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NON-CHAOTIC DC-DC CONVERTER FOR SOLAR/WIND ENERGY APPLICATIONS BY VARIABLE STRUCTURE CONTROL

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ABSTRACT

Solar and wind promises to be a clean supply of renewable energy. The variation in the energy level of these sources due to various environmental factors can put together the entire system into chaos. This necessitates robust DC-DC converters that can manage the nonlinear input as well as load discrepancy while staying in the desired operating range. This paper proposes a robust variable structure controller that ensures the stability of the converter over a wide operating range. This makes the converter suitable for energy sources with nonlinear voltage-current characteristics.

INTRODUCTION

Renewable energy is the way forward for the energy security of the world. The growing wind and solar power demand has spurred more number of installations around the world. However, wind and solar power plants generate electricity when the wind and sun are available. Many electricity system operators see this variability as a threat to system stability and reliability. The fundamental solution to the variability challenge is physical storage of electricity and use of that stored electricity to smooth the output of variable electricity sources. Such physical storage technologies require DC-DC converters that are nonlinear and time-variant systems. PV energy produced by panels and PV systems suffer from a lack of optimization and the divergence after sudden variations of the illumination and the load. To obtain a stable voltage from an input supply (PV cells) that is higher and lower than the output, a high efficiency and minimum ripple DC-DC converter is required (Geoffrey *et al.,* 2004). Extra electricity may be stored, usually in storage batteries, thereby extending the operating time of the system. The (typical 12V) storage batteries are ordinary used in the home solar conversion systems to satisfy its operation and maximize power tracking purpose (Arulmurugan and Suthanthira Vanitha 2012).

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With the increase in the capacity of offshore wind farms and the distance between the offshore wind farm and the land, the DC transmission, with the advantages such as reactive power and harmonics and so on, becomes attractive under the growing trends of the offshore wind farm development (Vladimir Lazarov *et al.,* 2009). The use of DC grid for the interconnection of the wind turbines in the wind farm may be an interesting and cost-effective solution. DC-DC converter plays a vital role in this scenario by adapting the output voltage of the wind turbine to the transmission level voltage (Max 2009). The stability is an important aspect in the design of DC-DC converters. Ideally the circuit is in steady state, but actually the circuit is affected by line and load variations (disturbances), as well as variation of the circuit component (Bernardo *et al.,* 1998). These parameters have a severe effect on the behavior of DC-DC converters and may cause instability. Though several control strategies are in vogue still there is the prevalence of irregular noise in such closed loop systems (Biswarup Basak and Sukanya Pauri 2010). It is identified to be chaos which may result due to the nonlinearity of the converter. The aperiodic behaviour of the state variables opens up the way for several nonlinear phenomena such as bifurcations, quasi-periodicity and chaos (Bozhang *et al.,* 2007). The analysis of the stages leading to chaotic behavior is necessary to predict the instant at which the system becomes oscillatory, so that effective anti-chaos strategies can be innovated to control chaos and thereby the functionality, reliability and performance of the system be improved (Cheung *et al.,* 2001).

A. Problem Formulation

The analysis of the stages leading to chaotic behaviour is necessary to predict the instant at which the system becomes oscillatory, so that effective anti-chaos strategies can be innovated to control chaos and thereby the functionality, reliability and performance of the system be improved. The control of chaos targets at better managing the dynamics of a nonlinear system on a wider scale, with a hope that more benefits may thus be derived from the special features of chaos. The mission is to foresee the adverse effect of chaotic behaviour on the performance of the buck and boost converters with a view to develop a strategy in order to minimise such adverse effects and ensure a stable operation over a wide range through VSC algorithm.

Modeling of buck and boost converters

The buck converter (Fig. 1) and the boost converter (Fig. 2) is powered from a DC source and uses a controlled IGBT switch to elicit unidirectional power flow from input to output. The circuit is assumed to be operating in the steady state continuous conduction mode (CCM).

