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FUZZY - SLIDING MODE CONTROLLER FOR SEPIC IN A SOLAR ENERGY SYSTEM

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ABSTRACT

The paper attempts to design a hybrid control strategy with a view to extract a regulated voltage from a Single Ended Primary Inductance Converter (SEPIC) over a range of operating loads. The converter energized from a solar source operates in the boost mode to suit the realistic needs of the practical utilities. The exercise endeavors to evolve a composite fuzzy - sliding mode (FSM) mechanism through which it surges to off- set the elemental non- linearities and parametric variations in the converter system and reach to the desired level of output. The procedure inscribes adequate artifacts to reject servo and regulatory disturbances and enable the SEPIC to perceive as an astute interface to the grid. The simulated response validated using experimental results exhibit the merits of the control methodology and suitability of the scheme for use in real world power systems.

INTRODUCTION

The incessant increase in the demand for electric energy associated with a resolute need to oblige environmental attributes such as global warming creates a focus to explore the use of sustainable source of energy. Solar energy evinces considerable scope to serve as alternatives and attempt to tide over the crisis plane. It exists either as a standalone generating unit or in the form of a grid connected system depending on the suitability and specific application requirements. Solar energy appears to offer a far reaching thrust and open up with an elaborate role for PV modules in this perspective. The PV module continue to grow with a stack of batteries that charge with a surplus energy from the PV panel and support the electricity demands over a period of time. The module formed by a series connection of solar photovoltaic (SPV) cells translates to collect the required output voltage. There lies a consistent effort to realize higher power output by increasing the surface area of each SPV cell or by connecting several of these in series and parallel. The output of the SPV array may directly feed loads or use a power electronic converter (Martins *et al.*, 2002) to serve different issues like controlling the power flow in the grid connected systems, track the maximum power available from the SPV array or feed the power to an utility load.

The dc-dc converters appear to emerge as an indispensable part of an energy source in many electronic circuits. SEPIC a fourth order variety belongs to this class and conceives listless options to effectively interface the system to the grid. It plays a significant role to control the energy flow between dc-dc systems and in applications that augurs the use of stabilized voltage. The structure of dc-dc converters changes with the status of the switch in the converter characterizing them as a class of continuous-time switched systems. The switching nature of dc-dc converters with energy storage elements characterizes them as a nonlinear system (Tse and Mario di Bernardo, 2002).

The power electronic converters form part of a periodic time-variant and non-linear system due to their inherent switching operation. The classical linear control methods find an extensive role in the design of regulators for dc-dc converters and determine their stability limits around their operating points (Ferdowsi and Emadi, 2004). Besides the dynamic performances of dc-dc converters using simple single-loop voltage-mode control appear to be generally not satisfactory under parameter variations, nonlinearities, large supply and load variations.

A dynamic model of a SEPIC has been developed through the use of PWM averaged switch model equivalent circuit. The performance has been examined using simulation and the converter dynamics found to depend on duty cycle and

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transformer ratio (Hren and Slibar, 2005). The SEPIC has been structured to inherit several advantages over boost and fly back topologies (Sebastian *et al.*, 2001). The influence of PWM and zero current switched quasi resonant techniques have been studied both in the continuous and discontinuous modes to determine the stress on the components. A family of high efficiency high step up dc-dc converter topologies which use diodes and coupled windings instead of active switches and involves the recycling of the leakage energy has been suggested (Zhao and Lee, 2003). A high efficiency dc-dc converter with high step up gain suitable for low PV voltages and based on the role of active clamping circuit and voltage doubler rectifier to achieve a high step up ratio and soft switching operation has been proposed (Woo-Young Choi, 2011). A variable structure controller scheme based on the average model has been outlined to operate a dc-dc converter with a constant switching frequency. A constant cost effective and dynamically fast algorithm along with reaching law theory has been analyzed using simulation results (Yiwen Hey *et al.*, 2010).

