed reliable controls for the PV system that use a modular multi-level inverter (MMI) to connect both stand-alone and grid-connected modes of operation. We also proposed a active and reactive power controller to lead the MMI of the PV array operating at MPP under various weather operating circumstances. Accordingly, the main contribution of this study is:

- Developing an active-reactive controller which is executed by PI controller. MMI has an additional degree of freedom in the generation/absorption of reactive power. The performances of MMI have been analysed using MATLAB/Simulink.
- Developing a fuzzy logic control to track MPP by P&O technique.
- Testing PV system on stand-alone and grid-connected modes under climate conditions of Tabuk, KSA.

2. SYSTEM UNDER STUDY

This article investigates smart fuzzy logic control to track MPP of PV system on stand-alone and grid-connected modes with MMI at different values of irradiation and temperature in Tabuk, Saudia Arabia. The fuzzy logic control uses P&O technique for fast tracking of MPP. MATLAB/Simulink is used to test fuzzy logic control of PV system on stand-alone and grid-connected modes. Figure 1 shows the PV system based on MMI on stand-alone and grid-connected modes [22].

2.1. PV module

The equivalent circuit of a photovoltaic module can be classified into three types according to the number of diodes, including single-diode, double-diode, and three-diode forms. The one-diode model is the most popular of the others due to its simple design and the small number of parameters used. The main elements of the equivalent circuit of a photovoltaic module are cells consisting of semiconductor diodes. Cells make from different semiconductor materials. DC current flows in the cell by absorbing photons from sunlight as electrons move from silicon atoms to metal conductors to generate electricity.

A PV cell is essentially a P-N junction with P-type silicon at the bottom and a thin N-type diffuse layer at the top. PV cells generate current when photons fall on their surface [23]. The open circuit voltage of PV cell is in vary between 0.5-0.7 according to the various strategies and prototypes reference of solar photovoltaic array system. A PV array contains several PV cells connected in series and in parallel according to the required classification of the PV array [24]. The electrical equivalent model of PV cell has a current source (I_{pv}), a diode connected in anti parallel (D), a series resistor (R_s) and a parallel resistor (R_p) as shown in Figure 2 [25].

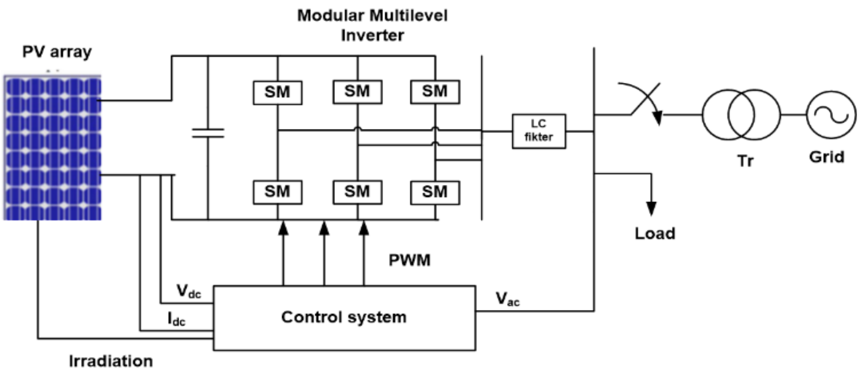

Figure 1. Stand-alone and grid-connected PV system based on MMI

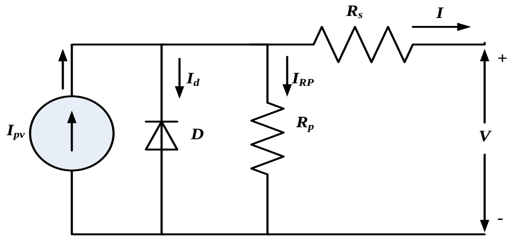

Figure 2. Electrical model of PV cell

The equivalent resistances of model of PV array are:

$$R_{se} = R_s(\frac{N_s}{N_p}) \ , \ R_{pe} = R_p(\frac{N_s}{N_p}) \tag{1}$$

where N_s is the number of PV modules per string connected in series and N_p is the number of PV modules per string connected in parallel. The output current of the PV cell is expressed as,

$$I = I_{pv} - I_s\{\exp\left(\frac{q}{A_k T_c N_s} V + IR_s\right) - 1\} - \frac{V+IR_s}{R_p} \tag{2}$$

where I_{pv} is generated current from sunlight, I_s is the saturation current of the diode, q is the electron charge which is 1.60 x 10^{-19} C. V and I are the output voltage and current of the PV cell respectively. A_k is Boltzmann constant (1.38x 10^{-23} J/K). The generated current from sunlight (I_{pv}) in (2) is expressed as,

$$I_{pv} = [I_{sc} + K_f(T_c - T_{ref})].G \tag{3}$$

where K_f is the temperature coefficient of short circuit current of the PV cell. T_c and T_{ref} are the operating and reference temperatures of PV cell respectively. G is the solar irradiation in W/m^2.