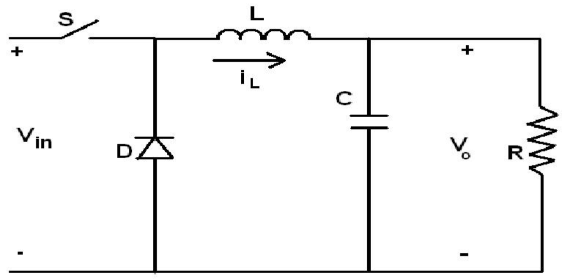

Fig.1. Buck converter

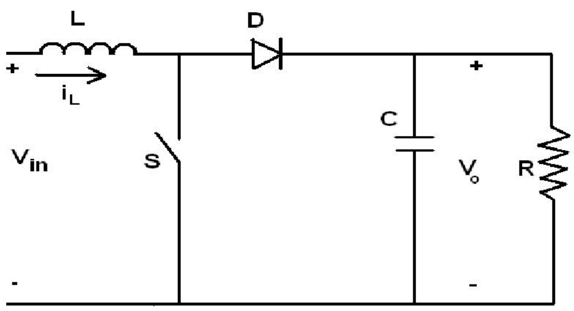

Fig.2 Boost converter

The matrix representation of the state space equations for buck converter is derived as:

When S is ON:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \quad (1)$$

When S is OFF:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \quad (2)$$

The matrix representation of the state space equations for boost converter is derived as:

When S is ON:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \quad (3)$$

When S is OFF:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \quad (4)$$

Design of control algorithm

The precise goal is to operate the DC-DC converter with regulated output voltage and with the specified current limit to meet the specifications of the IGBT. However it is seen when the specified inductor current is varies to a wide range, the system deviate from the desired periodic trajectory and generate multiple periodic orbits and eventually reach the chaotic state. The proposed variable structure control technique protects the converter within the desired operating trajectory which is presented as a switching surface function. The converter is forced to slide across this switching surface by the construction of a suitable switching control law.

A. Control Law for buck converter

The switching function proposed for this control scheme is given by:

$$\sigma(X) = G \cdot X \pm K \quad (5)$$

Where σ is switching function, G is gain vector, X is state vector and K is constant

The sliding manner exists if all the state trajectories are directed towards the surface. The mathematical form for such a condition is given by:

$$\sigma \dot{\sigma} < 0 \quad (6)$$

In order to obtain a continuous system, the above discontinuity may be replaced by a smooth continuous control law, which is given by:

$$\sigma(X) = \dot{\sigma}(X) = 0 \quad (7)$$

The condition for the existence of the sliding line should be such that whatever the initial conditions, the system trajectories must reach the sliding line, and is given as:

$$\begin{aligned}[X+] &\in \sigma(X) < 0\\ [X-] &\in \sigma(X) > 0\end{aligned} \tag{8}$$

Where (X+) and (X-) are the steady state responses corresponding to the inputs m+ and m- respectively. Using the function given in equation (5), the switching function for buck converter is chosen to be:

$$\sigma = C_1 . e_1 \tag{9}$$

Where C_1 is constant gain, e_1 is error in the output voltage and $e_1 = V_{ref} - V_o$. A variable (u) is defined that depends on the state of the switch(s), such that:

$$u = \begin{cases} 1 & when \quad S \quad is \quad ON \\ 0 & when \quad S \quad is \quad OFF \end{cases} \tag{10}$$

Thus the overall state space model is given by:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{u}{L} \\ 0 \end{bmatrix} V_{in} \tag{11}$$

and the control law is given by

$$u = \begin{cases} 1; & \sigma < 0 \\ 0; & \sigma > 0 \end{cases} \tag{12}$$

The condition for the existence of the control law to occur is given by:

$$C_1 < \frac{1}{RC} \tag{13}$$

The sliding condition exists and the system moves along the designed trajectory as long as the above condition is satisfied.

A. Control Law for boost converter

Using the function given in equation (5), the switching function for boost converter is chosen to be:

$$\sigma = K_1 . e_1 \tag{14}$$

where K_1 is constant gain, e_1 is error in the output voltage and $e_1 = Vo_{ref}$ — vo. A variable (u) is defined that depends on the state of the switch(s), such that:

$$u = \begin{cases} 1 & when \quad S \quad is \quad ON \\ 0 & when \quad S \quad is \quad OFF \end{cases} \tag{15}$$

Thus the overall state space model is given by:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-u)}{L} \\ \frac{-(1-u)}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{16}$$

and the control law is expressed as

$$u = \begin{cases} 1; & \sigma < 0 \\ 0; & \sigma > 0 \end{cases} \tag{17}$$

The condition for the existence of the control law to occur is related by:

$$K_1 < \frac{RC}{L}\frac{V_{in}}{V_{ref}} \tag{18}$$

The sliding condition exists and the system moves along the designed trajectory as long as the above condition is satisfied.
Thus the overall state space model is given by:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{u}{L} \\ 0 \end{bmatrix} V_{in} \tag{11}$$

