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Hysteresis Controller for SEPIC Converter

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***Abstract*—A hysteresis based control of a SEPIC converter is introduced in this paper. The advantage of this method is that it does not need a PWM modulator. The Routh-Hurwitz stability criterion and generalized root loci are used to find the PI gain values.The SEPIC converter is controlled using hysteresis based control which is then implemented using MATLAB and the results are presented.**

***Index terms* –Hysteresis control, SEPIC converter.**

I.INTRODUCTION

SEPIC (Single Ended Primary Inductor Converter) converter is a fourth order non-inverting converter, which can either step up or step down depending on the duty ratio of the switch. The advantage of a SEPIC converter is its non-pulsating input current and can be used as an alternative to a boost converter, with a higher efficiency and a non-inverting output.

Traditional control of a SEPIC converter uses a Proportional Integral Derivative (PID) algorithm. This control technique is a linear control technique. But since the converters are non-linear and time variant, their efficiency can be improved when the control is also non-linear.

The Sliding Mode Control is a non-linear control technique which is used for Variable Structure Systems such as DC-DC converters. Sliding Mode Control with first order, second order and third order control have been implemented in DC-DC converters[1]. The order of Sliding Mode Control depends on the number of state variables controlled. Order reduction is a remarkable advantage in Sliding Mode Control. The Sliding Mode Control technique is combined with constant switching frequency technique [2] , PWM control [3] and soft computing techniques [5].

In this paper, the fourth order and second order Sliding Mode control of SEPIC converter have been performed and the results of simulation are shown. The Sliding Mode Control is combined with PI controller and the combination has also been simulated. The sliding coefficients are calculated using equivalent control method and PI gains are calculated using Routh-Hurwitz criterion.

This paper is organized as follows : Section II gives a brief overview of some of the control techniques used for SEPIC converters such as hysteresis control, Sliding Mode Control- fourth order and second order control and PI and Sliding Mode Control. Section III discusses the simulation results of SEPIC converter with different control techniques. The simulation circuits are also shown in this section. Section IV compares the simulation results. Section V concludes this paper.

II. CLOSED LOOP CONTROL OF SEPIC CONVERTER:

A.SEPIC converter with hysteresis control

SEPIC converter is a modified form of Cuk converter, with a non-inverting output. A hysteresis controller is used here to control the SEPIC converter during closed loop operation. The hysteresis controller uses a PI controller and a hysteresis block which controls the switch. The actual current value is compared with the output of the PI controller and the error signal is given to the hysteresis block. The output is limited within the hysteresis band using the switch.

The output of the hysteresis block is decided by the error input given to the hysteresis block. When the error is greater than the limit ς (a small value) given in the hysteresis, the pulse goes high. When the error signal is below the limit ς then the pulse is made low. The simulation block diagram and the results of SEPIC converter with hysteresis control are shown in section III.

B. Sliding Mode Control

The theoretical and mathematical concepts of Sliding Mode Control are explained in detail in [5], [6].Sliding-mode control extends the properties of hysteresis control to multi-variable environments. The Sliding Mode Control can be applied to any Variable Structure Systems (VSS). The DC-DC converters are said to be VSS, since they have different structures depending on the switching condition. Sliding Mode Control for generalized DC-DC converters is explained in [7], [8] The sub-topologies are derived based on the switching. This motion of the system Representative Point (RP) along a trajectory, on which the structure of the system changes and which is not part of any of the substructure trajectories, is called the sliding mode and the switching surface is called the sliding surface. When the sliding mode exists, the performance of the resultant system is independent of the sub-topologies and it depends only on the control law.

The sliding surface must ensure the following conditions:

i. Existence condition

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ii. Hitting condition and
iii. Stability condition.

In Existence condition, the system trajectories near the surface (in both the sub-topologies) are directed toward the sliding surface.

In Hitting condition, the sliding surface must be reached by all the system trajectories irrespective of their initial status of the system.

In the stability condition, the system under sliding mode should operate in the stable point.

The state-space average model of the converter is used in the mathematical expressions of the Sliding Mode Control. Consider a Single Input Single Output system which is controlled by a switch, the state space average model of the system is represented by,

$$\dot{x} = Ax + B\sigma + G \tag{1}$$

Where σ is the switch status, A,B,G are state matrices, x is the vector of state variable errors.

$$x = v - V^{*} \tag{2}$$

where v is the state variable vector, V* is the vector of their DC references.

The sliding surface can be a line, plane or any surface. So we can consider a hyper plane as a sliding surface which is expressed as,

$$\Psi = K^{T}x \tag{3}$$

where ψ is the sliding surface,
K^T is the vector of the sliding coefficients.

