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An Efficient Controller for Standalone Hybrid - PV Powered System

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ABSTRACT This paper presents a new technique for enhancing the dynamic performance of a conventional proportional integral (PI) controller to achieve faster and ripple-free Maximum Power Tracking (MPPT) for standalone hybrid photovoltaic (PV) systems using an augmented fuzzy logic controller (FLC) with PI controller. The dynamic performance of the augmented PI-Fuzzy Control Scheme is compared with conventional PI controller. The additional requirement of battery bank State of the Charge (SOC) regulation is added to ensure battery charging based on PV power condition using the common DC bus voltage. The dynamic performance is examined using Matlab-Simulink software environment and simulation under different operating conditions such as uniform, irregular insolation/irradiation level, disconnected battery and electric load changes. AC side loads are connected to the standalone hybrid PV system using six pulses inverter. Dynamic simulation results validated the fast response and reduced transients and ripple content using the proposed Fuzzy-PI controller while achieving MPPT for uniform and varying insolation/irradiation levels.

Keywords: Maximum power point tracking (MPPT), Modeling of standalone PV system, Fuzzy -PI augmented controller.
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1. INTRODUCTION

Electrical power generated from PV arrays and farms is emerging as a viable, clean and economical alternative energy for residential, commercial industrial as well as electric utility back up and additional energy sources [1]. The power of PV arrays is varied due to weather changes, such as variations in insolation/irradiation levels and operating temperatures [2]. Maximum Power Point Tracking (MPPT) controller is customarily used to achieve the maximum Power/Energy Utilization of the PV system, where MPPT search algorithm or dynamic tracking is embedded in the regulation system. Nonlinear characteristic of the PV Volt-Ampere relationship is one of the major challenges in dealing with PV source-nonlinearity under PV array-insolation/irradiation changes [3-4].

Many techniques are utilized to achieve MPPT such as hill climbing, incremental conductance methods and perturb and observe (P&O). P&O is considered the most commonly used method in industrial PV applications yet it has drawbacks when the process reaches MPP, the controller forces the operating point to go back and oscillate around MPP. In this study, the PI controller is used to achieve MPPT due to changing the weather conditions such as irradiance level. In partly cloudy weather condition, the performance of PV output reduces. Partial shading may also be caused by adjacent buildings and shadow of panel, since the irradiation level is intermittent. Therefore, it is required to parallel PV with an energy storage source to compensate the load demand. It is also necessary to store the unused solar power. Li-Ion rechargeable batteries provide highly efficient, reliable, and convenient performance in both high energy and low energy applications [6]. They can be used in linear generators, backup and hybrid vehicle systems.

The control algorithm, on the other hand, plays a vital role in reliable and continuous operation of the hybrid system. The performance of the controller is studied under crucial cases, such as battery disconnection or defected battery. In such cases, the output powers oscillate and loose the tracking point. In PV- hybrid system, backup storage batteries play a vital role in storing energy, and delivering the load during the night, or compensate the required power to the load under partial shadow [6].

The DC output voltage from PV arrays is used to charge the battery using DC-DC converter. Battery disconnects/defective state is considered one of the major problems of the hybrid PV- stand-alone systems. When the battery is disconnected, the performance of the controller is affected as the PV array output is significantly reduced. The proposed augmented FLC-PI controller is utilizing a fuzzy logic controller (FLC) stage, added to the PI controller, to achieve the MPPT charging state and environmental conditions. Also, PI controller is used to control the charging state of the battery (SOC) [7]. The dynamic performance of the proposed FLC-PI controller is studied under different conditions, such as changing irradiance levels, partial shadow and battery disconnection.

2. SYSTEM CONFIGURATION

The block diagram of the proposed system is shown in Figure 1. The system consists of an energy conversion unit (solar PV system), a backup storage nickel metal hydride (Ni-MH battery), main control unit (MPPT controller), DC-DC converter, and an inverter converting DC power to AC power. The major function of the controller is to achieve MPPT and provides the PWM (Pulse Wide Modulation) signal for the DC-DC converter to charge the battery based on the SOC. Parameters of the PV array, controller and battery are provided in the Appendix1.