2.2. Maximum power point tracking (MPPT) method

The MPPT method plays an important role in the PV system to ensure maximum power. The observed current and voltage of the PV system will change due to the change in the electrical characteristics of the PV system under sudden climatic conditions. Thus, correct voltage regulation at the terminals of the PV device leads to the achievement of MPP. The MPP of the PV system will vary according to different climatic conditions. The corresponding MPPT method is used to obtain the MPP of the PV system that regulates the voltage and current values.

2.3. Modular multilevel inverter

An essential design of the three-phase MMI, as shown in Figure 3, consists of sub-modules, passive elements such as capacitors and inductors, DC inputs, and AC outputs. Each phase is represented by two sub-leg containing n number of sub-modules. The sub-modules are under control to create a proper terminal voltage through each sub-leg. Each SM contains a DC capacitor and two semiconductor devices with anti-parallel diodes.

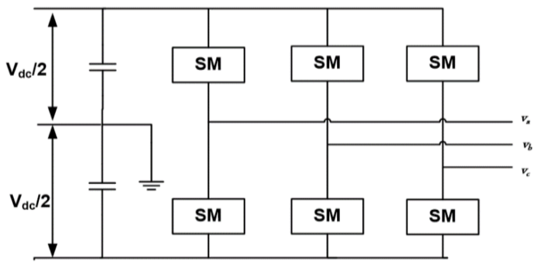

Figure 3. Basic structure of a 3-phase MMI

3. CONTROL SYSTEM

The PV system control device contains of four main areas: phase-locked loop (PLL), MPPT, active and reactive power controller and modulation technology. The active and reactive power control depends on active and reactive current control signals. The fuzzy logic and PI controllers are used for MPPT control of the PV system.

3.1. Active and reactive power control

Figure 4 shows the block diagram of the proposed PV system by MATLAB/Simulink. Generation of reference waveforms for synchronizing MMI voltages using PLL control. The MPP is obtained by the MPPT method to drive the PV system operation for various climate circumstances. The active and reactive power of MMI have been regulated by controlling power factor using active and reactive power controller. The inventive modulation method used to decrease the overall harmonics of output voltage and current, and to ensure equal capacitor voltages and circulating current levels. The control of circulating current is verifiably executed in the modulation technique and the primary control.

(5)

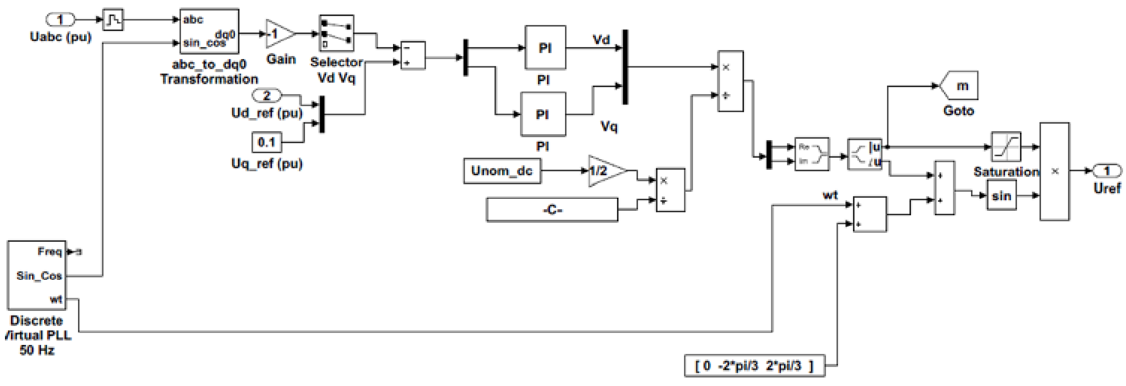

Figure 4. MATLAB/Simulink block diagram of PV system

Active and reactive power control has been developed in the research as the main control element. The active and reactive power of the MMI is linked to the direct- component voltage and the current components as specified in,

$$P = \frac{3}{2} v_d i_d . Q = -\frac{3}{2} v_d i_q \quad (4)$$

The active and reactive powers are associated with the d-axis and q-axis current components respectively. Assuming no MMI loss, DC input power equals active output power.

