FUZZY-LOGIC-CONTROLLER-BASED SEPIC CONVERTER FOR MAXIMUM POWER POINT TRACKING

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Abstract—*This paper presents a fuzzy logic controller(FLC)-based single-ended primary-inductor converter (SEPIC) for maximum power point tracking (MPPT) operation of a photovoltaic (PV) system. The FLC proposed presents that the convergent distribution of the membership function offers faster response than the symmetrically distributed membership functions. The fuzzy controller for the SEPIC MPPT scheme shows high precision in current transition and keeps the voltage without any changes, in the variable-load case, represented in small steady-state error and small overshoot. The proposed scheme ensures optimal use of PV array and proves its efficacy in variable load conditions, unity, and lagging power factor at the inverter output (load) side.. The results show that the proposed FLC-based MPPT scheme for SEPIC can accurately track the reference signal and transfer power around 4.8% more than the conventional PI-based system.*

Index Terms—*DC–DC power converters, fuzzy control, photovoltaic (PV) cells, proportional–integral (PI) controller, real-time system.*

I. INTRODUCTION

DUE to its output gain flexibility, the single-ended primary inductor converter (SEPIC) acts as a buck–boost dc–dc converter, where it changes its output voltage according to its duty cycle. The selection of a proper dc–dc converter plays an important role for maximum power point tracking (MPPT) operation. The criteria for photovoltaic (PV) converter selection depend on many factors, such as cost, efficiency, flexibility,and energy flow. In this case, the flexibility represents the ability of the converter to maintain the output with the input arying, while the energy flow is assured by the continuous current of the converter. Among known converters, the SEPIC, conventional buck–boost, and Cuk converters have the ability to step up and step down the input voltage. Hence, this converter can transfer energy for all irradiation levels. Another desirable feature is continuous output current, which allows converter output parallel connection, or conversion to a voltage source with minimal capacitance. The buck or boost converters are not preferable, due to the lack of output voltage flexibility. For example, for PV system battery charging, both buck and boost converters are unable to charge the battery continuously with MPPT operation because the power–voltage curve changes with irradiation level, and hence, the voltage corresponding to maximum power changes. There are many factors that can be considered for proposing the dc–dc converters, such as input/output energy flow, cost, flexibility, and PV array effect. Unlike a buck–boost converter, the SEPIC has a noninverted output, and it uses a series capacitor to isolate input from output [1]. The buck and buck–boost converters have discontinuous input current, which causes more power loss due to input switching. The boost converter usually has higher efficiency than the SEPIC; however, its output voltageis always larger than the input, which causes inflexibilityin maximum power extraction. Both the SEPIC and the Cukconverter provide the choice to have either higher or lower output voltage compared to the input voltage. Furthermore, they have contentious input current and better efficiency compared to buck–boost and fly-back converters [2]. There is no general agreement in the literature on which one of the two converters is better, i.e., the SEPIC or theCuk [3]–[10]. This paper seeks to use the SEPIC converter because of the Cuk converter's inverted output. The MPPT algorithm represents optimal load for PV array, producing opportune voltage for the load. The PV panel yields exponential curves for current and voltage, where the maximum power occurs at the curve's mutual knee [11], [12]. The applied MPPT uses a type of control and logic to look for the knee, which in turn allows the SEPIC converter to extract the maximum power from the PV array. The tracking method used, i.e., perturb and observe (P&O) [13], [14], provides a new reference signal for the controller and extracts the maximum power from the PV array. Researchers have been working on traditional proportional– integral (PI) controllers to apply for dc–dc converters, as in literature [15]–[20]. Rahim et al. [15] used a five-level inverterto reduce the total harmonic distortion (THD) level of the output wave employing the PI controller. However, the cost of the system increased, and the control of the inverter became complicated. Furthermore, the THD level did not decrease that much at the expected level. Sera et al. [16] applied optimization for MPPT using a PI controller for their converter. Femia et al. and Fortunato et al., in [17] and [18], respectively, used onecyclecontrol for MPPT and a single-stage inverter, whereas in [11] and [15], the authors used conventional PI controllers along with the MPPT scheme. The limitations of the PI controller are well known because it is sensitive to parameter variations, weather conditions, and other uncertainties. Therefore, there is need to apply a more efficient controller that can handle the uncertainties, such as unpredictable weather, for the PV system. The sliding-mode controller is famous for its large signal stability, robustness, and simple implementation [21]–[23]. Effectively, the sliding-mode controller operates at infinite, varying, and self-oscillating switching frequency; hence, the control variables follow a specific reference path to accomplish the wanted steady-state process. However, the advantage of an intelligent controller is that its design does not require an accurate system mathematical model, and it can handle the nonlinearity of arbitrary complexity. Among different intelligent controllers, fuzzy logic is the simplest to integrate with the system. Recently, the fuzzy logic controller (FLC) has received an increasing attention to researchers for converter control, motor drives, and other process control because it provides better responses than other conventional controllers [25]–[30]. The imprecision of the weather variations that can be reflected by PV arrays can be addressed accurately using a fuzzy controller. In order to take the advantages of the fuzzy logic algorithm, the MPPT algorithm is integrated with the FLC so that the overall control system can always provide maximum power transfer from the PV array to the inverter side, in spite of the unpredictable weather conditions. This paper presents an FLC-based MPPT operation of the SEPIC converter for PV inverter applications. As the proposed method always transfers maximum power from PV arrays to the inverter side, it optimizes the number of PV modules. The proposed scheme is implemented in real time using a digital signal processor (DSP) board, i.e., TMS320F28335. The fuzzy controller for the SEPIC MPPT scheme shows high precision in current transition and keeps the voltage without any changes, in the variable-load case, represented in small steady-state error and small overshoot. As the inverter is used in a PV system, FLC is employed for more accurate output sine wave, higher dynamic performance under rapidly varyingatmospheric milieu exploiting maximum power effectively, andimproved THD, as compared to conventional PI-controlled converters.