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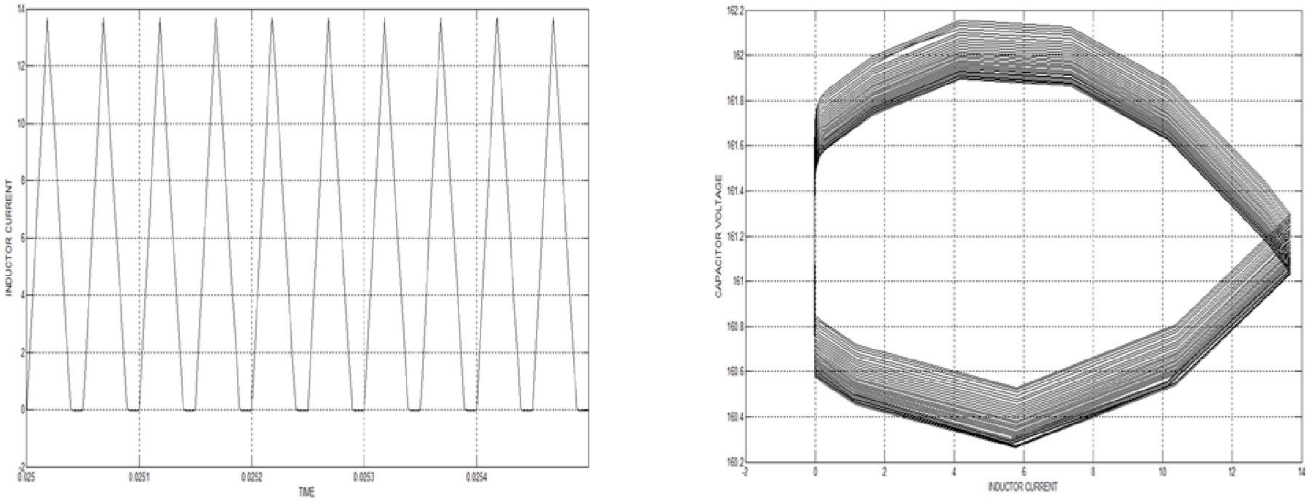


