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Implementation of Sliding Mode Control in a Full Bridge (DC-DC) Converter

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Abstract

Converters are widely used in many fields specially Distributed Generation applications. Because of the non-linear and the uncertain characteristics of DC-DC converters, Sliding Mode Control (SMC), which is robust against uncertainties and disturbances, is implemented in a full-bridge converter in order to control the converter output by varying the duty cycle of the converter. The proposed method is explained and formulated using state-space average model of the full-bridge converter. Additionally, the effects of changing the design parameters of the introduced sliding mode controller in tracking performance and tracking are discussed. Moreover, the system behavior during load and source sudden changes is analyzed. High performance and tracking accuracy of the system under parameter variation are confirmed appropriately using simulations.

Keywords: Full-Bridge Converter, Sliding Mode Control, Nonlinear Control, DG.

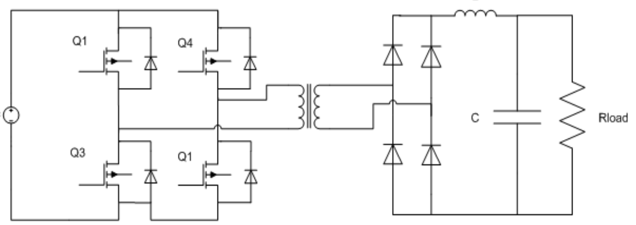
Introduction

Nowadays, environmental and energy issues appear as considerable concerns of the world (Ali Asghar Ghadimi & Ali Keyhani, 2007). Clean Power Generation (CPG) is at the center of the attention because of its important role in reaching a compromise between development and environment. One of the solutions to tackle the energy related problems such as greenhouse gas emission, energy demand rise and energy resources depletion is environmental-friendly distribution system. New technical achievements in power distributed generation systems have significantly developed during recent years (Kakigano, 2010; Sarhangzadeh, 2011; Seyed Ali Mohammad Javadian & Maryam Massaeli, 2011a,b,c; Ali Aref *et al*., 2012). Generation systems such as wind turbines, hydro turbines, photovoltaic arrays, biomass and fuel cells can be the best solution to satisfy the rising demand of electric power and environmental concerns (Marwali, 2004; Marwali & Keyhani, 2004). Advances in energy storage devices have greatly assisted the flourishing penetration of distributed generation (DG) into installation and operation of power generation plants (Fathi, 2011; Hassan Rastegar, 2011). Improvement in interaction with the grid is one of the main objectives of the power electronics (Ibarra, 2011).

Since most of the DG applications have a non-considerable dc output, a DC-DC power electronic converter is used in order to boost and regulate the DG output voltage. These type of power converters can perform several functions including voltage regulation under defined load variation, active power flow control, power quality improvement, and flexibility in power system control and energy management (Chung, 2011). Several types of converters like forward boost converter, Buck-Boost converter, push-pull boost converter and full-bridge converter can be used in order to regulate and boost the output of a DC source (Ali Asghar Ghadimi & Ali Keyhani, 2007). The main challenge in DC-DC converter design and operation is controlling the steady state and transient response of the output and also minimizing the cost of converter(Jafarian & Nazarzadeh, 2011).

To reach a desired regulation, several control methods and algorithms has been implemented in previous studies. PID controllers are proposed in some control applications such as improving the transient response during a load step change (Kurokawa, 2010a; Kurokawa, 2010b), using look up tables instead of multiplier in order to minimize energy consumption (Prodic & Maksimovic, 2002). These types of controllers rely on the exact model of system around operation point and cannot have proper response in large scale disturbances. Intelligent modern controllers such as fuzzy controller are alternatives controllers to get better performance of converters (Guesmi, 2008; Guo, 2011b). They are robust against such disturbances and uncertainties. In (Kexin, 2008), PID method and fuzzy logic theorem are combined via a Linear Quadratic Regulator (LQR) to have a better performance. Some other combinations of fuzzy logic and PID are presented in (Guo, 2011a; Guo, 2010). Besides Fuzzy and PID controllers, the most robust controllers are nonlinear controllers. These types of controllers are the best option because most of the electrical devices and specifically converters have many inherent uncertain characteristics and behavior due to their structure and elements Nonlinear controllers are widely used because they can reach control objectives in the presence of uncertainties in model and nonlinear state of converters (Jean-Jacques E.Slotine, 1991; K.Khalil, 2002). This basis is derived from the non-minimum phase nature of converters, variability in their structure and unpredictable nonlinear load changes which are emphatic reasons for the use of nonlinear control in these systems (Chan, 2007; Al-Dabbagh, 2010). Sliding mode control is one of the most popular and robust methods in converter studies especially in DG connected samples. In (da Silva, 2003;