II. PROPOSED SYSTEM

The change of voltage level fed to the inverter is the main function of the dc–dc converter. In this paper, the voltage level increases or decreases depending on the maximum power. Furthermore, the controller changes the voltage level by changing the duty cycle of the pulsewidth-modulated (PWM) signal, which tracks the reference signal.

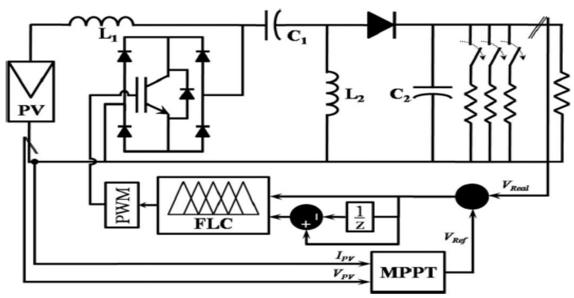

Fig. 1. Circuit diagram of the SEPIC converter for the FLC-based MPPT scheme.

A sinusoidal reference signal is compared with the output signal to produce a supposedly zero error signal. Another reference signal is used to compare the SEPIC's output, to achieve the maximum power. This reference signal is adaptive, changing its shape according to weather conditions. The SEPIC's output signal is, thus, compared with the adaptive reference signal, to feed the inverter with the most suitable power. The inverter's input signal should be as smooth as possible, but the SEPICMPPT generates a nonsmooth signal, owing to its tracking of maximum power. This problem is not as big, since the nonsmooth signal can be enhanced by the inverter's fuzzy controller and the low-pass filter connected to the inverter. Hence, although the input signal is not smooth, the exploitation of the maximum power is possible, as well as the creation of a smooth output signal. Fig. 1 is the circuit diagram of the SEPIC dc–dc converter together with the MPPT and the fuzzy controller. The design ofthe fuzzy controller was done usingMamdani's method for boththe converter and the single-phase inverter. The selection of themembership functions will be discussed in the next section. The PWM changes its duty cycle according to the control signal, configuring a feedback from the output signal represented in voltage, current, and power to get the reference signal, which is unpredictable and adapts itself depending on the maximum power achieved by the duty cycle's changes. The ximumpower point can be achieved in case of a grid-connected system, a full-load condition, or using battery charging in case of a standalone system. However, if the load need is lower than PV capacity, the PV voltage will move right in the PV curve, achieving the opportune power. This case happens even if the batteries of the standalone system are full and the load is lower than PV power. In grid-connected systems, the load is always there due to the huge number of clients. Therefore, the maximum power point can always be achieved subject to the load need.

