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Current Observation Based Control of Full-Bridge DC/DC Converter : A Super Twisting Approach And Robust Controller Comparison

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Abstract— **This paper addresses the current control of output coil of a full-bridge power converter topology using super twisting algorithm despite the lack of current measurement. Also we designed high frequency robust like controller to compare performances of two controllers in terms of chattering effect under load change The proposed controllers ensure the coil current to track the desired value within a small range (ultimately bounded stability result). The observer is constructed through a Lyapunov type analysis and under the assumption that observer has sufficiently fast response so that no coupling with the control of current is required. Observer stability analysis ensures asymptotic convergence of the current estimation error. Simulation results illustrates validation of the approach under different load and observer schemes.**

Keywords— **Full-bridge dc-dc converter, Lyapunov stability analysis, current observer, super twisting sliding mode control, sensorless control, robust control.**

I. INTRODUCTION

Full bridge dc/dc converter is an important element of the power supplies. It has numerous applications in different power levels; low power like power supplies of illumination controllers for machine vision applications that need a few watts, high power like electric welding or tyre curing a few kW. The accurate regulations of output voltage and current are of significant importance in obtaining satisfying performance for the connected loads or devices [5]. Moreover, industry demands strict limits on the converter size and weight, together with high performance and efficiency. These aspects move the focus on current mode control, which allows for faster transient response[4].

Essentially, the PWM converter is a nonlinear circuit[6]. Due to coupling between duty cycle and the state variables in the full bridge DC/DC converter, linear controllers are not able to perform optimally for the whole range of operating conditions. In contrast with linear control, nonlinear approaches can optimise the performance of the converter over a wide range of operating conditions. Thus, advanced nonlinear control methods need to be adopted. When the parametric uncertainties are constant or slowly time-varying and the error dynamics containing the overall uncertainties can be linearly parametrizable, due to its continuous nature, adaptive control [7] would be the preferred choice. Unfortunately, because each uncertain parameter of the mathematical model has to be adapted separately, the tuning process of the parameter update gains is moderately tedious. On the other hand, when the uncertainties of the system are bounded by some norm-based function, the theory of robust control [8]-[9] can be applied. Sliding mode control(SMC) [10] is one of the most popular robust control strategies. The main disadvantage of SMC is chattering [11] . To avoid the chattering effect, several methodologies are proposed in sliding mode literature, super twisting algorithm (STA) [12] is one among them.

In this work, motivated by the simple controller structure of STA we have designed an observer based controller scheme for full bridge dc/dc converter depicted in Figure 1. We have also eliminated the use of the current sensor. Only a voltage sensor is required for measuring the output voltage. The proposed control ensures the coil current to track the desired value within a small range (ultimately bounded stability result). We also designed a robust controller for the accurate dynamic model depicted in [2] to illustrate superiority of STA in terms of chattering effect.

II. DYNAMIC MODEL OF FULL BRIDGE DC/DC CONVERTER

Proposed super twisting sliding mode based control approach is implemented on the circuit topology illustrated in Fig. 1. This topology has been used extensively in applications including telecommunications and aerospace power supplies [1].

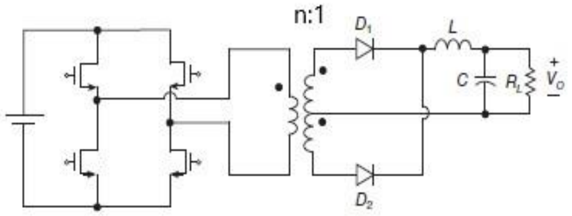

Fig. 1 Full-Bridge Dc/Dc Converter Topology

The equation of simplified dynamic model of the full bridge dc-dc converter depicted in Fig. 1 can be written in matrix form as,

$$\frac{d}{dt}\begin{bmatrix} i_L \\ V_0 \end{bmatrix} = \begin{bmatrix} 0 & 1/L \\ 1/C & 0 \end{bmatrix}\begin{bmatrix} i_L \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{V_i}{nL} \\ 0 \end{bmatrix} u + \begin{bmatrix} \frac{V_D}{L} \\ \frac{-i_0}{C} \end{bmatrix} \quad (1)$$