Fig.1. The full-bridge converter



Shtessel, 2003; Navarro-López, 2009), investigations on Buck, Boost and Buck-Boost converters is carried out using SMCs in order to reach a desired voltage profile tracking during a load change, start-ups and transients. Furthermore, in (Pires & Silva, 2002; Mahdavi, 2005) the SMC is implemented using state space averaging models on an N-Paralleled boost converter and Cuk converter, respectively. In order to omit some problems of SMCs in experimental results, Quasi Sliding mode is presented in (Siew-Chong, 2005; Vidal-Idiarte, 2011). Full Bridge buck converter is studied in a part of the (Biel, 2004) in comparison with a cascaded connection boost converter for voltage, but without using any transformers which are an optional but important part of Full-Bridge converter. Moreover, in most of the mentioned works, the DG connection objective is not considered.

In this paper, a proposed SMC is explained and implemented in a full-bridge converter using state averaging model. The study investigates two aspects of the proposed sliding mode; firstly, the effects of the controller parameters on the output and tracking performance. Secondly, the responses of the converter to sudden load and source changes are analyzed. The simulation results are demonstrates the robustness and accuracy of the proposed method.

General performance of a full-bridge converter and average model derivation

Operational principles of a full-bridge DC-DC converter

The general schematic of a full-bridge converter circuit is shown in Fig.1. The sample full bridge converter comprises a full bridge power converter ($Q_1 to Q_4$), a very high turns-ratio transformer with ratio 1: n, a diode bridge rectifier and an output filter. The switches ($Q_1 to Q_4$) are located diagonally and turned on and off. The pulses are sent to the switches using a PWM pulse generator with the time duration of $D.T_S$. The PWM pulse generator has the value D as duty cycle input. After a complete cycle time passes and all the switches trigger once, the load current freewheels through the diode bridge for $T_s / 2 - D.T_s$. It should be mentioned that there must be a compromise between switching frequency and switching losses. High switching frequency results in magnetic components reduction, however it leads to switching losses (Ali Asghar Ghadimi, 2007).

Average model of full-bridge converter: The average model of a Full-Bridge DC-DC converter is derived in (Ali Asghar Ghadimi, 2007) and its state space model is shown in (1)-(5).

In this circuit and model there are two state variables; inductor current (x_1) and capacitor voltage (x_2).

$$\dot{X} = AX + BV_d \quad (1)$$

$$V_O = CX \quad (2)$$

$$A = \begin{bmatrix} -\dfrac{2R_{th}d + r_D(1-2d)}{L} & -\dfrac{1}{L} \\ \dfrac{1}{C} & -\dfrac{1}{RC} \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} \dfrac{2dn}{L} \\ 0 \end{bmatrix} \quad (4)$$

$$C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad (5)$$

The average model is beneficial for simulation because of not using multiple switches and other electrical elements. Therefore, the time of simulation decreases. Also the state space model is suitable for controller design and stability analysis.

Design of sliding mode control for a full-bridge converter

Principle of SMCs

Sliding mode control is a robust control technique in order to control any kind of systems especially nonlinear systems with model imprecisions and uncertainties. Controlling a 1st order system is much easier than controlling the general nst system. To achieve this goal, first of all a first order system which is called sliding surface should be proposed in order to provide a sliding condition to make the surface. In this controller in the first stage a first order system which is called sliding surface should be determined to provide a sliding condition to make the surface an invariant set of the system stability. In the second stage, a control is designed to reach the sliding surface.