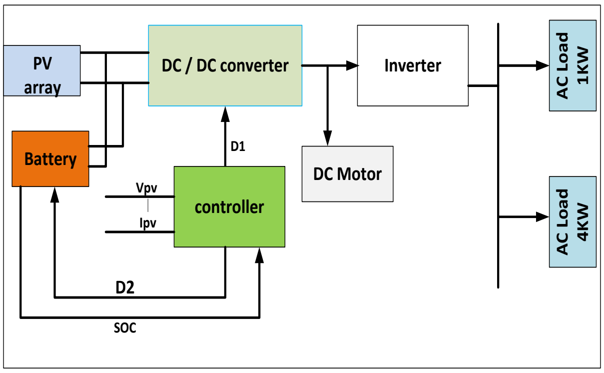


Fig. 1. Sample study system configuration

2.1. Fuzzy Logic Control (FLC)

The basic structure of fuzzy logic controller, which includes scaling factors, fuzzification, and inference engine, rule base and membership function, defuzzification, is shown in Figure 2. Fuzzy controllers are very simple in concept [9]. They consist of an input stage, a processing stage, and an output stage. The input stage maps sensors or other inputs, such as switches, thumb-wheels, etc. to the appropriate membership functions and truth-values. The processing stage invokes each appropriate rule and generates a result for each, then combines the results of the rules. Finally, the output stage converts the combined result back into a specific control output value. The most common shape of membership functions is triangular, although trapezoids, Gaussian, and bell curves are also used. Nonetheless, the shape is generally less important than the number of curves and their placement. Fuzzy-controller has many benefits over PID [9], for example, they can cover a much wider range of operating conditions than PID, and can operate with noise and disturbances. The input for the fuzzy controller is chosen to be powered from the PV array (*P*) where *P* is an error (e) signal. *Δe* is defined as the change of ΔP. Under varying irradiation and temperature, FLC achieves better performance than the PI control method [10]. Nevertheless, the choice of the rule base table of FLC affects greatly the effectiveness [15].

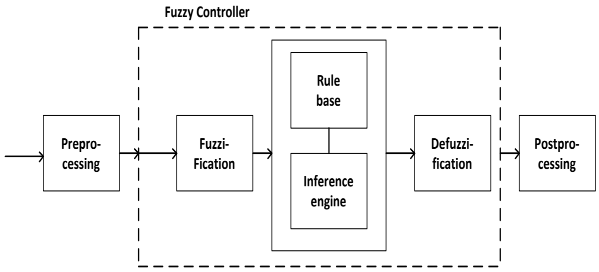


Fig. 2. Fuzzy controller structure

The proposed fuzzy-controller was designed according to Table 1, the two inputs for (FLC) are error (e), and change in error (*Δe*). Inputs for the proposed fuzzy controller are power *P* and change in power ΔP. A triangular membership function was selected to describe the input (e), and change in error, (*Δe*)

Table 1. FLC assignment matrix with rules*

e \ Δe	NB	NS	Z	PS	PB
NB	PB	PB	PS	PS	Z
NS	PB	PS	PS	Z	PS
Z	PB	PS	Z	NS	NB
PS	NS	Z	NS	NS	NB
PB	Z	NS	NB	NS	NB

*Membership States: Z: zero, S: small, B: Big, P: positive, N: negative, NB: negative big, PB: positive big, etc.

According to Table 1, both error and change in error are described through the rules. For example, if error is PB (positive big), a change in error is PS (positive small), and then the control signal is PM (positive medium). The error (*e*) and change of error (*Δe*) are given by Equations (1) and (2), respectively.

$$e = P(k) \quad (1)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (2)$$

2.2 Modeling of PV Array

Accurate mathematical model is necessary to represent the electric characteristics of PV module [2, 5]. The conventional equivalent circuit of a solar cell is expressed by one or two diodes, whereas representing by a photo-current source, parallel diode, shunt resistance (R_{sh}), and series resistance (R_s) as is seen in Figure 3. The current source (I_{pv}) models the sunlight energy conversion, the shunt resistance represents the consequence of leaks, the series resistance represents the various resistances of connections, and the diodes model the *p-n* junctions.