Where i_L and V_0, i_0 are output coil current (L is induction value of output coil in Henry), output voltage (C is capacitance of output capacitor) and output current, respectively. Here, V_i is input voltage, n is transformation rate of transformer, V_D is voltage across each rectification diode, u is control signal. To observe coil current accurately, more accurate dynamic model is required. The observer should take into account voltage drop across internal resistances of output coil and rectification diodes. Taking into account derived average model in [2], an accurate dynamic model can be given as,

$$\frac{d}{dt}\begin{bmatrix} i_L \\ V_0 \end{bmatrix} = \begin{bmatrix} -\frac{r_d+r_l}{L} & -\frac{1}{L} \\ \frac{1}{C} & \frac{-1}{(\hat{R}+\Delta R)C} \end{bmatrix}\begin{bmatrix} i_L \\ V_0 \end{bmatrix} + \begin{bmatrix} \frac{2V_i}{nL} \\ 0 \end{bmatrix} u + \begin{bmatrix} \frac{-4R_{on}}{n^2 L} \\ 0 \end{bmatrix} i_L u + \begin{bmatrix} -\frac{v_d}{L} \\ 0 \end{bmatrix} \quad (2)$$

Where $r_d, r_l, R_{on}, \hat{R}, v_{d,} \Delta R$ are internal resistance of rectification diodes D_1 and D_2 shown in Fig. 1, internal resistance of output coil, turn-on resistance of switching component, load resistance and forward voltage of D_1 and D_2, bounded known load perturbation, respectively.

III. Control Objective And Design

The control objective can be stated as ensuring output coil current i_L to track a desired trajectory, i.e., make $i_L(t) \to i_{Ld}(t)$ where $i_{Ld}(t)$ is the desired trajectory which is assumed to be chosen as sufficiently smooth with bounded time derivatives, ultimately converges to a constant value. In order to quantify the control objective we define tracking error signal as,

$$e \triangleq i_{Ld}(t) - i_L(t) \quad (3)$$

Using the simplified mathematical model given in (1), super twisting sliding mode control approach can be constructed if it can be ensured that output voltage is bounded to obtain

$$\|\rho\| \triangleq \left\| \frac{d}{dt}\left(\frac{nL}{V_i} i_{Ld}(t)\right) + \frac{n(v_d+V_0)}{V_i} \right\| \in \mathcal{L}_\infty \quad (4)$$

with $\frac{d}{dt} i_{Ld}(t) = 0$ in steady state. The assumption above enables us to rewrite the error dynamics in the form

V_i

$$\frac{d}{dt}\frac{nLe}{V_i} = \rho - u. \quad (5)$$

where the super twisting algorithm is defined as,

$$u = k|e|^{\frac{1}{2}} sign(e) + \alpha \int_0^t sign(e) d\tau \quad (6)$$

with some positive constants k,α. In view of equation (6), equation (5) can be can rewritten as,

$$\frac{de}{dt} = -k' |e|^{\frac{1}{2}} sign(e) + \varphi' + \rho' \quad (7)$$
$$\frac{d}{dt}\varphi' = -\alpha' sign(e)$$

where

$$k' \triangleq \frac{kV_i}{nL}, \alpha' \triangleq \frac{\alpha V_i}{nL}, \rho' \triangleq \frac{\rho V_i}{nL}, \varphi' \triangleq \frac{\varphi V_i}{nL}$$

The structure obtained in (7) is a dynamic system of which stability analysis is given in [3.] Given that the gains of super twisting algorithm are chosen as in [3], a Lyapunov function and its derivative can be found so that the the trajectory will not converge to the origin, but it will be globally ultimately bounded [3], that is, there exists a positive constant b, and for every $a > 0$, there is $T = T(a,b) \geq 0$ such that

$$\|\sigma(t_0)\| \leq a \Longrightarrow \|\sigma(t)\| \leq b,\ \forall(t) \geq t_0 + T. \quad (8)$$

Here vector σ^T=$[\sigma_1, \sigma_2] = \left[|e|^{\frac{1}{2}} sign(e), \varphi'\right]$.