Consider the following single input dynamics.

$$x^{(n)} = f(x) + b(x)u(t) \quad (6)$$

$f(x)$ and $b(x)$ both are not exactly known but the former is upper bounded by a known continuous function of x named F where $\left| f - \hat{f} \right| \le F$ and the latter sign is known and it is also upper bounded by a continuous function of x. The objective is determination of u

In order to force x track x_d in the presence of imprecision on $f(x)$ and $b(x)$. The tracking error vector is defined by the following equation;

$$\tilde{x} = x - x_d = \begin{bmatrix} \tilde{x} & \dot{\tilde{x}} & . & . & . & \tilde{x}^{(n-1)} \end{bmatrix} \quad (7)$$

$$s(x;t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} \quad (8)$$

Where $\lambda > 0$ and $n > 0$ are design parameter and system order respectively.

If the initial condition of x and x_d are equal to zero then the problem of tracking $x \equiv x_d$ is exactly equivalent to remaining on the surface $s(x;t)$ for all $t > 0$. In the simplest words;

$\tilde{x} = x - x_d = 0 \Leftrightarrow s(x;t) = 0$ (9)

Where x_d is the desired output value.

It is necessary to mention that the above situation is not always satisfied.

Therefore, it is possible to keep s at zero with a proper choice of $u(t)$ at (1).

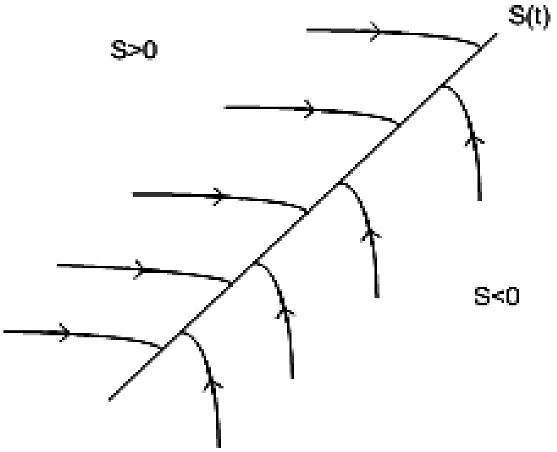
A control law is introduced in order to keep the s at zero.

$\frac{1}{2}\frac{d}{dt}s^2 \le -\eta|s|$ (10)

where $\eta > 0$ is a design parameter.

Equation (10) shows that the squared distance to the surface which is measured by s^2, decreases along all system trajectories. Therefore, all the trajectories move towards $s(t)$ obligatory. Satisfaction of (10) or sliding condition leads to set the sliding surface invariant. This means that the sliding condition is guaranteed for nonzero initial condition. Hence, remaining on the surface is assured (Fig.2).

Fig.2. The sliding Condition



Moreover, (10) guarantees that if $x \ne x_d$ i.e. if the system starts with any initial conditions then the trajectory reaches the surface in a finite time. This time is determined with (11).

$t_{reach} = \left|\frac{S(t=0)}{\eta}\right|$ (11)

There are some other details of SMCs, which are discussed afterward.

Implementation of sliding mode control in Full-Bridge Converter

State-space equations of the full-bridge converter can be obtained from (1) - (5) as

$\dot{x}_1 = \frac{-R_{th}2d - r_d(1-2d)}{L}x_1 - \frac{1}{L}x_2 + \frac{2dn}{L}V_d$ (12)

$\dot{x}_2 = \frac{1}{c}x_1 - \frac{1}{RC}x_2$ (13)

$V_O = x_2$ (14)

Now, we change (12) and (13) into the form of (6)

$\dot{x}_1 = \frac{-r_d}{L}x_1 - \frac{1}{L}x_2 + \left(\frac{2(r_d - R_{th})}{L}x_1 + \frac{2n}{L}V_d\right)d$ (15)