PV cells are usually interconnected in series-parallel configuration, to form PV modules and arrays. PV array is modeled [1] by Equation 3.

$$I_m = I_{ph} - I_d\left[\exp\left(\frac{q(V_{ph}+I_m R_s)}{nK_T}\right) - 1\right] - \frac{V_{ph}+I_m R_s}{R_{sh}}) \quad (3)$$

Where q is the charge on electron, n is the number of cells in series, k is the Boltzmann constant and T is the absolute temperature (Kelvin), I_{ph} is the photo-electric current, and I_m is the current generated by PV array.

$$I_{ph} = I_{sco}\left(\frac{G}{G_0}\right)\left(1+\alpha(T-T_0)\right)\left(\frac{R_s+R_{sh}}{R_{sh}}\right) \quad (4)$$

Where I_{sco} is the short circuit current of the module at standard irradiation G_o (1000W/m²) and standard temperature T_0 (25 °C), and α is the module's temperature coefficient. The PV array is modeled using the equations mentioned above. The PV module specifications at standard test conditions are given in Appendix 1.

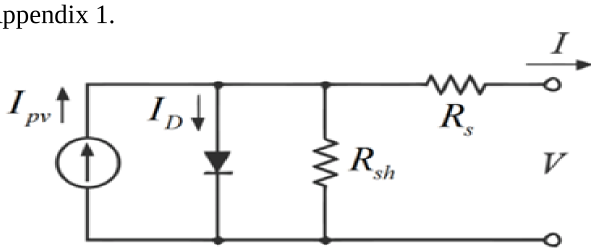


Fig. 3. Equivalent circuit of PV

2.3. Proposed Controller

The configuration of the proposed controller is based on using a cascading controller. The primary controller is a fuzzy logic controller (FLC), and the second controller is PI. The configuration of FLC is used according to Figure 2. The trapezoidal membership function is used to describe both input and output. The inputs of the proposed controller are (P), where P is the output power from PV, and then the output from the FLC controller is considered as a reference DC value of the PI controller. When the solar power is higher than the output power, since there is no need to discharge the battery, the duty cycle (D_2) is controlled by PI control for regulation. In this case, PV energy flows to the output as well as to the battery. Therefore, extra power generated by PV system can be stored, and then can be transferred to the output when necessary. The PI controller is used to control the charging state of the battery (SOC), where power from PV array is used to charge the battery through a buck converter, which acts as a maximum power point tracker.

The FLC-PI is used to achieve MPPT of PV- hybrid system under crucial conditions, such as large changes in the irradiance level, partial shadow, battery disconnection, and short circuit in AC side. A comparison between the traditional PI controllers was implemented in this study.

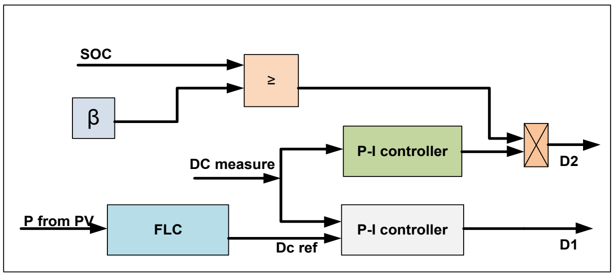


Fig. 4. Proposed augmented FLC-PI controller

3. SIMULATION RESULTS

To ensure the effectiveness and validation of the augmented FLC-PI controller, its comparison with conventional MPP-PI controller is presented. Tracking MPP under varying load insolation/irradiation and battery state of the charge is achieved. The proposed controller and the convention PI were tested, and then their performance was compared. The step response of the proposed controller is examined under two different set points. The set points were considered the power output of the system at the solar irradiances of 950 W/m² and 450 W/m². Initial set point was 950 W/m² where the obtained power was determined as 940 W, for the time period of 900 msec. the irradiance level falls down to be 450 W/m². Figure 5 shows a comparison between the PI, and proposed controller under changing in radiation level. Both algorithms are successful to reach the operating point quickly, but it's noticed that the over shot in case of using FLC-PI is less than that for PI controller.