The multivariable fuel cell cascaded converter system has been controlled through the use of SM theory and the simulation results found to explain the robustness and accuracy in controlling the outputs (Farzad Abdous, 2009). A soft switching dc-dc converter with high voltage gain has been constructed to suit a hybrid power system, formed as a combination of renewable energy resources. The soft switching characteristics have been exploited to reduce the switching loss of the active power switches and raise the conversion efficiency (Francis and Narasimharao, 2012). The control of dc-dc converters espouses interesting challenges in the sense it attempts to increase the efficiency, reduce the size, lower the cost and enhance its reliability to be suitable for many applications. The second aspect orients to an exhaustive effort to address the discontinuities, nonlinearities and their non-minimum phase characteristics. The most popular control techniques hover over voltage control and current injected control whose parameters generally depend on the operating point (Yang and Sen, 1999). Though a host of control schemes continue to surface and invite attention to propel methodologies that increase the frame work of the utilities, the use of SM controller carries an edge for traversing the right direction. Besides the introduction of intelligent techniques together with the non linear approach predict a further flexibility in the control challenge and erudite its definite role in the solar energy system.

Problem Statement

The main emphasis relates to cohesively integrate the nuances of SM theory with fuzzy decision making principles to allow a SEPIC to offer a variable regulated output voltage in tune with the requirements of the load entities. The procedure incites to augment the intrinsic variations in voltage using the hybrid formulation of the control mechanism to reflect an ordained change in duty cycle and in turn an appropriate change in the width of the PWM pulses. The focus spreads to evaluate the performance through simulation in the MATLAB platform and investigate its viability using a DSPIC (Digital Signal Peripheral Interface Controller) based hardware realization.

MATERIALS AND METHODS

The primary theory owes to evolve a PWM strategy to switch the semiconductor devices in the power module through a control mechanism that incorporates the principles of a SM action with the reasoning articulates of fuzzy logic. The exquisite need to address the circuit parasitics and their influence on the rate of change of current forges a structural change in the system and sandwiches the ingenious role of a non linear surface trajectory theory together with the ilusions of reasoning. The structure of the SEPIC power module of SEPIC shown in Fig.1 consists of two inductors, two capacitors and a diode in its configuration. The two different configurations depending on the state of the relate to the case of continuous conduction mode seen in Figs. 2 and 3.

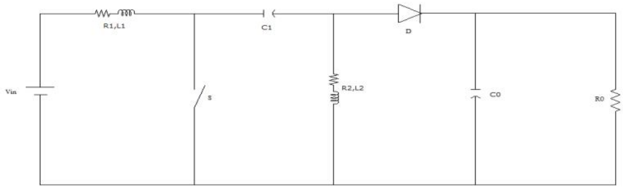

Fig.1. Power module

When the power switch S is turned ON, the first inductor, L_1 is charged from the input voltage source and the second inductor L_2 draws energy from the first capacitor C_1. The output capacitor C_0 is left to support the load and deliver the load current. The fact that both L_1 and L_2 are disconnected from the load when the switch is ON leads to complex control characteristics.

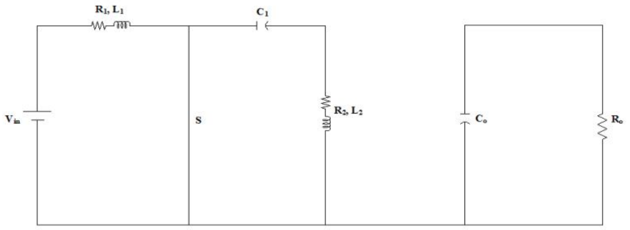

Fig.2. ON mode SEPIC

When the power switch S is turned OFF, the first inductor L_1 charges the first capacitor C_1 and simultaneously provides current to the load. The energy stored in the second inductor L_2 is transferred to the second capacitor C_0 through D and supplies energy to the load.

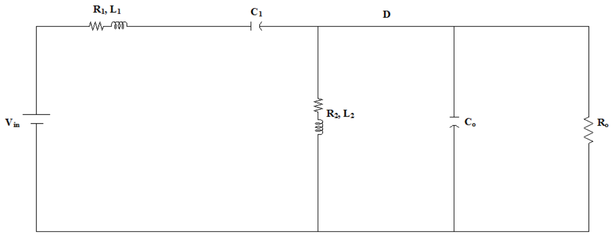

Fig. 3. OFF mode SEPIC

Modeling

The modeling of networks which contain switches invites greater attention in light of the unusual properties of switches in comparison with other circuit elements. The philosophy owes to express the nonlinear time varying phenomena that govern the operation of the converter in a mathematical form. Though many techniques are available, the state space average method hails to be the best and arrive at simple average models which can easily be realized (Forsyth and Mollov, 1998). It creates a platform to analyze and establish the static and dynamic characteristics of the system.

ON and OFF mode state equations

The two inductor currents (i_1 and i_2) and the capacitor voltages (V_{c1} and V_0) are chosen as the state variables. The dynamic behavior governing the operation of this converter is explained using the two state matrices in (1) and (2) for ON and OFF modes respectively.