IV. Observer Dynamics And Design

The objective is to design a continuous observer to estimate the current of the output coil. Output voltage across the capacitor is measurable. Let the observed current $\hat{x}_1$ and observed voltage $\hat{x}_2$ have an estimation error $\tilde{x}_1$ and $\tilde{x}_2$, respectively, defined as follows:

$$\tilde{x}_1 = x_1 - \hat{x}_1 \quad (9)$$
$$\tilde{x}_2 = x_2 - \hat{x}_2$$

Define $\delta(\Delta R)$ as in [4],

$$\delta(\Delta R) = -\frac{\Delta R}{(\hat{R}+\Delta R)\hat{R}} \quad (10)$$
$$\bar{\delta}=\min(\delta(\Delta R^{min}), (\delta(\Delta R^{max}))$$

where $R_L \equiv \Delta R + \hat{R}$, ΔR^{min} and ΔR^{max} are known upper and lower limits of known load perturbation to obtain observer dynamics as

$$L\frac{d}{dt}\hat{x}_1 = -(r_d + r_l)\hat{x}_1 - \hat{x}_2 + 2\frac{V_i}{n}u - \frac{4R_{on}}{n^2}\hat{x}_1 u - v_d$$
$$C\frac{d}{dt}\hat{x}_2 = \hat{x}_1 - \frac{1}{\hat{R}}\hat{x}_2 + K\tilde{x}_2 + \gamma(\tilde{x}_2) \quad (11)$$

where K is observation gain and $\gamma(\tilde{x}_2)$ observer term that will be designed. Using the observer dynamics above, it is easy show that the observer error dynamics is,

$$L\frac{d}{dt}\tilde{x}_1 = -(r_d + r_l)\tilde{x}_1 - \tilde{x}_2 - \frac{4R_{on}}{n^2}u\tilde{x}_1 \quad (12)$$
$$C\frac{d}{dt}\tilde{x}_2 = \tilde{x}_1 - \left(\frac{x_2}{\Delta R+\hat{R}} - \frac{\hat{x}_2}{R_L}\right) - K\tilde{x}_2 - \gamma(\tilde{x}_2)$$

We designed $\gamma(\tilde{x}_2)$ as,

$$\gamma(\tilde{x}_2) = \frac{\Delta R}{(\hat{R}+\Delta R)\hat{R}} \quad \hat{x}_2. \quad (13)$$

If ΔR is unknown, we designed the term in (13) as,

$$\gamma(\tilde{x}_2) = (|\hat{x}_2\bar{\delta}| + \alpha)sign(\tilde{x}_2) + \beta\tanh(\tilde{x}_2) \quad (14)$$

where α and β are positive constants.

V. Observer Stability Analysis

In this section, the stability of the current observer design in (9-13) will be presented. To facilitate the stability analysis, we define following function

$$V \triangleq \frac{1}{2}L\tilde{x}_1{}^2 + \frac{1}{2}C\tilde{x}_2{}^2 \quad (15)$$

Note that the expression in (15) is positive, globally unbounded, upper and lower bounded as

$$\alpha_1(\|\tilde{x}_1, \tilde{x}_2\|) \le V(\tilde{x}_1, \tilde{x}_2) \le \alpha_2(\|\tilde{x}_1, \tilde{x}_2\|). \quad (16)$$

Based on (15), the class $\mathcal{K}$ functions α_1 and α_2 are defined as

$$\alpha_1(\|\tilde{x}_1, \tilde{x}_2\|) \triangleq \frac{1}{2}\min\{L, C\}(\tilde{x}_1{}^2 + \tilde{x}_2{}^2) \quad (17)$$

$$\alpha_2(\|\tilde{x}_1, \tilde{x}_2\|) \triangleq \frac{1}{2}\max\{L, C\}(\tilde{x}_1{}^2 + \tilde{x}_2{}^2) \quad (18)$$