$\dot{x}_2 = \frac{1}{c}x_1 - \frac{1}{RC}x_2$ (16)

d is the controlling parameter of the system is the same as u in (6). By comparing (15) with (6), the following matrix is obtained but it is necessary to difference between f and $\hat{f}$. Because of some uncertainties in the full-bridge converter parameters, an estimation of f which is called $\hat{f}$ is required. As it is mentioned previously, $\hat{f}$ should be upper-bounded. Since the controlling function is appeared only in the first equation, the control of the variable x_1 is achievable. It is highly probable that entire tracking and controlling over x_1 leads to the stability of x_2. Hence

$\hat{f}_1(x) = \frac{-R_d}{L}x_1 - \frac{1}{L}x_2$ (17)

Also, all of the above explanations for f and $\hat{f}$ are applied for b and $\hat{b}$.

$\hat{b}_1(x) = \left(2\left(\frac{r_d - R_{th}}{L}\right)x_1 + \frac{2n}{L}V_d\right)$ (18)

Considering $n = 2$ in (8), the sliding surface becomes

$s = \dot{\tilde{x}} + \lambda\tilde{x}$ (19)

The general form of (12) in comparison with (6) can be written as (20)

$\dot{x}_1 = f(x) + b(x)u(t)$ (20)

Where $f(x)$ and $b(x)$ can be the function of x_1 and x_2.

By replacing (20) in (19) we have

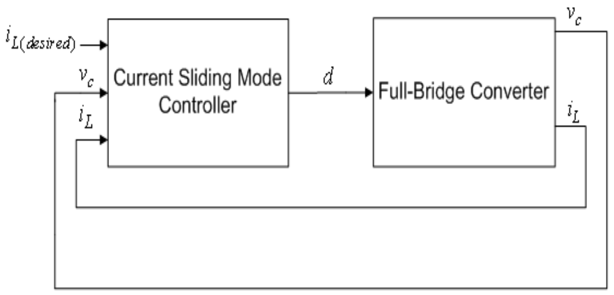
$s = f + bu - \dot{x}_d + \lambda\tilde{x}$ (21)

Now the effort is on the finding of the appropriate u in order to make $s = 0$.

by taking the estimations on f and b into account, the best u is found to satisfy $s = 0$

Firstly by considering $b = 1$, the following equation is derived:

Fig.3. General Scheme of the Proposed SMC



$\hat{u} = -\hat{f} + \dot{x}_d - \lambda\tilde{x}$ (22)

The above conditions in (21) and (22) are formulated with the assumption of $s = 0$, but there are some uncertainties in the parameters and the problem is out of the s plane. Therefore, u should be defined as

$$u = \hat{u} - k\,\mathrm{sgn}(s) \qquad (23)$$

Where

$$\mathrm{sgn}(s) = \begin{cases} 1 \; if \; s > 0 \\ -1 if \; s < 0 \\ 0 \; if \; s = 0 \end{cases}$$

Secondly, u is derived from (24) while $b \neq 1$

$u = \hat{b}^{-1}\left(\hat{u} - k\,\mathrm{sgn}(s)\right)$ (24)

Combining (22) and (24) results in

$u = \hat{b}^{-1}\left(-\hat{f} + \dot{x}_d - \lambda\tilde{x} - k\,\mathrm{sgn}(s)\right)$ (25)

By putting (25) in (21) and after some simplifications, the sliding surface could be achieved as

$$s = f - b\hat{b}^{-1}\hat{f} + b\hat{b}^{-1}\dot{x}_d - b\hat{b}^{-1}\lambda\tilde{x} - b\hat{b}^{-1}k\,\mathrm{sgn}(s) - \dot{x}_d + \lambda\tilde{x}$$

(26)

In order to calculate k, $s = 0$ must be solved, hence

$b\hat{b}^{-1}k\,\mathrm{sgn}(s) = (f - b\hat{b}^{-1}\hat{f}) + (1 - \hat{b}b^{-1})(-\dot{x}_d + \lambda\tilde{x})$ (27)