When S is ON:

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & 0 & 0 & 0 \\ 0 & -\frac{R_2}{L_2} & -\frac{1}{L_2} & 0 \\ 0 & \frac{1}{C_1} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{R_0 C_0} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{in} \tag{1}$$

When S is OFF:

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & 0 & -\frac{1}{L_1} & -\frac{1}{L_1} \\ 0 & -\frac{R_2}{L_2} & 0 & \frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ \frac{1}{C_0} & -\frac{1}{C_0} & 0 & -\frac{1}{R_0 C_0} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{in} \tag{2}$$

Invoking the state space averaging technique by using (3).

$$\left.\begin{aligned} A &= A_1\,(D) + A_2\,(1-D) \\ B &= B_1\,(D) + B_2\,(1-D) \end{aligned}\right\} \tag{3}$$

where A's and B's respectively represent the ON and OFF mode coefficient matrices of the state space equations. Using state space averaging technique the final state matrix reduces to the following form in (4).

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & 0 & \frac{D-1}{L_1} & \frac{D-1}{L_1} \\ 0 & -\frac{R_2}{L_2} & -\frac{D}{L_2} & \frac{1-D}{L_2} \\ \frac{1-D}{C_1} & \frac{D}{C_1} & 0 & 0 \\ \frac{1-D}{C_0} & \frac{D-1}{C_0} & 0 & -\frac{1}{R_0 C_0} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{in} \tag{4}$$

CONTROL ALGORITHM

The SM controller inherits a method to design the system in such a way that it is insensitive to parameter variations and external load disturbances. The approach is realized by the use of high speed switching control law which creates a structural change in the system to allow it to move in the predetermined path in a state variable space and stay in that surface thereafter. The approach allures to intertwine the error accrued along with the rate of change of error to evince a corrective action and there from generate a reference for the PWM pulses. It gathers the necessary change in duty cycle to arrive at the regulated value of the output voltage through the entire operating range. The principle of variable structure control endeavors to forcibly constrain the system by designing a switching surface through a switching function. The switching function can be written as in (5).

$$\sigma\,(X\,) = G.X \pm K \tag{5}$$

Where σ - Switching function, G - Gain vector, X - State vector, K - Constant

A typical variable structure control law is expressed in (6).

$$\begin{aligned} m &= m+ \;\; for \;\; \sigma\,(X\,) > 0 \\ m &= m- \;\; for \;\; \sigma\,(X\,) < 0 \end{aligned} \tag{6}$$

The compliance of the constraint ensures the state trajectories to be directed towards the surface. The mathematical relation for realizing the condition is given in (7).

$$\begin{aligned} &\lim_{\sigma \to 0+} \frac{\partial \sigma\,(X\,)}{\partial X} < 0 \\ &\lim_{\sigma \to 0-} \frac{\partial \sigma\,(X\,)}{\partial X} > 0 \end{aligned} \tag{7}$$

The above equation can be alternatively stated as

$$\sigma\dot{\sigma} < 0 \tag{8}$$

The discontinuity in (8) reaches out to the continuous control law in (9) and represent a continuous system.

$$\sigma\,(X\,) = \dot{\sigma}\,(X\,) = 0 \tag{9}$$

The focus orients to develop a voltage regulating mechanism using nonlinear principles and facilitate the converter to ascribe a satisfactory performance in the range of operating loads.The desired objective inserted into the controller through the design of a switching surface serves to predicted the switching pattern. The converter switch as across this sliding surface through the construction of a switching control law, which satisfies a set of necessary conditions for its operation.

The switching function is chosen as in (10).

$$\sigma = \left[\, g_1\, g_2\, g_3\, g_4 \,\right] \begin{bmatrix} e_{i1} \\ e_{i2} \\ e_{V_{c1}} \\ e_{V_o} \end{bmatrix} = g_t.E \tag{10}$$

where g_1 to g_4 are constant gains. e_{i1} and e_{i2} , $e_{vc1}$and e_{v0} are the errors in the current of inductors and the errors in capacitor voltages respectively. The input current and output voltage are measured and controlled directly, which is equivalent to setting gains g_2 and g_3 to zero. The sliding surface is given through (11).

$$\sigma = g_1.e_{i1} + g_4.e_{V0} \tag{11}$$

The term D representing duty cycle in (4) is replaced by a variable u, such that it depends on the state of the switch. Thus the overall state space model is given in (12).