When the sliding coefficients are selected properly, the advantages of the Sliding Mode Control such as fast response, high control robustness, stability, order reduction, etc., can be achieved in any operating condition.

In mathematical terms, the existence condition is expressed as in [9] by,

$$\frac{\partial\psi}{\partial t} = K^{T}Ax + K^{T}G < 0, 0 < \psi < \epsilon \tag{4}$$

$$\frac{\partial\psi}{\partial t} = K^{T}Ax + K^{T}B + K^{T}G > 0, -\epsilon < \psi < 0 \tag{5}$$

Here the switch is kept on when ψ is negative and off when ψ is positive, where ϵ is a small positive quantity.

When the existence condition is satisfied, then the hitting condition can be achieved by the expression,

$$K^{T}A_{4} \leq 0 \tag{6}$$

Where A_4 is the 4-th column of matrix A. In order to maintain the sliding surface near zero, a hysteresis block is used in the control circuit. In practice, an additional hysteresis block is used to prevent the system from input over-current.

The existence condition and the hitting condition expressions have inequalities which shows the degree of freedom in choosing the sliding coefficients.

For an ideal sliding mode operation, the switching frequency is infinite. Practically it is not possible to attain infinite switching frequency. In order to make the system work in a finite switching frequency, the equivalent control method is utilized in the sliding mode operation of a converter.

The stability condition has to maintain the system RP in the sliding surface,this condition is given by the expression as in [9],

$$\psi = 0 \tag{7}$$

The equivalent control method replaces σ by σ_{eq} , so that the system equation becomes,

$$\dot{\psi} = K^{T}\left(Ax + B\sigma_{eq} + G\right) = 0 \tag{8}$$

From this equation, expression for σ_{eq} is derived,

$$\sigma_{eq} = -(K^{T}B)^{-1}.[K^{T}Ax + K^{T}G] \tag{9}$$

Substituting σ_{eq} in (1),

$$\dot{x} = [I - B(K^{T}B)^{-1}K^{T}].(Ax + G) \tag{10}$$

The system eigen values are calculated as a function of coefficients K^T. To find the solutions the eigen values should have negative real part and suitable damping factor. In practice, several solutions are found, those values ensuring the stability, robustness and good dynamic response are selected.

In fourth order control K^T=[K_1 K_2 K_3 K_4], where one of the coefficient is assumed as one. Only the ratio among the coefficient must be maintained not the values. The remaining values are calculated using the mathematical expression.

In second order control K^T=[K_1 0 0 K_4], here also one of the coefficient is assumed as one. Here two of the coefficients are zero and one of it is one making the calculation simple and easy.

Some of the disadvantages of Sliding Mode Control such as calculation of state references, sliding coefficients are reduced in second order control. Where only two of the state variables are sensed, a high pass filter is used in order to prevent high state variable error during transient condition.

C.SEPIC converter with Sliding Mode Control

Sliding Mode Control technique used for Cuk converter is explained in [9]. Based on the method used in [9], SEPIC converter is also controlled using SMC. The circuit diagram of SEPIC converter is shown in figure.1. The circuit shows the state variables and the direction of state currents.

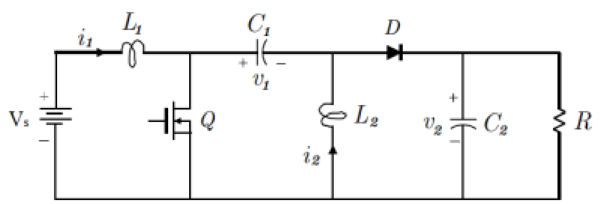

Fig.1 SEPIC converter

The state space equations of a SEPIC converter from [10],

$$L_1 \frac{di_1}{dt} = -(1-u)(v_1 + v_2) + V_s \quad (11)$$

$$L_2 \frac{di_2}{dt} = uv_1 - (1-u)v_2 \quad (12)$$

$$C_1 \frac{dv_1}{dt} = (1-u)i_1 - ui_2 \quad (13)$$

The parameters of SEPIC converter used in the simulation are given in the TABLE I.

TABLE I

SEPIC CONVERTER PARAMETERS

Parameter	Value
V_{in}	24V
V_{ref}	40V
L_1,L_2	110mH
C_1	600uF
C_2	5mF
R	10 Ohms

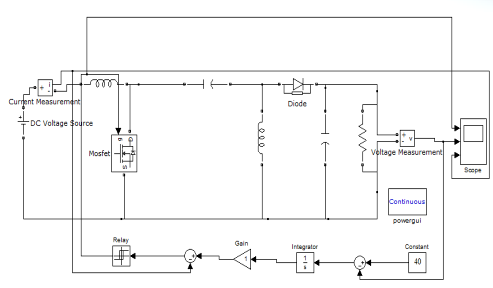

Fig.2 SEPIC converter with hysteresis control.

$$C_2 \frac{dv_2}{dt} = (1-u)(i_1 + i_2) - \frac{v_2}{R} \quad (14)$$

where i_1,i_2,v_1 and v_2 are state variables, V_s is the source variable and u is the control variable.