Where $\hat{b} = (b_{\min} b_{\max})^{0.5}$

After some simplifications with regard to $f = \hat{f} + (f - \hat{f})$ k is represented as

$k \geq \beta(F + \eta) + (\beta - 1)\left|\hat{u}\right|$ (28)

Where

$$\beta = \left(\frac{b_{\max}}{b_{\min}}\right)^{0.5}$$

and

$$0 < b_{\min} \leq b \leq b_{\max}$$

After calculation of k, x is capable of tracking x_d and it can be controlled.

Thus in orders to design a SMC two steps are required. First, reaching mode and second sliding mode and remaining on the surface. The two mentioned steps are explained in the above equations.

There are different parameters in a SMC design such as F, λ and η. F is assumed radius of the error between the real f and $\hat{f}$. As it was mentioned earlier, f is uncertain and this uncertainties are rooted from the converter elements. Therefore, in order to determine an appropriate radius of estimation error, in this case, the value of F is assumed constant.

λ and η are both design parameters. λ is used as a coefficient of the non-derivative term of the sliding surface. It represents as a weight coefficient for non-derivative term and also determines the resolution of tracking the desired specific point in comparison with the speed of reaching to that point. Tracking performance can be improved significantly at the price of chattering by increasing λ. η is a positive constant design parameter and defines the sliding condition. It also implies that some of the system uncertainties and disturbances can be tolerated while still keeping the surface invariant set. η also can be influential on system dynamic specially in the system speed and changing in the proportion of chattering.

The general scheme of the SMC is illustrated in Fig.3.

Simulation

Table 1. Specification of full-bridge converter

Description	Parameter	Nominal Value
Input Voltage	V_d	50 V
Inductance	L	7 mH
Capacitance	C	330 µH
Diodes Resistance	R_d	1 mΩ
Switches On-Resistance	R_T	5 mΩ
Transformer Ratio	N	100
Switching Frequency	f_s	2000 Hz
Load Resistance	R_L	12.5 Ω
Equivalent Thevenin Resistance	R_{th}	100.002 Ω

The proposed control approach is verified through simulations. Simulations are obtained using MATLAB/SIMULINK. The specification of the 5 kW sample Full-Bridge converter is given in Table 1.

These parameters are chosen in order to have a 2% ripple in inductor current and a 1% ripple in output voltage.

Validation of the proposed method is studied over variety of conditions. But, the influence of the SMC parameters such as F, λ and η on the resolution and quality of the tracking is discussed beforehand.

Analysis of the SMC parameters on the tracking performance of the inductor current

To have a better understanding of SMC parameters, in this part the effect of some of the key-parameters of SMCs on the tracking performance is discussed. It should be mentioned that in most of the DG applications, the output voltage is settled using a battery or ultra-capacitor (Fathi, 2011). Hence, tracking the output current

Fig.4. Simulated wave forms of Inductor Current for F=0.1, F=10, F=100, F=1000

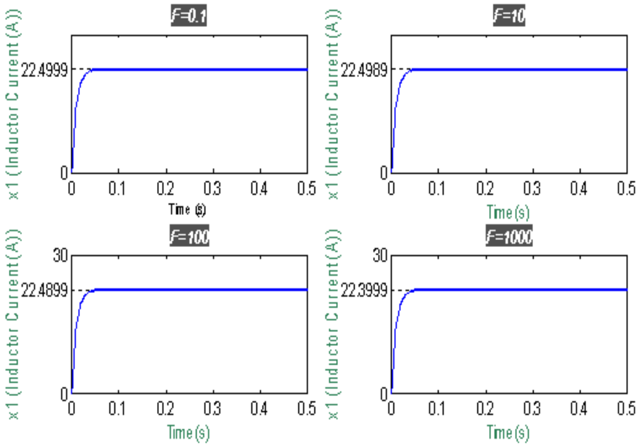


Fig.5. Simulated Waveforms of Inductor Current for $\lambda = 0.1, \lambda = 0.5, \lambda = 1, \lambda = 10, \lambda = 100$