Fig. 3 Inductor current and Phase portrait in open loop at tolerance ± 6

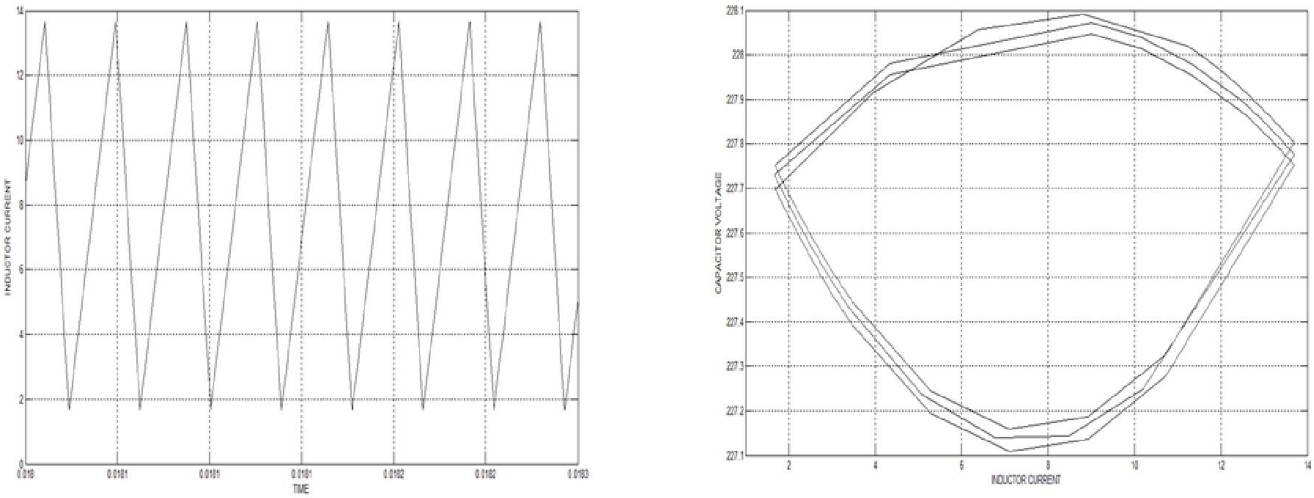


Fig. 4 Inductor current and Phase portrait in VSC at tolerance ± 6

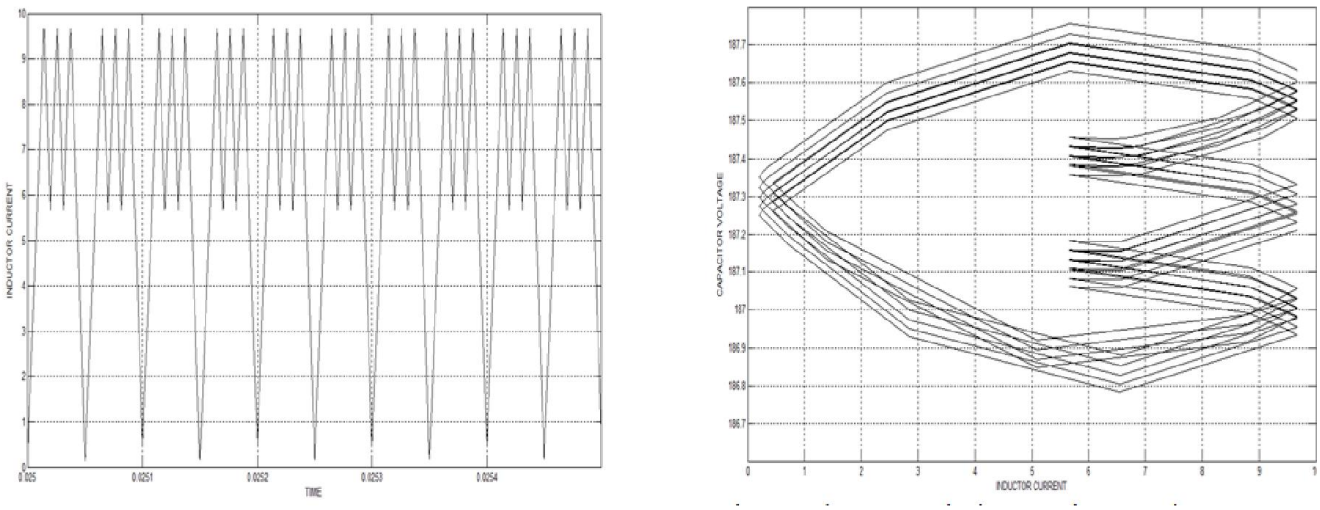
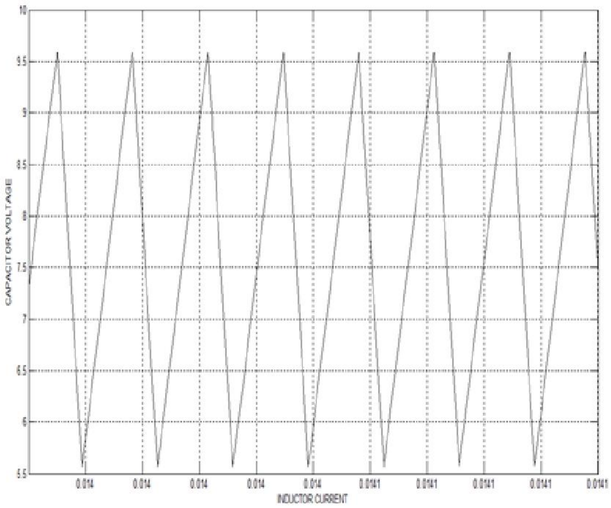