The response of both controllers are analyzed under partial shadow [14] according to irradiance profile Figure 6(a) , the PV array divided into two groups, first group subject to irradiance profile level 1, and the other subjected to irradiance profile level 2. Figure 6(b) shows the rapidness of the proposed FLC- PI controller to reach the operating point and was achieved better performance tracking than using the conventional PI. Furthermore the responses of both controllers are examined during disconnection of the battery. PV array is kept under partial shadow, to evaluate the system performance, and prove the effectiveness of the proposed controller. There are many applications using the hybrid PV system (PV & battery) [8], such as cathodic protection system. When the battery was defected or disconnected, the system cannot accomplish the requirement. Simulation results proved this fact. Figure (7) shows the output power that obtained from both controllers. The augmented FLC-PI is successful to reach the operating point quickly, and achieve MPPT, and keeps the system working properly as compared with the PI controller.

Another point should be taken into consideration is to study the effect of short circuit (SC), when it's occurred in the AC side for a certain time. Figure 8 show the performance of the FLC-PI under short circuit (SC). It's noticed that the large value of reactive power in case of using PI as compared with augmented FLC- PI. The results also revealed that the proposed controller able to achieve better performance under this crucial condition and tracking of MPP. Battery bank was installed for better utilization of PV array off grid system. During sunlight the output power from PV is used to charge the battery bank and feeding the inverter. At night there is no output power from the PV array, then the battery bank is used to feed the load, also under partial shadow the demand out power from PV array was reduced. Hence; the battery bank compensates the required power to the inverter to feed the load. Figure 9 (b), (d), and (e) show the battery power with respect to time. It observed that PV power changes with respect to the solar irradiance. The compensation from a battery under partial-shadow and night is presented when the demand output power is higher than PV power. In addition the AC load was changed from 1kW to be 4 kW. Figure 9 (f) shows the performance of the controller.

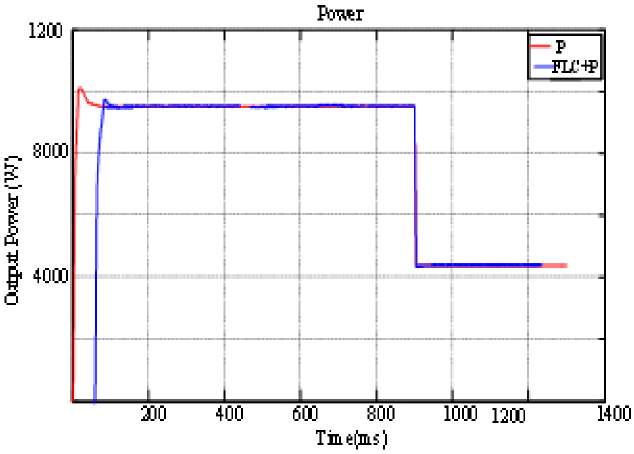


Fig. 5. Output power under insolation/the irradiance levels from 9560 to 4560 W/m^2