In Fig. 1, the SEPIC converter can use single switch. However, for PV applications, the dc–dc converter can be used to supply the inverter, as well as to charge the batteries in standalone systems, hence using bidirectional switch.

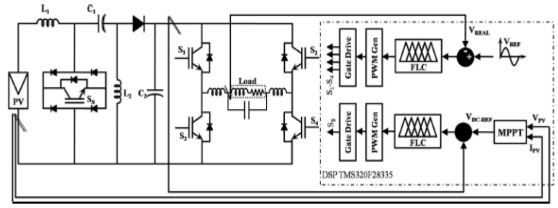

Fig. 2. Overall control scheme for the proposed FLC-based MPPT scheme for the SEPIC converter.

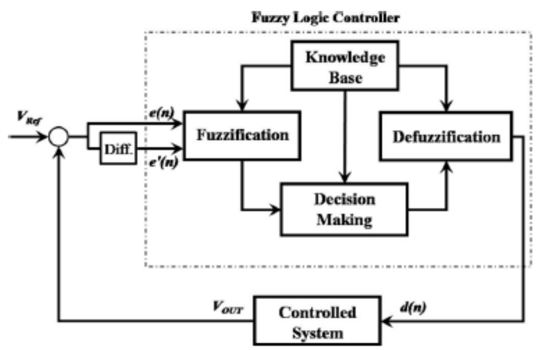

Fig. 3. Structure of the proposed FLC.

III. FLC ALGORITHM

The overall control scheme of the proposed system is shown in Fig. 2. In FLC design, one should identify the main control variables and determine the sets that describe the values of each linguistic variable. The specific structure of the FLC is shown in Fig. 3. The input variables of the FLC are the output voltage error e(n) and the change of this error e'(n). The output of the FLC is the duty cycle of d(n) of the PWM signal, which regulates the output voltage. Figs. 4 and 5 show the membership functions of the inputs and the outputs of the SEPIC-side FLCs. The triangular membership functions are used for the FLC for easier computation. A five-term fuzzy set, i.e., negative big (N-II), negative small (N-I), zero (Z), positive small (P-I), and positive big (P-II), is defined to describe each linguistic variable. The fuzzy rules of the proposed PV SEPIC dc–dc converter can be represented in a symmetric form, as shown in Table I. Moreover, as in Figs. 4 and 5, the membership functions of the output variables are ninetermfuzzy sets with classical triangular shapes, i.e., negative very big (N4), negative big (N3), negative small (N2), negative very small (N1), zero (Z), positive very small (P1), positive small (P2), positive big (P3), and positive very big (P4). The Mamdani fuzzy inference method is used for the proposed FLC, where the maximum of minimum composition technique is used for the inference and the center-of-gravity method is used for the defuzzification process.

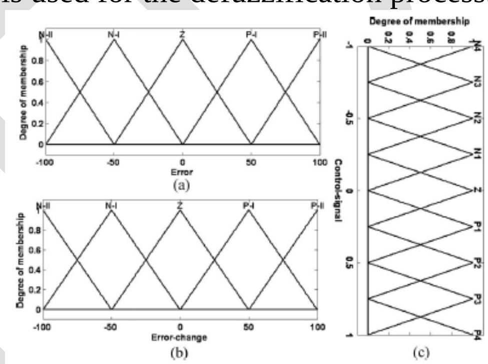

Fig. 4. Symmetrical membership function of the FLC: (a) e(n), (b) e'(n), and (c) d(n).

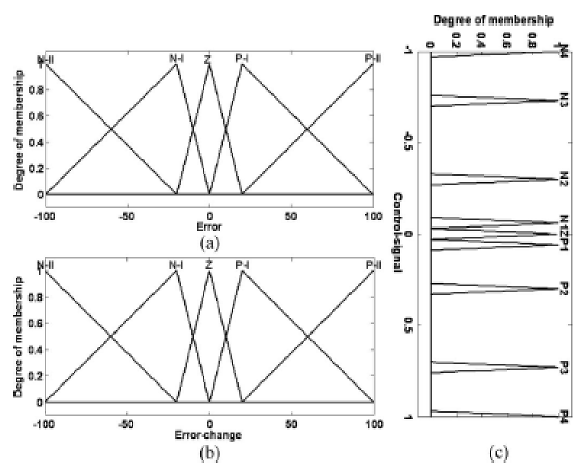

Fig. 5. Unsymmetrical focused membership function of the proposed FLC: (a) e(n), (b) e'(n), and (c) d(n).