$$P = \frac{3}{2} v_d i_d = V_{dc} I_{dc}$$

3.2. Fuzzy logic control

The main part of fuzzy logic (FL) is the change of erroneous and subjective data into mathematical qualities. When applied to PV systems as MPPT control calculation, FL stands apart due to the absence of an exact numerical model and the non-straight handling of the PV system. The MF input settings and the appropriate FL rules as shown in Table 1. The MPPT is utilized to make the PV system operate at MPP in various climatic conditions. The FL controllers are extraordinary on account of their arrangement depending on the experience of the creator, and not on the information on the numerical model of the system. The FL controller involves normal principles in its construction. The fuzzy block incorporates three sequential modules: fuzzification, inference and defuzzification as shown in Figure 5.

In FL controller, there are two variables in fuzzification called ΔV(K) and ΔP(K) and the output from the fuzzification is the digital value it sends to the resolution and also contradicts the vaguely represented basic base system, and at the end the output variable of the FL controller system is generated to power and control the extraction method of the maximum photovoltaic power. MATLAB/Simulink of FLC as shown in Figure 6. To get MPP faster, when irradiation value changes the value of voltage and current are multiply by the change percentage between new and old of irradiation values. The output of FLC is the duty ratio (D) where it is used to calculate the new reference voltage of MMC inverter. The output reference voltage is the input of PWM generation, these signals is compared with triangular signals to generate six signals for 6 SM. Pulse width modulation (PWM) signals are three signals with 120º angle difference and others with 180º angle difference for two signals of the same leg.

Table 1. Shows the input MF settings and the fuzzy rules applied

		ΔV				
		NB	NS	ZE	PS	PB
	NB	NS	NB	PB	PB	NS
	NS	ZE	NS	PS	PS	ZE
ΔP	ZE	ZE	ZE	ZE	ZE	ZE
	PS	ZE	PS	NS	NS	ZE
	PB	PS	PB	NB	NB	PS

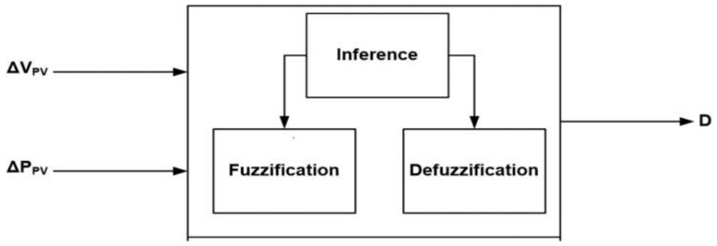

Figure 5. FLC of MPPT

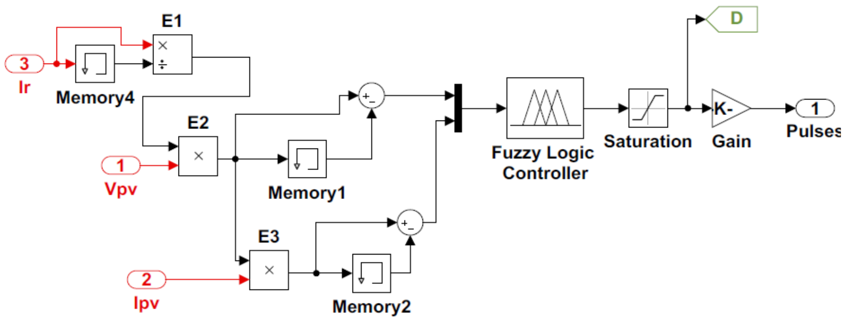

Figure 6. MATLAB/Simulink of FLC

4. RESULTS AND DISCISSIONS

The fuzzy logic control of PV system based on MMI on stand-alone and grid-connected modes was simulated using MATLAB/Simuink. PV array contains 300 modules, rated power of module is 230 W at 40 V and 6 A, the 15 modules of string are connected in series, and the 20 strings are connected in parallel. FL and PI controllers are used to control SPWM of MPPTof PV array with MMI. Small size three-phase LC filter (30 mH, 100 μF) is connected to the output of the inverter of three-phase 20 kW load or the 11 kV grid by 400V/11kV transformer.