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} = \begin{bmatrix} -\frac{R_1}{L_1} & 0 & \frac{u-1}{L_1} & \frac{u-1}{L_1} \\ 0 & -\frac{R_2}{L_2} & -\frac{u}{L_2} & \frac{1-u}{L_2} \\ \frac{1-u}{C_1} & \frac{u}{C_1} & 0 & 0 \\ \frac{1-u}{C_0} & \frac{u-1}{C_0} & 0 & -\frac{1}{R_0C_0} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ V_{c1} \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} V_{in} \tag{12}$$

The control law is written as in (13)

$$u = \begin{cases} 1; if\,\sigma < 0 \\ 0; if\,\sigma > 0 \end{cases} \tag{13}$$

A necessary condition for the sliding surface to exist is given in (14).

$$g_t.A_4 \le 0 \tag{14}$$

where g_t is the gain matrix and A_4 is fourth column of matrix A of the overall state space model at which u is set to zero. The basic analogy of a fuzzy logic control (FLC) relates to offer decisions that are more closely approximate to human perception and reasoning principles. It enlivens as an emerging choice for initiating control actions and revolves around a rule based methodology implemented in the IF-THEN format. The closed loop corrective approach encapsulates a procedure to derive rules and establish a platform for arriving at a regulatory action. The trapezoidal and triangular membership functions shown in Fig.4 cater the attributes of decision making rules and create a relation between the observed input and output entities. The antecedents in this formulation are error (e), change in error (ce) of the voltage and the consequent (u) is the reference wave to the PWM generator. The logical decisions constitute the Table 1 and travel to derive the appropriate reference quantity for generating the PWM pulses. The power switch in the converter is forced to switch in accordance with the PWM pulses generated from a cohesive combined role of the SM and FLC in order to effectively regulate the output voltage of the converter in the defined range of operation.

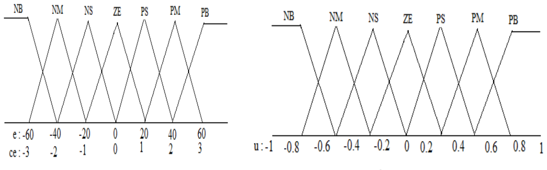

Fig.4. Chosen membership Functions for Input and Output Variables

Table 1. Fuzzy Rule Base

AND		CE						
		NB	NM	NS	ZE	PS	PM	PB
E	NB	NB	NB	NB	NB	NM	NS	ZE
	NM	NB	NB	NB	NM	NS	ZE	PS
	NS	NB	NB	NM	NS	ZE	PS	PM
	ZE	NB	NM	NS	ZE	PS	PM	PB
	PS	NM	NS	ZE	PS	PM	PB	PB
	PM	NS	ZE	PS	PM	PB	PB	PB
	PB	ZE	PS	PM	PB	PB	PB	PB

RESULTS AND DISCUSSION

The proposed strategy avails a MATLAB-SIMULINK platform to examine the performance of the controller across an operating range of load power varied up to 5Kw. The SEPIC constructed with the parameters R1 = 0.1Ω, L_1 = 100 μH, R_2 =0.2Ω, L_2 = 510 μH, C_1 = 47 μF, C_0 = 200 μF forges to rig out a stable output of 230 V from a fixed input of 144 V. The scheme includes a procedure to investigate the servo and regulatory disturbance rejection characteristics of the converter.

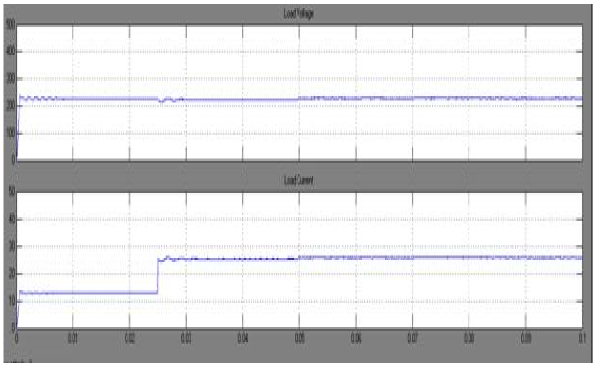

Fig.5. Steady state and transient response

The Figs. 5 depicts the output voltage and current corresponding to a load of 3 Kw in the boost mode of the SEPIC. The creation of a sudden load disturbance at 0.025 sec causes the output current to increase and voltage to decrease as seen from the waveforms. Similarly the instantaneous rise in supply voltage at t = 0.05sec reflects an increase in the load voltage, though with negligible change in current. However the intricacies of the hybrid mechanism evince in such a way as to modify the duty cycle, in order to minimize the error generated because of the deviation of the output from its reference value and maintain the desired output voltage in both the cases. The response details to elucidate the fact that it settles rapidly and portray the merits of the FSM in terms of an enhanced time response characteristics.