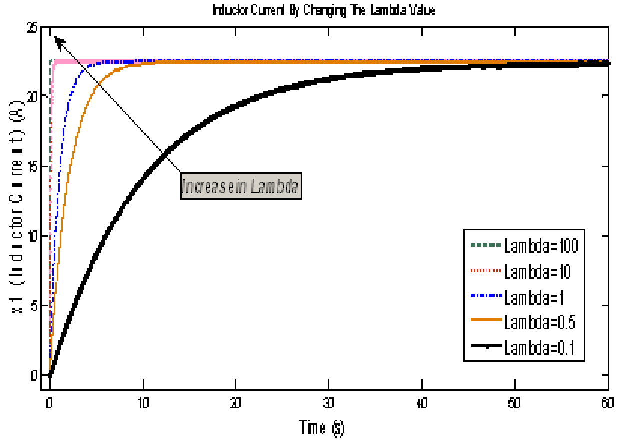


Fig.6.Tracking accuracy for $\lambda = 0.5, \lambda = 1, \lambda = 10, \lambda = 100$

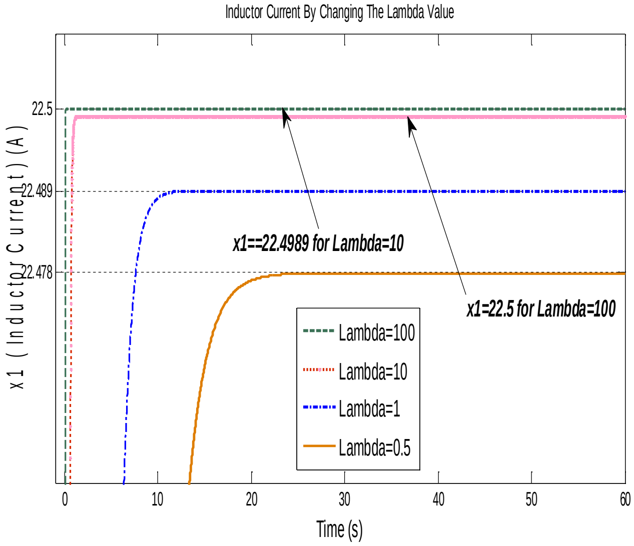


Fig.7. Simulated waveforms for inductor current for $\eta = 0.1, \eta = 1, \eta = 10, \eta = 100, \eta = 1000$

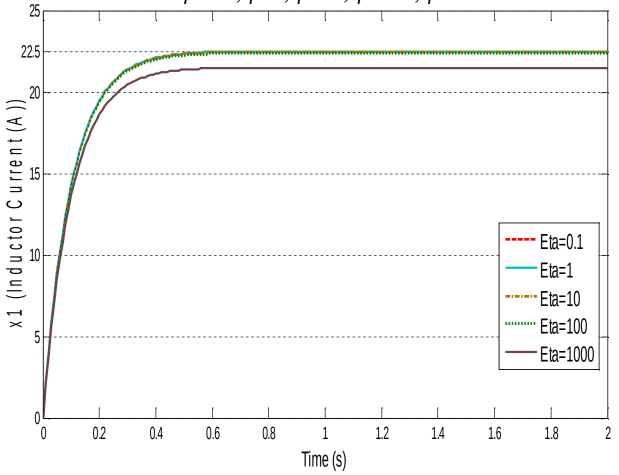


Fig 8. Tracking error and settling time for $\eta = 0.1, \eta = 1, \eta = 10, \eta = 100$