Fourth order SMC and second order SMC are implemented and the results are shown in section III. The sliding coefficients are calculated based on the equation. The fourth order SMC and second order SMC are compared. The complexity fourth order SMC is reduced in second order control. But second order control also has some drawbacks. The state reference values should be calculated, whenever the source or load or reference value is changed. The drawbacks are overcome by the combined action of PI and Sliding Mode Control.

III.SIMULATION RESULTS

A.SEPIC converter with hysteresis control.

SEPIC converter is simulated with hysteresis controller, the simulation circuit is shown in figure.2. SEPIC converter is simulated with hysteresis control, Sliding Mode Control- fourth order and second order control techniques, finally it is simulated using combined PI and Sliding Mode Control technique. This technique has some added advantages than the traditional PID controller.

The process of hysteresis controller is already explained in section I of this paper. The error is maintained within the hysteresis band given in the hysteresis block. The dynamic response of the controller is slower than Sliding Mode Controller. The simulation result of SEPIC converter with hysteresis control is shown in figure.3. The output shows that the dynamic response of the system is slow and needs to be improved.

B.SEPIC converter with Sliding Mode Control – fourth order control.

The Sliding Mode Control technique with fourth order control is implemented in SEPIC converter. The fourth order control defines that all the four state variables i_1, i_2, v_1, v_2 are controlled. All the state variables needs a reference value that must be calculated based on the output reference. This is one of the disadvantages of Sliding Mode Control. The sliding coefficients are also to be calculated. The simulation circuit diagram of SEPIC converter with fourth order Sliding Mode Control is shown in figure.4.

In Sliding Mode Control of SEPIC converter, the reference values for all the state variables are calculated and compared with the measured value of the same state variables. The error signals are given to corresponding gain. The gain values are the sliding coefficients. Except the

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output voltage all the remaining errors must be given to a high pass filter. The use of high pass filter prevents the error values becoming very high during transient condition. The output voltage error is given directly to the gain. The output from the all the gain blocks are added and the final signal is given to the hysteresis block. The added signal represents the sliding surface. The sliding surface has to be maintained in or near zero. The hysteresis control parameter should be very small so that the sliding surface is maintained in or near zero.

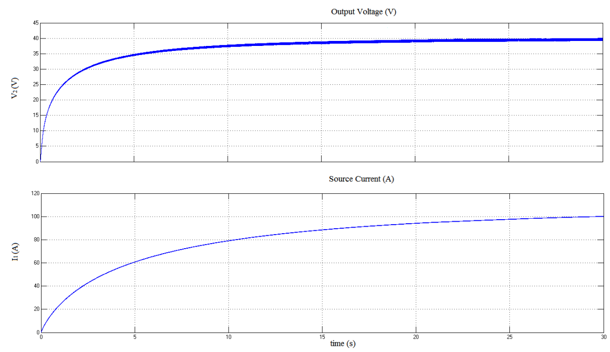

Fig.3 Simulation output of SEPIC converter with hysteresis control.

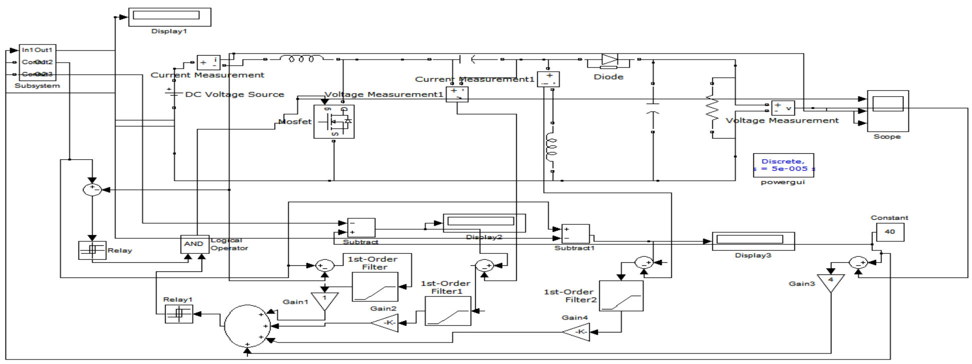

Fig.4 SEPIC converter with Sliding Mode Control-fourth order control.

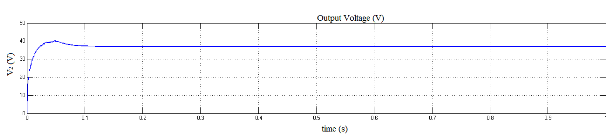

Fig.5 Simulation result of SEPIC converter with Sliding Mode Control-fourth order control.