Figs. 4 and 5 show the membership functions of the inputs and the outputs of the fuzzy system. Fig. 5 illustrates a focused membership function, where the sets go toward zero, whereas Fig. 4 memberships show symmetrical membership functions with equilateral triangle.

TABLE I
FUZZY RULE-BASED MATRIX

e' \ e	N-II	N-I	Z	P-I	P-II
N-II	N4	N4	N4	N3	Z
N-I	N4	N2	N1	Z	P3
Z	N4	N1	Z	P1	P4
P-I	N3	Z	P1	P2	P4
P-II	Z	P3	P4	P4	P4

The effect of this gathering around zero is explained in Figs. 6 and 7. Fig. 6, which is the surface in Fig. 4, shows four convex areas around zero; that means the stability point will be unfocused at zero and will cause disturbance in the output signal. On the other hand, Fig. 6 presents the convex only at zero because of the focused membership functions. Thus, the membership functions in Fig. 5 are guaranteed to produce the stable output signal. The design of the focused membership function values depends on the natureof the signal.The control signal value is confined between −1 and 1,owing to the PWM carrier wave. The input signal values are between −100 and 100 because of the error signal,

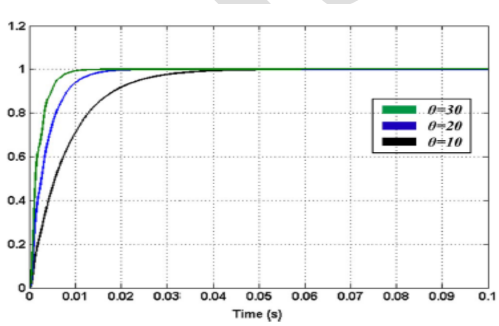

Fig. 8. Step response with unsymmetrical membership functions.

which is resultant from the difference between the output signal and the desired reference signal. In addition, most of error values are centered from −20 to 20. The sharpness of the control signal is very essential for minimizing the error signal to zero in short time; wherefore, the pulse membership function is used to configure the control signal fuzzy sets. Fig. 5(c) does not showpulse membership functions, but the center-of-gravity result gives the same value of pulse membership function due to the absence of overlapping between the neighboring sets, which are designed for that reason. The FLC performance changes with unsymmetrical distribution of membership functions, where both convergent and divergent types of asymmetry will be considered with varying degrees of the unsymmetrical membership functions. The unsymmetrical distribution of membership functions can generally be represented as follows:

$$\text{N-II} : [-\infty, -100, -50 + \theta]$$
$$\text{N-I} : [-100, -50 + \theta, 0]$$
$$\text{Z} : [-50 + \theta, 0, 50 - \theta]$$
$$\text{P-I} : [0, 50 - \theta, 100]$$
$$\text{P-II} : [50 - \theta, 100, \infty]$$

whereθ represents the factor of asymmetry, and its valuevaries within −50 and +50. Obviously, $\theta = 0$ for symmetricaldistribution for membership functions, $\theta > 0$ for convergentdistribution, and $\theta < 0$ for divergent distribution. The valueof θ increases until achieving the time response specifications,which is tuned to achieve the fastest response without generating oscillations on the steady state. The divergent distributionrepresents slow response for the system, whereas the convergentdistribution represents fast response. Fig. 8 shows the step response for the unsymmetrical cases. As estimated, the errorand the change of error are improved with increasing degreeof convergence of membership functions. Alternatively, withdivergent membership functions, the response was found to beslow. Furthermore, the value of convergent distribution cannotreach a high value because the response starts to be oscillatedaround the steady state. The settling time (*ts*) at different *θ*is shown in Fig. 8. For θ = 30, ts = 0.016s, whereas at θ = 20 and θ = 10, the settling time are ts = 0.025 and 0.059 s,respectively. The steady state error and the maximum overshotfor all cases are zero.