Fig. 5. Inductor current and Phase portrait in open loop at tolerance ± 2



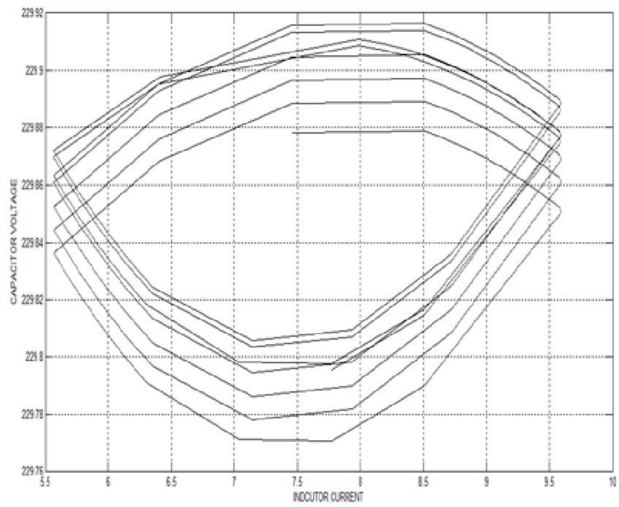


Fig. 6. Inductor current and Phase portrait in VSC at tolerance ± 2

$$u = \begin{cases} 1 & when \quad S \quad is \quad ON \\ 0 & when \quad S \quad is \quad OFF \end{cases} \tag{15}$$

Thus the overall state space model is given by:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_o \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-u)}{L} \\ \frac{-(1-u)}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{16}$$

and the control law is expressed as

$$u = \begin{cases} 1; & \sigma < 0 \\ 0; & \sigma > 0 \end{cases} \tag{17}$$

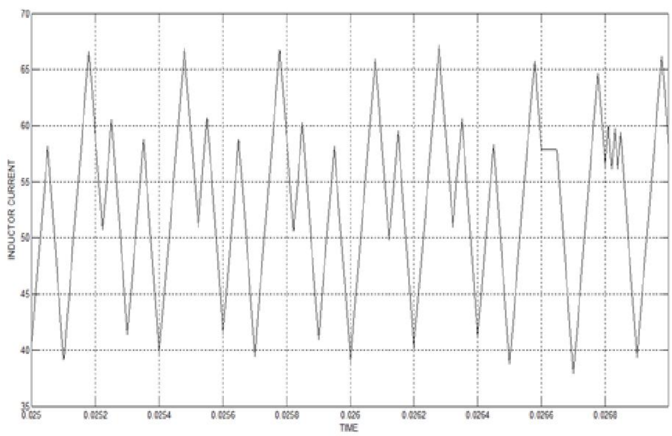
The condition for the existence of the control law to occur is related by:

$$K_1 < \frac{RC}{L}\frac{V_{in}}{V_{ref}} \tag{18}$$

The sliding condition exists and the system moves along the designed trajectory as long as the above condition is satisfied.

A. Boost converter

The performance of the proposed schematic is evaluated through Matlab based simulation. The boost converter parameters are chosen as L = 1mH, C = $50\mu F$, R = 30Ω, Fs = 10 KHz. A rectified DC of 350V is applied to the boost converter and the duty cycle calculated with a view to obtain 700V at the output. The boost converter is characterised such that the ripples in the inductor current is reflected inversely in the output voltage. It is evident that equal charging and discharging of the inductor with a constant average value can minimise its ripple content which in turn enhances the quality of output voltage. Thus the current limit control assuages the upper limit and lower limit of inductor current to vary by