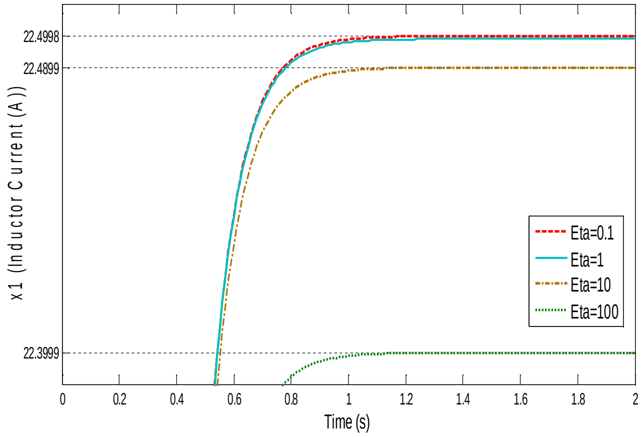


Fig.9. The simulated waveforms of inductor current and capacitor voltage during a Step change in load from 12.5Ω to 25Ω

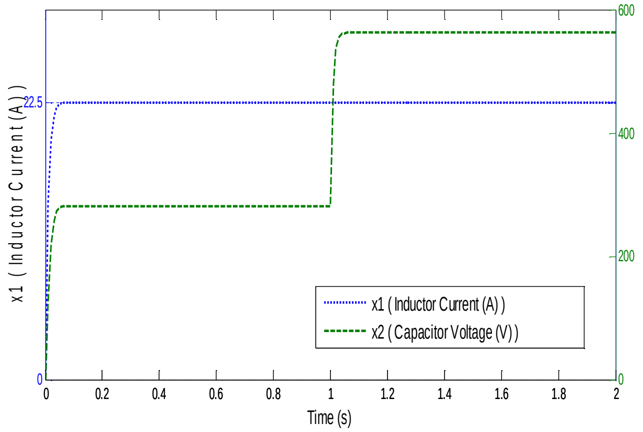
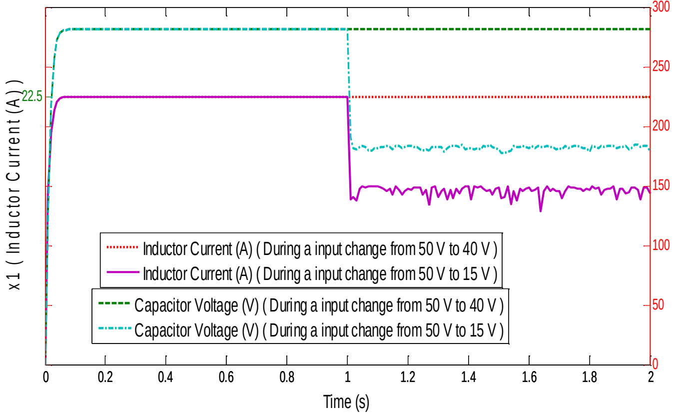


Fig.10. Simulated waveforms of inductor current and capacitor voltage during step changes in the input voltage



which is dependent to load has the main priority. Moreover, since the proposed control method make the total system stable, voltage output changes in that the current remains at its desired value.

Study the effect of "F": As it was explained earlier, F is the radius of the absolute error between f and $\hat{f}$ .Allocating a larger number to F may decrease the resolution of tracking. For example, $F = 10$ expresses that the absolute deviation of the available values of the converter elements from original values are less than 10. It is important to mention that this radius is applied to all of the estimated parameters.

The default values of other SMC parameters are as follows:

$$\begin{cases} \eta = 1 \\ \lambda = 10 \end{cases}$$

The desired value for x_1 to track is 22.5 (A). Also, the simulation is run in a 2 seconds period.

As it can be seen in above waveforms, the final value of i_L is much identical to the desired value for lower F .For $F = 0.1$ tracking performance is excellent and relative tracking error is around 0.005% but while $F = 1000$, this value changes to 4.45%. Hence, the lower radius of estimated error i.e. F results in a better tracking precision Fig.4.

Study the effect of "λ": λ is design parameter and defines the weight coefficient of the non-derivative term of (19). The simulation is performed for different values of λ and the following values for other parameters of the SMC.

$$\begin{cases} F = 0.1 \\ \eta = 1 \end{cases}$$

Also, in this study, the desired value of current is equal to 22.5 (A).