IV. PROPOSED MPPT-BASED SEPIC CONVERTER.

The fuzzy controller is applied to the SEPIC converter tomimic the new reference signal coming from the MPPT. Thenew duty cycle δ(k) of the SEPIC converter switch was adjustedeither by adding or by subtracting the previous duty cycleδ(k−1) with the duty cycle's perturbation step size. Equation (1)presents the relation between the present and previous dutycycles, i.e.,

$$\delta_{(k)} = \delta_{(k-1)} \pm \Delta\delta \qquad (1)$$

whereΔδ is the change in duty cycle, resulting from the change of reference signal. The MPPT control technique is applied to achieve a new reference voltage for the fuzzy controller, which changes the duty cycle of the PWM signal for the SEPIC converter. The P&O algorithm has a simple structure and requires few parameters (i.e., power and voltage); that is why it is extensively used in many MPPT systems [31]–[34]. In addition, it can be easily applied to any PV panel, regardless of the PV module's characteristics for the MPPT process. The P&O method perturbs the duty cycle and compares instantaneous power with past power. Based on this comparison, the PV voltage determines the direction of the next perturbation. P&O shows that, if the power slope increases and the voltage slope increases also, the reference voltage will increase; otherwise, it will decrease. The drawback of most of the fuzzy-based MPPT algorithms is that the tracking point is located away from the maximum power point when the weather conditions change. However, a drawback of P&O technique is that, at steady state, the operating point oscillates around the maximum power point giving rise to the waste of available energy, particularly in cases of constant or slowly varying atmospheric conditions. This can be solved by decreasing the step size of perturbation. The step size of the P&O method affects two parameters: accuracy and speed. Accuracy increases when the step size decreases. However, accuracy leads to slow response when the environmental conditions change rapidly. Larger step size means higher speed for the MPPT operation, but this will lead to inaccuracy and larger intrinsic oscillations around the maximum power point in steady state. Step sizes should, thus, be chosen well to achieve high speed and accuracy. The step-size rate for the voltage reference signal in this paper is 0.5 V/ms.Two types of simulations for the MPPT converter were done using MATLAB/Simulink. The first simulation used the characteristic equations of the PV array given in [35], whereas the second simulation used the solar-panel module given in Simulink. The MPPT algorithm was built via (.m) file and linked withSimulink. The SEPIC circuit was built via SimPower toolbox.Fig. 9 shows the curves for power versus voltage, at 25 ◦C and50 ◦C, for radiation variations, from 250 W/m2 to 1000 W/m2. For simulation purposes, the PV panel values and the number of PV arrays were taken depending on the experimental setup,as detailed in the next section. The reference voltage signal, tracking the maximum power, is shown in Fig. 10. The relation between Figs. 9 and 10 can now easily be determined. Hence, it is clearly noted that the maximum power occurs around 330 V.

V. SIMULATION RESULTS

Simulation Results Simulation was applied on MATLAB/Simulink to verify the practical implementation of the proposed SEPIC fuzzy controller for the single-phase inverter. Fig. 10 presents the reference signal for the SEPIC's output, where it tracks the maximum power. The results introduced in Fig. 12 belong to voltage and current signals of the conventional PI controller. The PI controller is selected for comparison because of its severe use in industry applications [36]–[38]. The converter conditions used in the PI controller are the same as that used in the FLC. The PI controller is designed well where it is optimized to produce minimum error signal. However, it clearly appears that the output signal cannot follow the reference signal in Fig. 10 fast.

Furthermore, the output voltage does not lie on the maximum power curve. Moreover, large amount of power can be lost due to the PI controller. The reason behind this that the PI controller addresses two main issues: the steady state error and the maximum overshoot. If one need focus on time, the derivative controller must be added to become the PI–derivative (PID) controller, but this causes instability in the steady state. Therefore, the PI controller cannot follow accurate changes in reference signal effectively.