4.1. Stand-alone PV system

Figure 1 is simulated by MATLAB/Simulink when the irradiation changed as shown in Figure 7 for two controllers FLC and PI for stand-alone PV system. Figure 8 shows the output DC voltage of PV array. Figure 9 shows the output DC power of PV array. From Figure 9, the output DC power of PV get MPP faster than the conventional method at the change of irradiation. Figure 10 shows the output ac power of load. The output voltage of MMI is shown in Figure 11. From Figure 11, the output voltage is approximate sinusoidal where the total harmonic distortion (THD) of output voltage of MMI is 20.83% by FFT as shown in Figure 12.

4.2. Grid-connected PV system

Figure 1 is simulated by MATLAB/Simulink when the irradiation changed as shown in Figure 10 for two controllers FLC and PI for grid-connected PV system. Figure 13 shows the output DC voltage of PV array. Figure 14 shows the output DC power of PV array. From Figure 14, the output DC power of PV get MPP faster than the conventional method at the change of irradiation. Figure 15 shows AC power from PV system to grid. The output voltage is approximate sinusoidal where the THD of output voltage of MMI is 17.36% by FFT as shown in Figure 16.

4.3. Case study: Tabuk City, KSA

Tabuk is the capital of the Tabuk region in northwestern KSA. Its population is 667,000 people. It is located near the Jordanian-KSA border and has the largest air base in KSA. It locates at latitude (N: 28° 23') and longitude (E: 36° 34'). The geographic area of KSA is very well positioned for solar energy with typical solar radiation levels up to 6 kWh/m2 and 80-90% clear sky days throughout the year. The annual level of solar radiation reaches 2400 kWh/m2. In spite of such rich potential, having started a huge solar-focused electrification project around 1981, the country has not yet exploited solar-dependent energy. The 2030 vision calls for solar power to contribute to the vast majority of the 9.5 GW renewable energy targets.

Figure 17 shows the hourly irradiation intensity of Tabuk city during year 2021. Figure 18 shows the average hourly irradiation intensity of Tabuk city during day. From Figure 18, the daily average value of irradiation is maximum during the day at 10-13 o'clock. This value is changed between 400 W/m^2 to 1100 W/m^2 for variable months. Figure 1 is simulated by MATLAB/Simulink for Tabuk city when the irradiation changed as shown in Figure 18 using FLC for stand-alone and grid-connected PV system. Figure 19 shows the intput irradiation of MATLAB/Simulink as average hourly irradiation intensity of Tabuk city during day of Figure 18. Figure 20 shows the output DC power of PV array for stand-alone and grid-connected PV system.