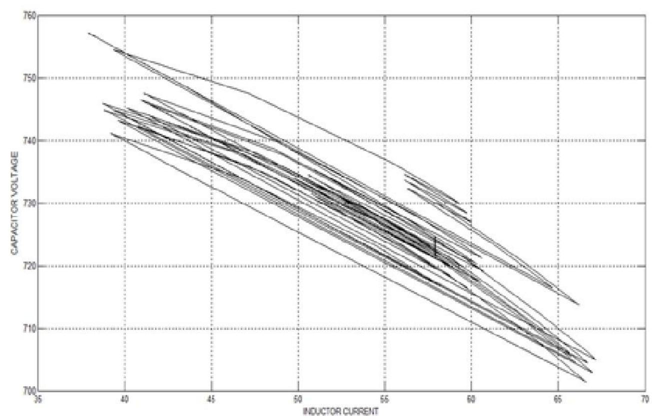


Fig. 7. Inductor current and Phase portrait in open loop at tolerance ± 10

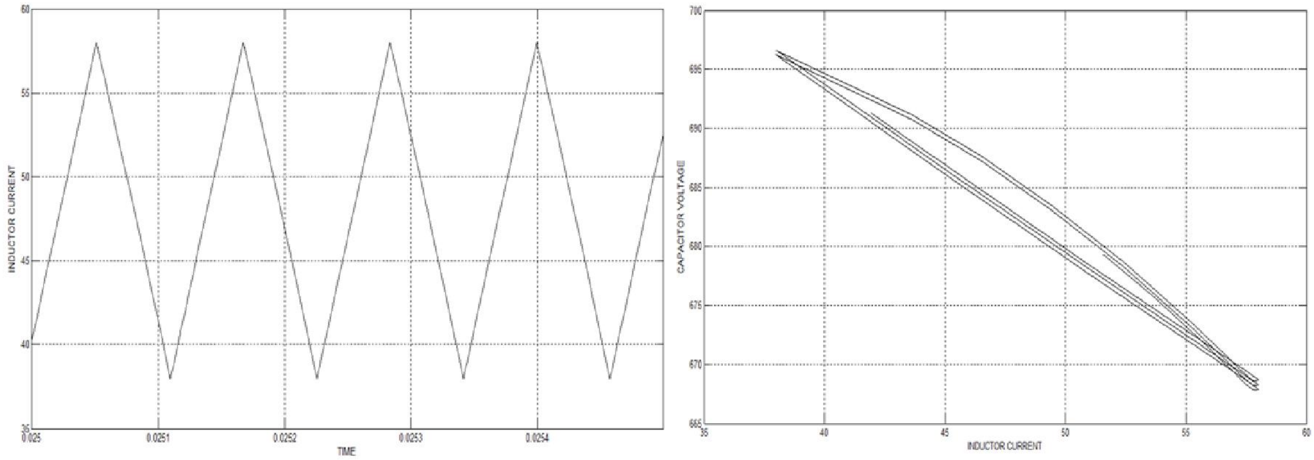


Fig. 8. Inductor current and Phase portrait in VSC at tolerance ± 10

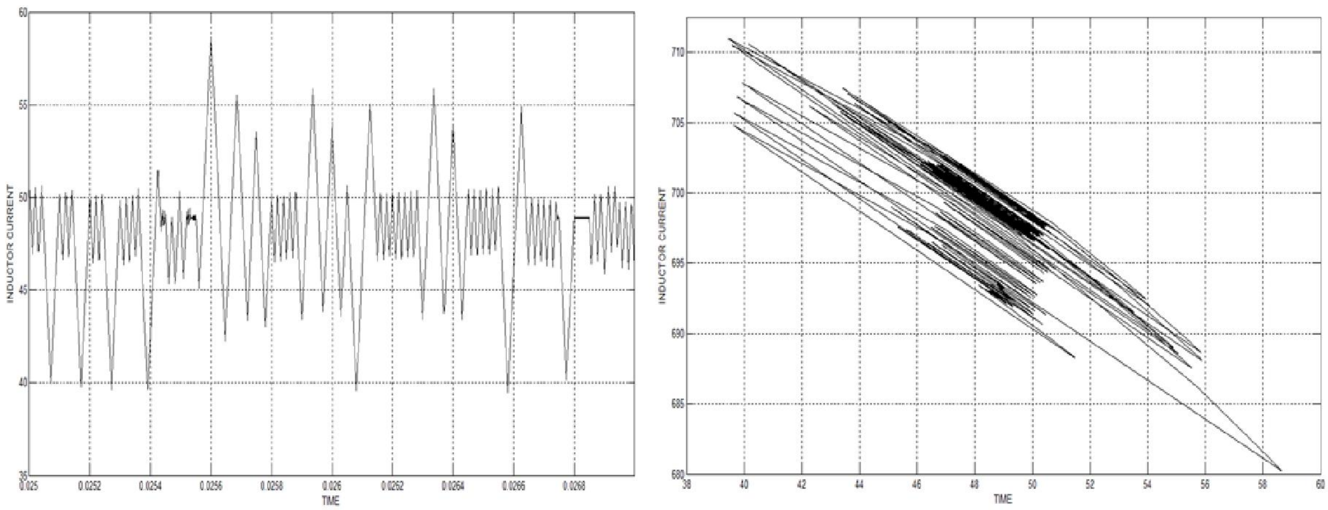


Fig. 9. Inductor current and Phase portrait in open loop at tolerance ± 1

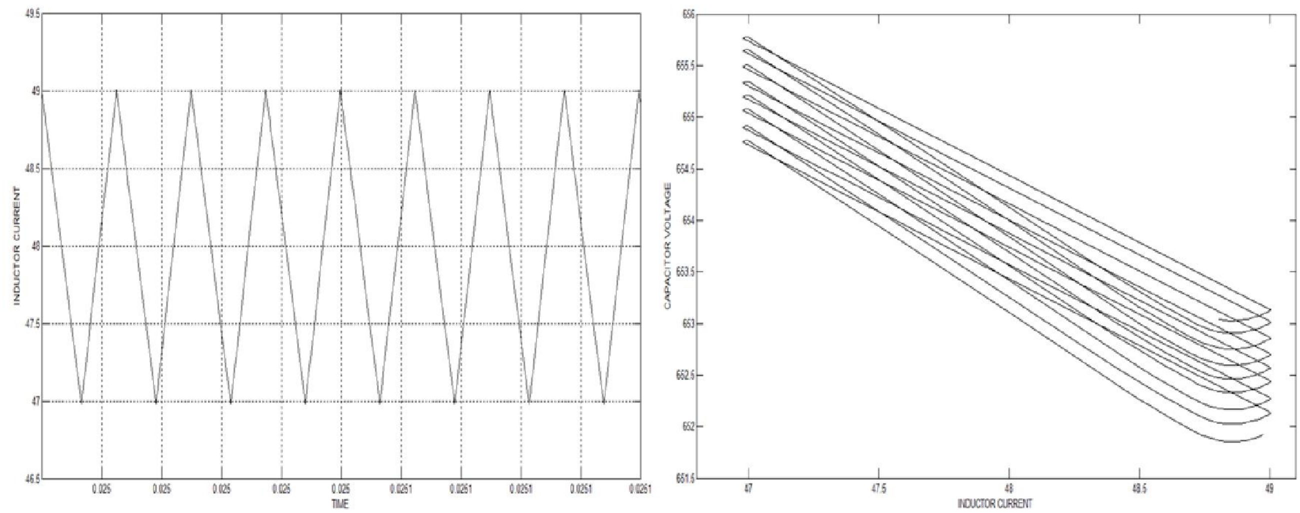


Fig. 10. Inductor current and Phase portrait in VSC at tolerance ± 1

keeping its average value constant (Iref). The inductor current waveforms in Fig.7 shows that the converter has entered into a region of second order bifurcation which can cause considerable noise some of which may fall in audible range. The phase portrait in Fig. 8 portrays the oscillatory nature of the converter which may eventually lead to chaos. The closed loop implementation model for a boost converter have reduced the ripples in the input current as in Fig. 9 and thus output voltage ripples is also reduced. The insertion of VSC creates a trajectory that spirals into a fixed one period orbit as seen in Fig. 10 and there by extracts the stable equilibrium point. When the buck converter is operated with a tolerance more than ± 6, the DC-DC converter does not exhibit a chaotic nature. It is only when the tolerances are further lowered; the chaosis necessitates measures to eliminate the nonlinear behaviour. The introduction of VSC facilitates a periodic operation throughout and a fairly good voltage regulation in buck converter. The influence of VSC prevents the boost converter from entering into chaotic region as well as reduces the ripples in the input current and output voltage. The erratic behaviour of the system is eliminated with the help of VSC. It is thus inferred that the