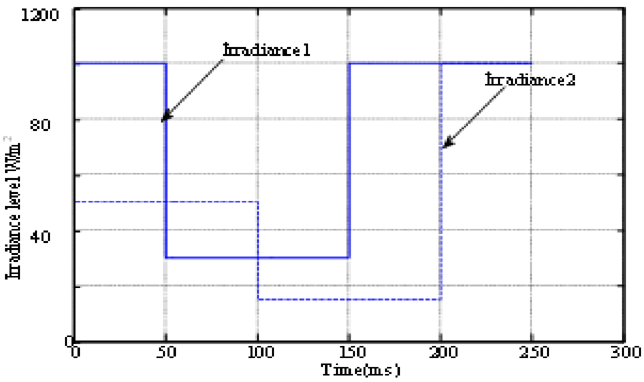


Fig. 6. (a) Irradiation level

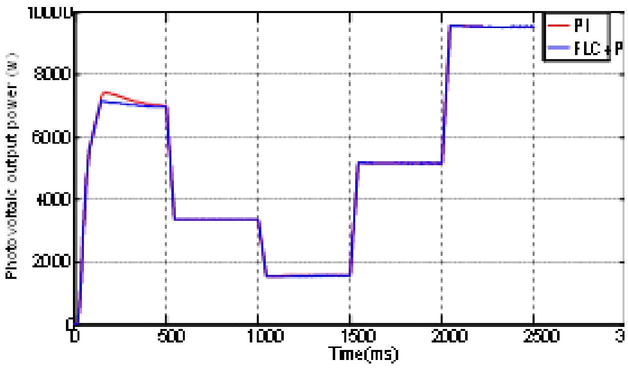


Fig. 6. (b) Output power under partial shadow

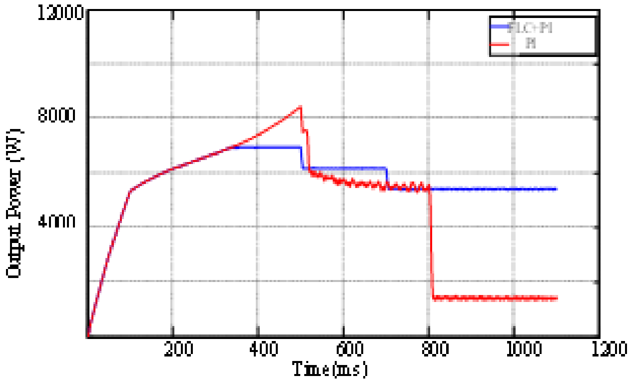


Fig.7. Output power under partial shadow when the battery bank disconnected

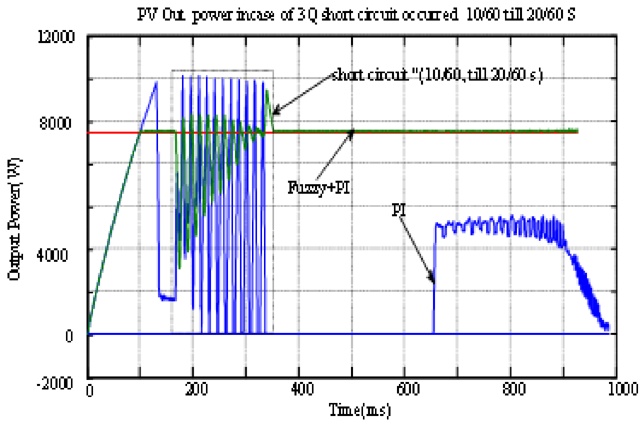


Fig. 8. (a) Output power under SC occurred from AC side for a certain time in case of battery disconnected