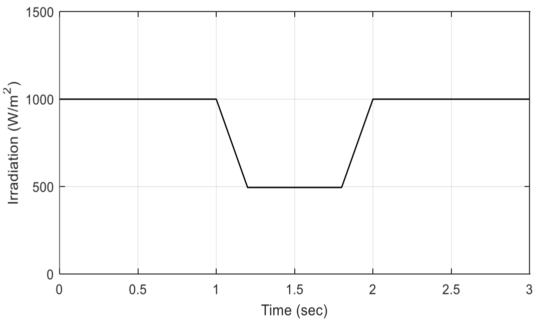

Figure 7. Irradiation

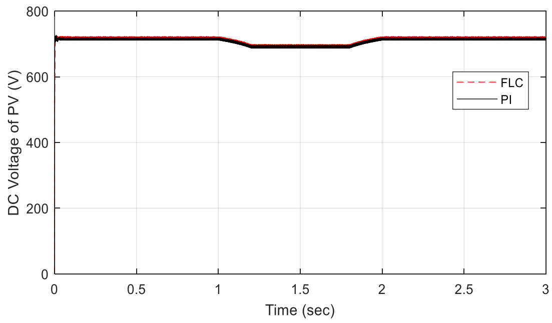

Figure 8. Output DC voltage of PV array

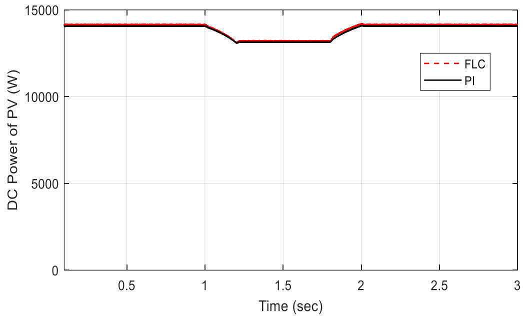

Figure 9. Output DC power of PV

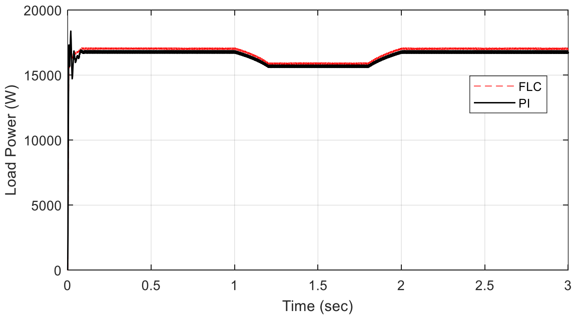

Figure 10. Load AC power

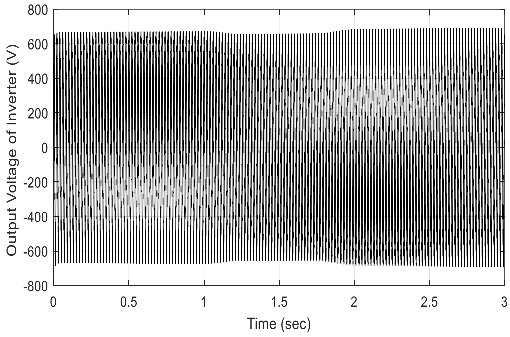

Figure 11. Output voltage of MMI

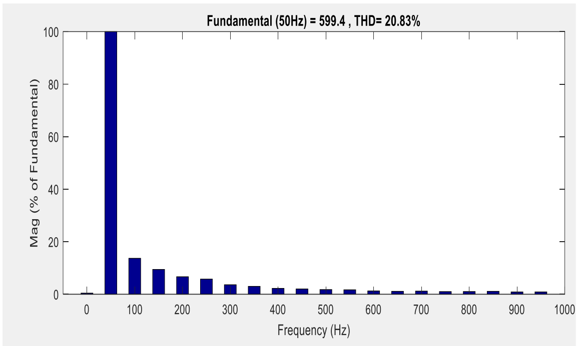

Figure 12. FFT of output voltage of MMI

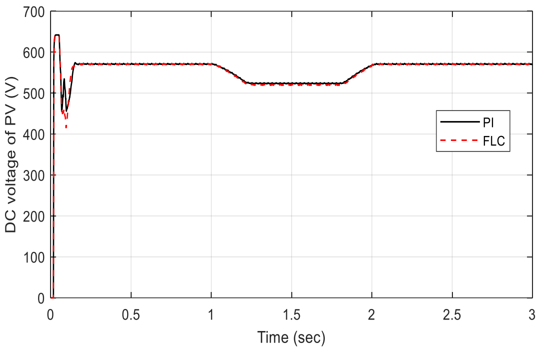

Figure 13. DC voltage of PV array

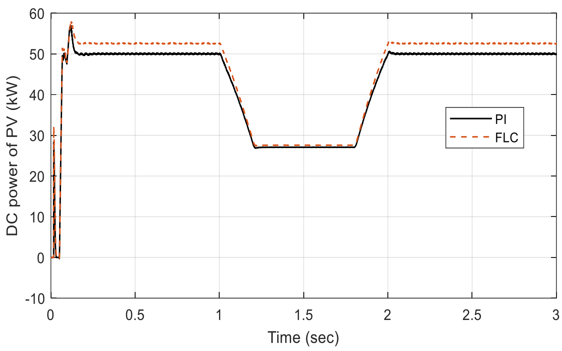

Figure 14. DC output power of PV array

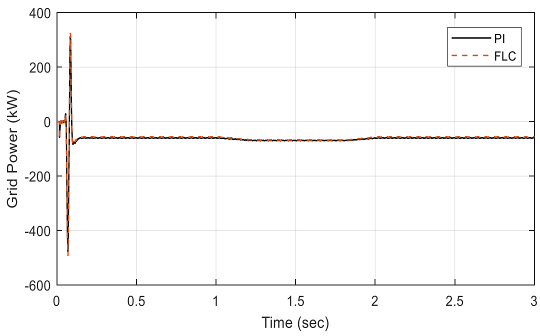

Figure 15. AC power from PV system to grid

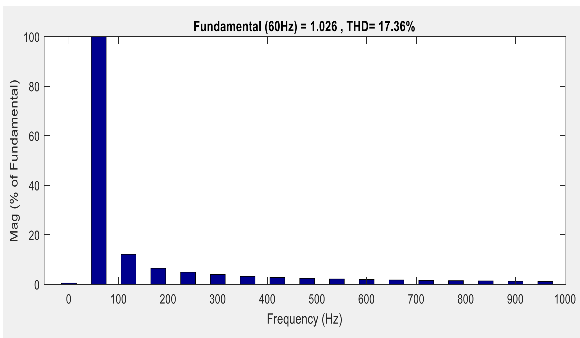

Figure 16. FFT of output voltage of MMI

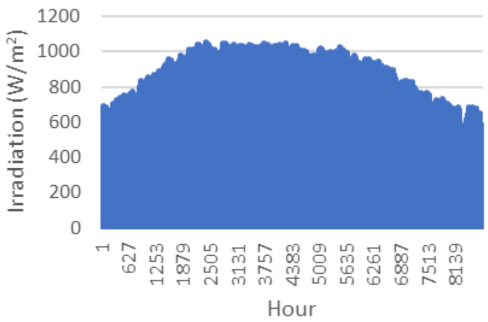

Figure 17. Hourly irradiation intensity of Tabuk city during year 2021

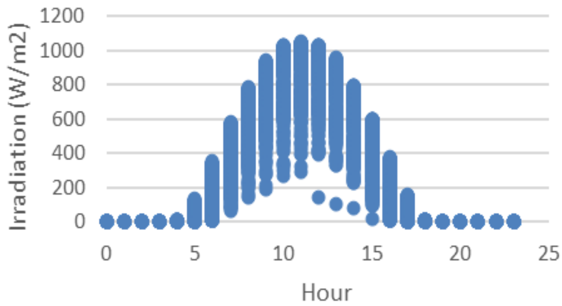

Figure 18. Average hourly irradiation intensity of Tabuk city during day

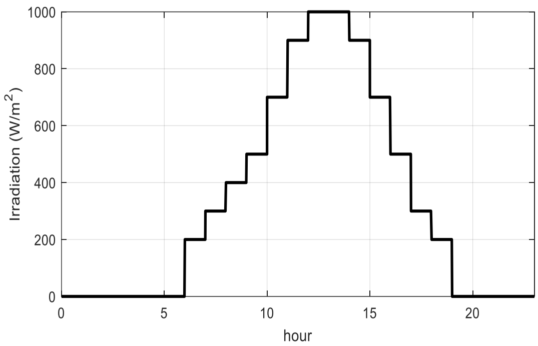

Figure 19. Intput irradiation of Tabuk city during day

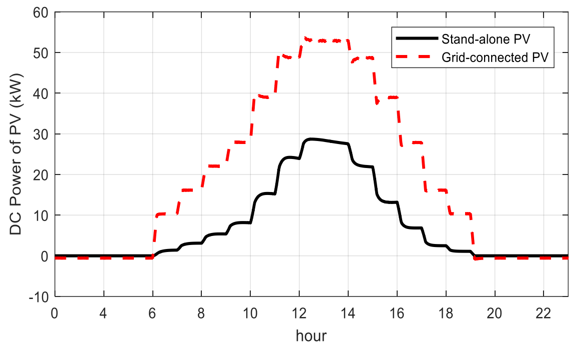

Figure 20. Output DC power of PV array for stand-alone and grid-connected PV system

From the above results, the FLC is more robust and faster controller than PI controller where the output power of PV array is higher than those of PI controller resulting to increase the efficiency of PV system for changing irradiation. The use of value of irradiation as parameter to get MPP, it helps controller to get MPP faster for FLC and PI controllers. The MMI is high quality multilevel inverter to get output voltage with minimum THD about 20%.

5. CONCLUSIONS

Robust controls of PV system with MMI application for interfacing operation on two modes stand-alone and grid-connected to overcome interfacing problems of two-level and three-level inverters. Fuzzy logic control is proposed to get MPPT using the P&O method. A fair comparison with PI and the MATLAB/Simulink. In concluded the results: a) The output power of PV system is maximum and faster using fuzzy logic control than PI control, b) Total harmonic distortion (THD) of MMI is minimum where the LC filter with a low rate is used to eliminate harmonics within IEEE limit. The output voltage is approximate sinusoidal where the THD of output voltage of MMI is 20.83% for stand-alone mode and 17.36% for grid-connected mode, c) The use of value of irradiation as parameter to get MPP, it helps controller to get MPP faster for FLC and PI controllers, d) The stand-alone and grid-connected PV system is tested under climate conditions of Tabuk, KSA. The high-performance applications of PV systems are used in abandonment areas and urban areas of KSA, and d) Due to the output power of PV array being higher by getting MPP of PV array, the efficiency of PV system is increased for changing of irradiation.

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