chaotic properties of the converter are suppressed and periodic orbits are obtained. The significant role of VSC is brought out in its ability to eliminate chaos and extend the operating range upto a tolerance of ± 2 in buck converter and ± 1 in boost converter. Thus the proposed algorithm tailors the DC-DC converters to exhibit the stable operating zone over a predicted tolerance range.

Conclusion

This paper presents a complete analysis and deign of variable structure controller for DC-DC converters to meet the requirements of good voltage regulation and minimum ripple voltage within the stable operating condition. The formulated switching control law has been simulated using MATLAB software to validate the design procedure and operation. The merits of the designed methodology have been portrayed through its ability to eliminate the phenomenon of chaos. Thus the DC-DC converters will stive to explore a wider operating region thus making them suitable for solar/wind applications.
The key advantages of the design are: 1) improved voltage regulation. This makes DC-DC converter appropriate for solar and wind applications with unpredictable energy supply, 2) minimised ripple in output voltage which reduces the losses in the inverter stage, thus improving the efficiency of the system. 3) Simplified design algorithm apt for various DC-DC converters. The algorithm can be extended to developing DC-DC converter topologies with improved performance. The design can be realized experimentally with solar panels are wind generators. The design can also be used as an interface between any DC source and storage batteries thus continuing the electricity supply for small scale solar and wind applications.

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