It is obvious that by increasing the value of λ, the slope of the current rises considerably and the system reaches the steady-state condition in a shorter time. As the system is entirely stable, some undesirable occurrences such as overshoot and undershoot is not observed. In spite of the fact that reaching the steady-state current is quite satisfactory, but high slope damage elements of the circuit Fig.5.

Besides slope and time, escalating tracking accuracy is another consequence of increasing λ .

As it is shown in Fig.6, tracking accuracy faces a kind of saturation while the value of λ increases. Tracking error for $\lambda = 10$ equals 0.0049%; therefore, the tracking performance is undeniably acceptable. Despite tracking accuracy, the system cost for a high value of λ will be increased. Hence, there should be a compromise between total system design and tracking accuracy.

Study the Effect of "η": In (11), η and initial condition of s at $(t = 0)$ determines the reaching time. Moreover, η is a coefficient in (10) or sliding condition which affects the velocity of reaching the trajectory to the sliding surface.

To study the effect of η, the default values for other parameters are

$$\begin{cases} F = 0.1 \\ \lambda = 10 \end{cases}$$

It is depicted in Fig.7 that η does not have a significant effect on the slope of the inductor current. The relative tracking error is around 4% for $\eta = 1000$ and around 0.44% for $\eta = 100$. This percentage is around zero for other values. Therefore, for a wide range of η , the tracking error is negligible.

The settling time for each η differs from another in milliseconds. By drawing the system trajectory it can be observed surely that higher value for η results in lower reaching time for system trajectory. The contrast between a system trajectory and a system output should be considered Fig.8.

Full-bridge converter performance using SMC

This study is performed for two cases; firstly a load step change and secondly an input voltage step change.

Step change in load: To study the robustness of this method, a simulation is run for a step change in load. The load resistance is changed from 12.5Ω to 25Ω at $t = 1\,(s)$. The total time for estimation is 2 seconds. All of the system parameters are from Table (I). The SMC parameters in this simulation are as follows:

$$\begin{cases} F = 0.1 \\ \lambda = 100 \\ \eta = 1 \end{cases}$$

To complete the analysis over the step change in load condition, another state variable i.e. the capacitance voltage or x_2 and the duty cycle are monitored simultaneously.

Fig.9 illustrates that by a sudden change in the load resistance, the capacitor voltage surges in order to keep the inductor current at the desired value. Sustaining the inductor current at the desired value was predictable because the entire system is stable and x_2 attempts to keep the whole system stable.

During a load step change, the system performance is absolutely perfect because of the law order of the system and robustness of the control method. It can be seen that the current value does not change at the instance of the load change and remains at 22 (A).

Step change in input voltage: In this case, a sudden change in input voltage occurs at t=1. Similar to the previous study, the simulation time is 2 seconds and the desired current value i.e. the desired current to track is 22.5 (A). All of the system parameters are the same as Table (I) and the SMC parameters are the same as previous study i.e. step change in load.

The first attempt is to decrease the value of the input voltage or V_d from 50 (V) to 40 (V). The system is supposed to maintain the current at its desired value with the lowest changes in amplitude and shape. Also, the system has to prevent any chattering and fluctuation.

Fig.10 reveals that the system is able to support the desired current for a 10 volts drop in the input source. But, as the decrease value exceeds 27 volts, the system faces chattering. Besides chattering, the system is not able to provide track the specified desired current. It is important to mention that the system elements capability for producing a desired current is limited. It means that the input power of the source is not enough to produce the desired value.

All in all, it is clear that the control system works perfectly from both aspects of tracking accuracy and responding to transients and sudden changes in load and input source voltage.

Conclusion

A SMC method is proposed and implemented in order to control the converter outputs by setting d and changing it. The analysis over two aspects of SMC is presented in this paper. The effects of the SMC design parameters on the tracking performance & accuracy and the behavior of the converter while a change in load or input source has been observed. The simulation results show the robustness and accuracy of the proposed method in both of the above mentioned aspects.

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