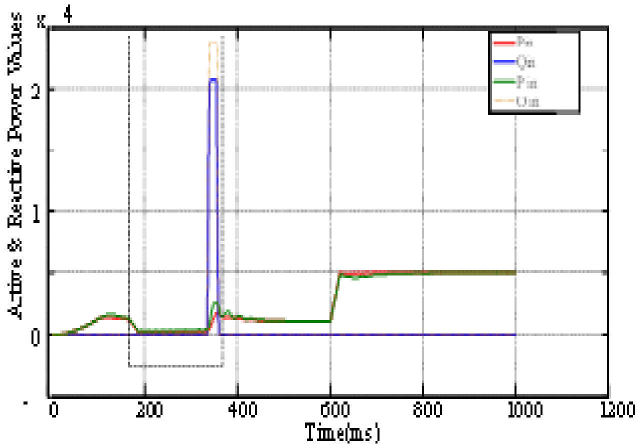


Fig. 8. (b) P&Q inverter AC power during SC

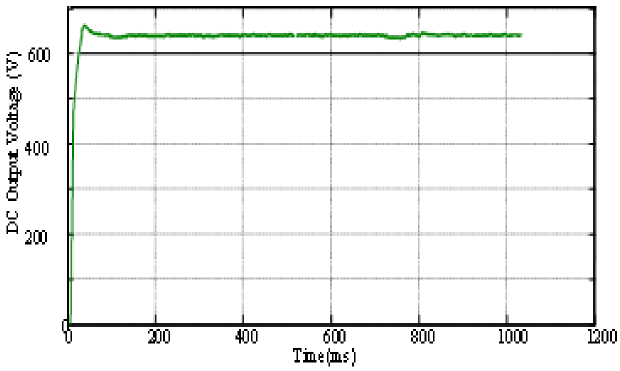


Fig. 9. (a) DC bus voltage at night

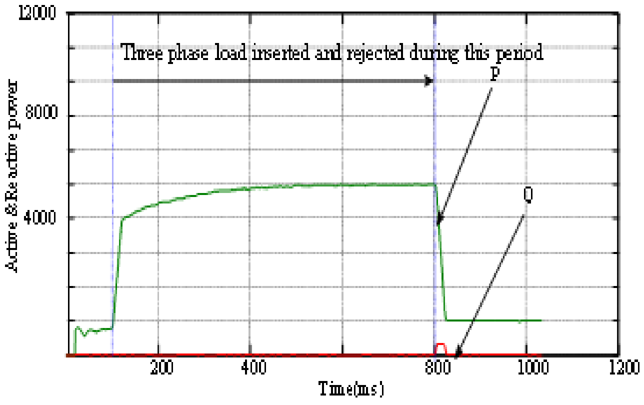


Fig. 9. (b) Load feeding from battery at night

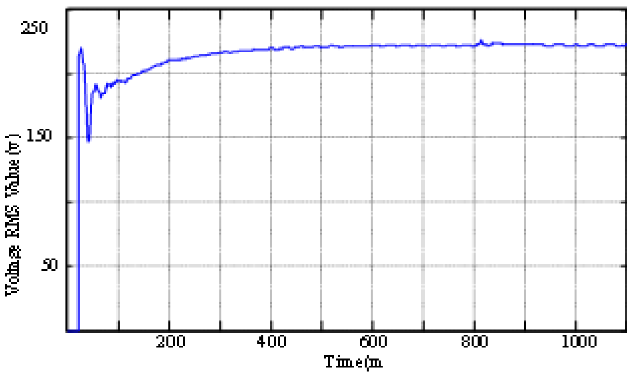


Fig. 9. (c) Inverter V_{rms} value for one phase

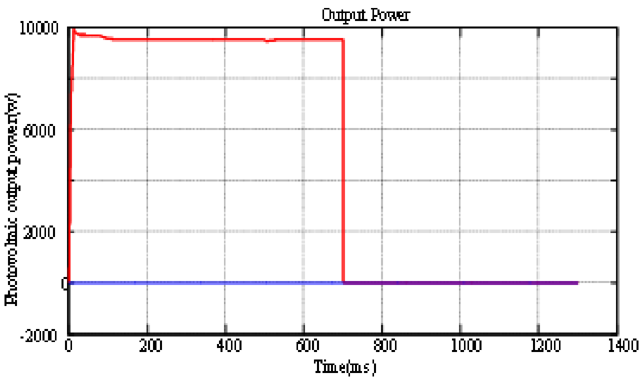


Fig. 9. (d) Output power under sunlight existing and night conditions

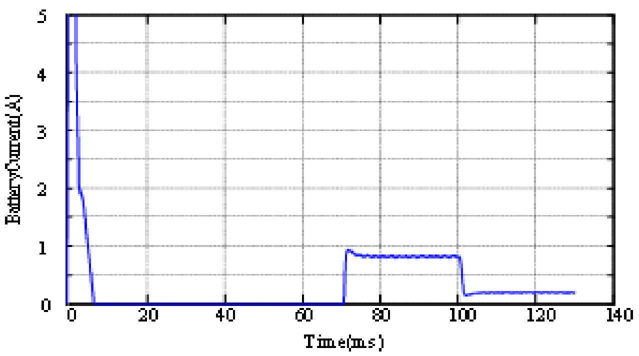


Fig. 9. (e) Battery current compensation levels

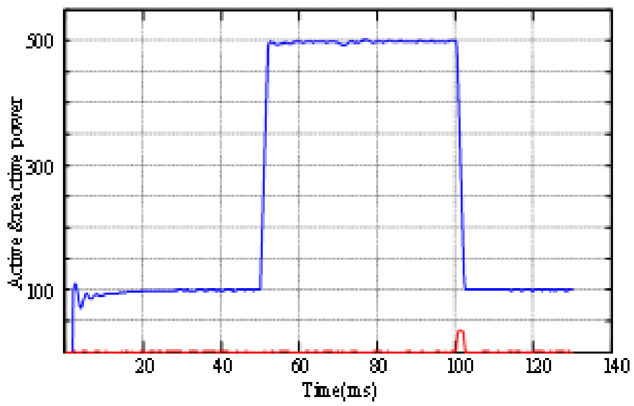


Fig. 9. (f) Active and reactive power during acceptance test

4. CONCLUSION

The paper presented an augmented FLC-PI MPPT control scheme for standalone PV-Battery hybrid system. The FLC-PI augmented controller is compared with classical PI-MPPT controller and evaluated for effectiveness under varying load, insolation/irradiation and battery state of the charge. PV array power is used to charge the battery through a double functional regulation of the buck DC/DC converter which also used for maximum power point tracking. The new augmented FLC-PI is compared with conventional MPPT PI controller and validated under different operating conditions, and digital simulation results validated its dynamic effectiveness in tracking and battery charging with less ripple, inrush and transient voltage conditions. The proposed structure of the FLC-PI is now being extended to multi array PV farms with DC and AC type loads and interface to smart grid with restrictions on total harmonic distortion and requirement for improved power quality using modified PWM switching strategies.

APPENDICES

Appendix i: PV array parameters

Parameters	Values
Rated Power	10 kW
Open circuit voltage (V_{oc})	406 V_{DC}
Number of parallel cells	44
Maksimum power point voltage (V_{mpp})	336 V_{DC}
DC bus value	640Vd_{DC}
Series resistance (R_s)	0.055 Ω
Shunt resistance (R_{sh})	550 Ω

Appendix ii: Battery parameters with charge control

Parameters	Values
Nominal Voltage	320 V
Rated Capacity	6.5 Ah
Maximum Capacity	7 Ah
Fully Charged Voltage	353 V

Parameters for charging PI(Discrete)	**Values**
Proportional value (Kp)	2
Integral term value (K(i))	120
β minimum charge value	0.8