Hardware Implementation

The Fig. 6 shows the prototype model built for 5 Kw and tested for similar values of load powers. The methodology involves the use of dsPIC30F4012 Digital Signal Controller (DSC) an advanced 16-bit processor that offers true DSP features with the fundamental real-time control capabilities of a microcontroller. The Harvard architecture in which the instructions and data originate from separate source offers to simplify the design and derives a host of advantages. The prioritized interrupts, extensive built-in peripherals and power

Table 2. Performance Comparison

Load (Kw)	Load current (Amps)				Load voltage (Volts)			
	Simulation			Hard Ware	Simulation			Hard Ware
	PI	SM	FSM		PI	SM	FSM	
1	4.35	4.35	4.35	4.20	229.95	230.00	230.00	229.50
2	8.70	8.70	8.70	8.60	229.91	229.98	229.99	229.20
3	13.05	13.05	13.04	12.90	229.80	229.84	229.99	229.00
4	17.41	17.41	17.39	17.30	229.68	229.78	229.98	228.50
5	21.78	21.76	21.74	21.70	229.60	229.75	229.98	227.00

management features combine attractively with a fully featured DSP engine. The processing appears to be faster because the DSPIC can pre fetch the next instruction from program memory while it executes the current instruction that accesses data RAM.

Fig.6. Prototype model

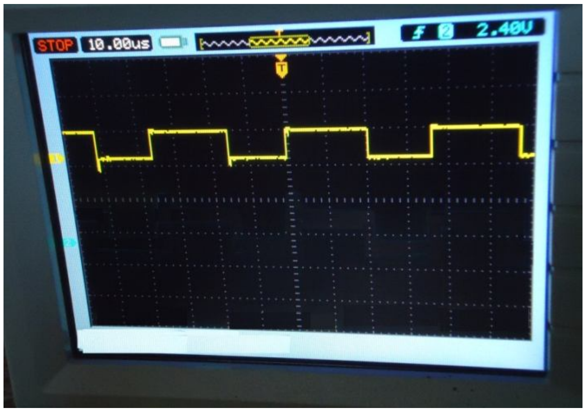

Fig.7. PWM Pulse

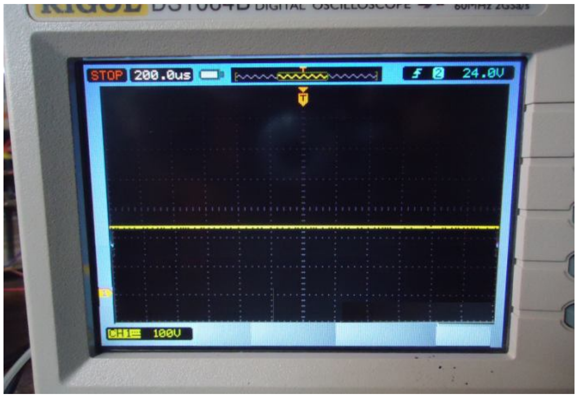

Fig.8. Output Voltage

It assuages to generate PWM pulses in accordance with the change in the duty cycle to retract the desired level of output voltage. The Figs. 7 and 8 display the PWM pulse and the steady state output voltage waveform captured using a RIGOL Digital Storage Oscilloscope (DSO) obtained using an attenuator probe of 1:10 from the prototype relate to the operating point of 3Kw and reveal the relevance of the experimental results to support the proposed formulation.The entries of the load current and voltage measured for the specified range of load powers in Table 2 closely compare with the simulated response and establish the voltage regulating capability of the control algorithm.

Conclusion

A FSM controller has been orchestrated to derive a regulated output voltage from the SEPIC interface through the range of operating loads. The control strategy has been allayed to offer an enhanced performance to accord a viable interconnecting arrangement between the solar energy source and the utility grid. The experimental readings obtained using the DSPIC based prototype have been found to validate the simulated response. The results acclaim the suitability of the proposed approach for use in critical applications and will go a long way in enhancing the scope of such converters.

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