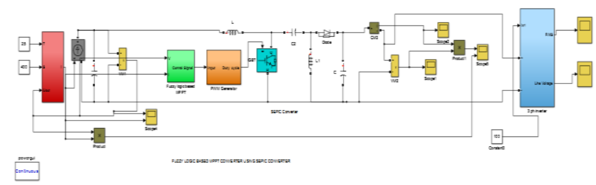

Fig.9. Simulation circuit for fuzzy logic controller

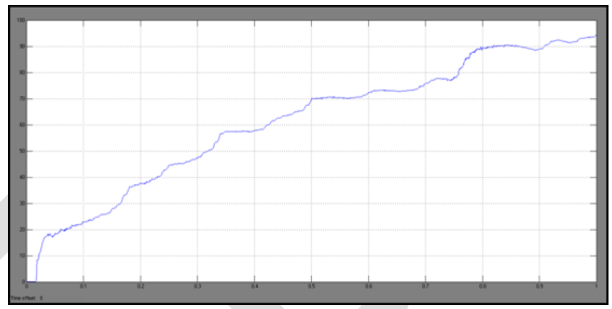

Fig. 10. RMS voltage

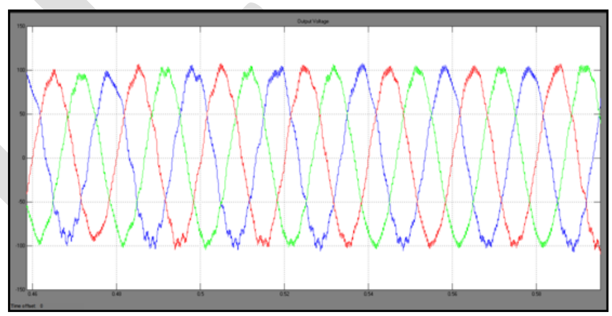

Fig .11.line voltage

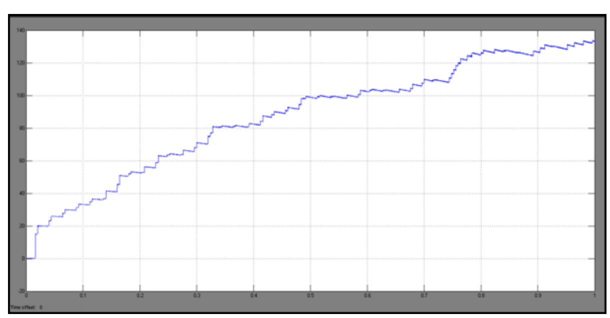

Fig.12.converter dc voltage

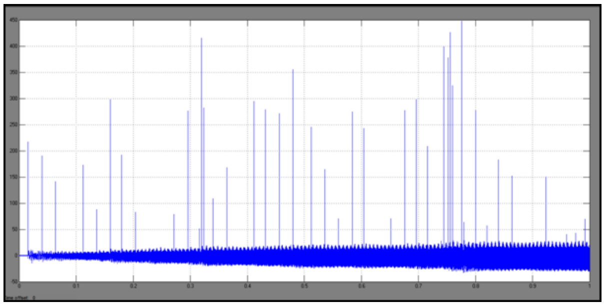

Fig.13. load current

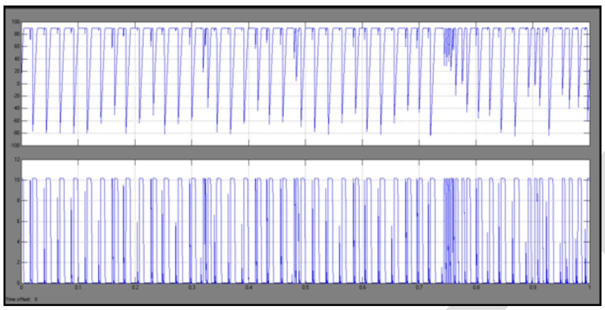

Fig.14. PV voltage and current

VI. CONCLUSION

An FLC-based MPPT scheme for the SEPIC converter and inverter system for PV power applications has been presented in this paper. A prototype SEPIC converter-based PV inverter system has also been built in the laboratory. The DSP board TMS320F28335 is used for real-time implementation of the proposed FLC and MPPT control algorithms. The performance of the proposed controller has been found better than that of the conventional PI-based converters. Furthermore, as compared to the conventional multilevel inverter, experimental results indicated that the proposed FLC scheme can provide a better THD level at the inverter output. Thus, it reduces the cost of the inverter and the associated complexity in control algorithms. Therefore, the proposed FLC-based MPPT scheme for the SEPIC converter could be a potential candidate for real-time PV inverter applications under variable load conditions.

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