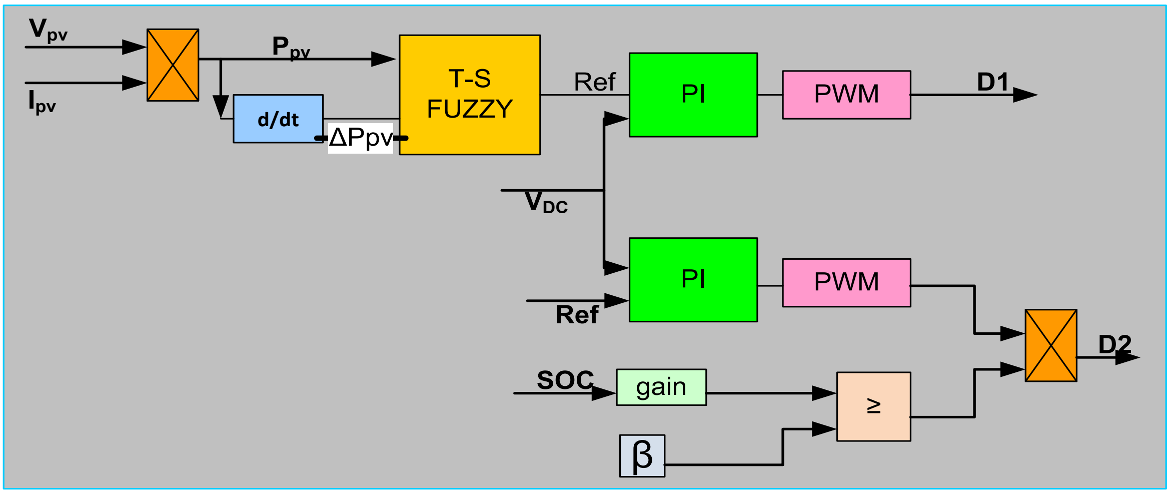
Appendix iii: Loads parameters

Parametres	Values
AC Load_1(Three phase RLC)	1kW, 50Hz, 400V_{AC}
AC Load_2(Three phase RLC)	4kW, 50Hz,400V_{AC}
DC load motor	5 HP
Field voltage	300V_{DC}
R_a	11.2 Ω
L_a	0.1215 H
R_f	281.3Ω
L_f	156 H
Load torque (constant)	1N.m
Motor Speed	1750 r.p.m

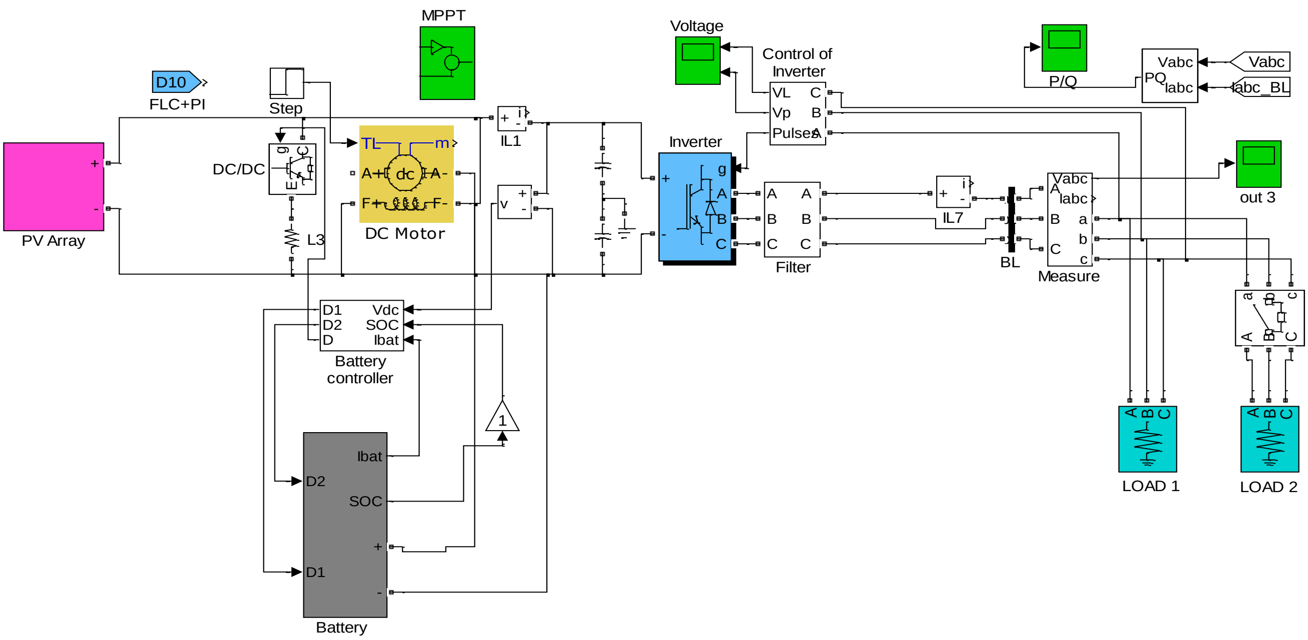
Appendix iv: Controller's & inverter parameters

Parameters for PI (Discrete)	Value
Proportional value (*Kp*)	60
Integral term value (*Ki*)	500
Parameters for FLC	**Value**
Error gain (*e(k)*)	0.16
Change of error (Δ*e*)	0.1
Control signal (D(u))	320
Universal bridge (inverter)	**Value**
Number of bridge arms	3
Power electronic devices	IGBT/Diodes
Snubber resistance (R_s)	5000

Appendix v: Proposed controller



Appendix vi: Matlab/Simulink model of general system



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Biographies

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