The circuit also shows that the current is limited. The current measured is compared with the reference calculated current , the error is given to a hysteresis control which limits the current error. The output of this hysteresis control block is AND with the output of the hysteresis control block taken from the sliding surface. The simulation result of SEPIC converter with fourth order Sliding Mode Control is shown in figure.5. Calculation or deciding the sliding coefficients is one important task in Sliding Mode Control. Expressions for calculating the sliding coefficients are shown in section II.

C.SEPIC converter with Sliding Mode control-second order control.

SEPIC converter is simulated with second order Sliding Mode Control. The second order control limits only the output voltage and the input current. The complexity in calculating Sliding coefficients is reduced in second order control.

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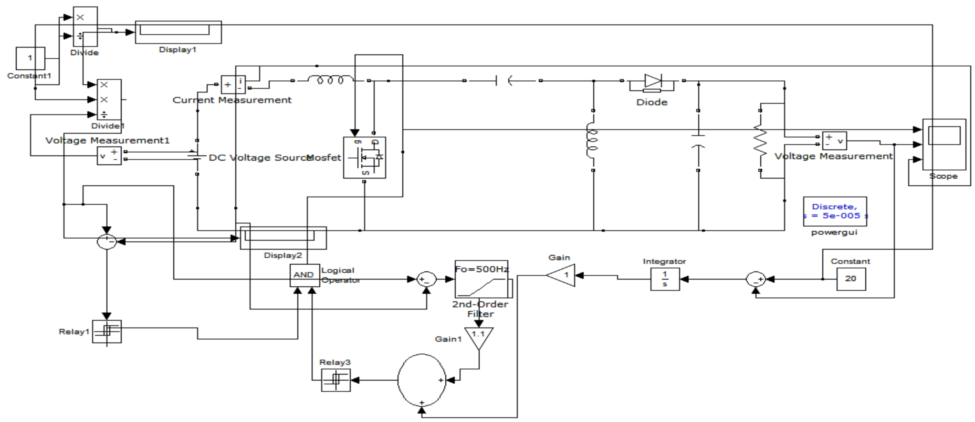

Fig.6 SEPIC converter with second order Sliding Mode Control.

The sliding coefficients and the reference values are the main parameters in Sliding Mode control. The simulation circuit of SEPIC converter with second order Sliding Mode Control is shown in figure.6. The concept of input power equal to output power is used in second order and fourth order control of Sliding Mode Control for calculating the reference current. The reference voltage is also taken into consideration. The simulation results of

SEPIC converter with second order Sliding Mode Control simulation output is shown in figure.7. The output shows that the current is also limited as done in the fourth order Sliding Mode control. In this control also high pass filter is used. The high pass filter is used only for the sliding surface current error. The output voltage error is directly given to the gain and then to a hysteresis control.

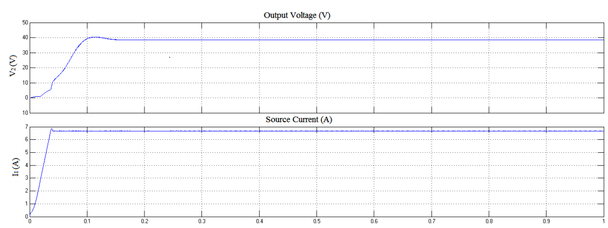

Fig.7 Simulation output of SEPIC converter with second order Sliding Mode Control.

IV.COMPARISON

The SEPIC converter with hysteresis control regulates the output voltage within limits but requires a high switching frequency and the settling time is also high. In fourth order Sliding Mode Control, the dynamic response is better than that of the hysteresis control. However, the fourth order Sliding Mode Control has many complexities in calculating state references and sliding coefficients. The sliding coefficient ratio needs to be maintained. In second order Sliding Mode Control, the dynamic response of the output is nearly as good as that of the fourth order control and the complexities associated with the fourth order control are reduced. Only two state variables are considered, so the calculation of sliding coefficient also becomes easy. In PI and Sliding Mode Control, the output reference is the only state reference. Even though the dynamic response of the output is slower than that of second order control, the control can be implemented without changing the state reference when there is any change in the source or load or in the reference value. If there is any perturbation in the source or load the current reference is calculated directly by the controller. The current reference is generated by the feed forward and PI controller even before there is any change in the output. The PI gain calculation is more straight-forward and not as tedious as the calculation of sliding coefficients.

V.CONCLUSION

The SEPIC converter is simulated with hysteresis control, fourth order Sliding Mode Control, second order Sliding Mode Control and combined PI and Sliding Mode Control. The results are shown and compared.

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