By taking the time derivative of (15), we obtain

$$\frac{d}{dt}V = -(r_d + r_l)\tilde{x}_1{}^2 - \frac{4R_{on}}{n^2}u\tilde{x}_1{}^2 - \frac{1}{\Delta R+\hat{R}}\tilde{x}_2{}^2 - K\tilde{x}_2{}^2 + \frac{\Delta R}{\hat{R}(\Delta R+\hat{R})}\hat{x}_2\tilde{x}_2 - \gamma(\tilde{x}_2)\tilde{x}_2 \quad (19)$$

Replacing the expression in (13) into (19) we have,

$$\frac{d}{dt}V \le -\left[(r_d + r_l) + \frac{4R_{on}}{n^2}u\right]\tilde{x}_1{}^2 - \left[K + \frac{1}{\Delta R + \hat{R}}\right]\tilde{x}_2{}^2$$

obtaining,

$$\frac{d}{dt}V \le -\beta\|\tilde{x}\|^2 \quad (20)$$

with $\beta = \min\{(r_d + r_l) + \frac{4R_{on}}{n^2}u, K + \frac{1}{\Delta R+\hat{R}}\}$.

From (15) and (20), it is clear that $V(\tilde{x}_1, \tilde{x}_2) \in \mathcal{L}_\infty$ and thus $\tilde{x} = [\tilde{x}_1\ \tilde{x}_2] \in \mathcal{L}_\infty$. Global asymptotic stability is achieved with $0 \le u < 1$. Note that, stability analysis of alternative design in (14) is similar to the analysis given from (15) to (20). The time derivative of (19) satisfies following condition

$$\frac{d}{dt}V \le -(r_d + r_l)\tilde{x}_1{}^2 - \frac{4R_{on}}{n^2}u\tilde{x}_1{}^2 - \frac{1}{\Delta R+\hat{R}}\tilde{x}_2{}^2 - K\tilde{x}_2{}^2 + |\bar{\delta}||\hat{x}_2||\tilde{x}_2| - \gamma(\tilde{x}_2)\tilde{x}_2 \quad (21)$$

Replacing the expression in (14), we have

$$\frac{d}{dt}V \le -\alpha|\tilde{x}_2| - \beta|\tanh(\tilde{x}_2)\,\tilde{x}_2| \quad (22)$$

From (15) to (18) and (14), (21), (22) global asymptotic stability is achieved, alternatively.

VI. Robust Controller Design And Stability Analysis

To compare performance of two nonlinear based algorithm we designed a robust controller. The control objective is same as illustrated in (3) based on the model depicted in (2). All signals are assumed to be measurable. From (2) it is easily shown that:

$$\frac{di_L}{dt} = -Ai_L - BV_0 + Cu - Di_Lu - \frac{v_d}{L} + d \quad (23)$$

Where,

$$A \triangleq \frac{r_d+r_l}{L}, B \triangleq \frac{1}{L}, C \triangleq \frac{2V_i}{nL}, D \triangleq \frac{4R_{on}}{n^2} \quad (24)$$

d is unknown disturbance term injected into the current. Defining a simple Lyapunov function as,

$$V = \frac{1}{2}e^2 \quad (25)$$

And by taking the time derivative of (25) and replacing (23) into (25) we obtain

$$\frac{d}{dt}V = e\left[\frac{d(i_{Ld}(t)}{dt} + Ai_L + BV_0 + u(Di_L - C) + \frac{v_d}{L} - d\right] \quad (26)$$

Designing control signal u as

$$u = \frac{1}{(Di_L - C)}\left(\frac{d(i_{Ld}(t)}{dt} - Ai_L - BV_0 - ke - \frac{v_d}{L} - V_R + \hat{d}\right) \quad (27)$$

Where,

$$V_R \triangleq \frac{\rho^2 e}{|\rho||e| + \epsilon} \quad (28)$$

And $\hat{d}$ is defined as estimated value of the disturbance term d. ρ, ϵ are positive constants. Replacing (27) into (26) we obtain

$$\frac{d}{dt}V = -ke^2 - \tilde{d}e - \frac{\rho^2e^2}{|\rho||e| + \epsilon} \quad (29)$$

Basic assumption of robust controllers are

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$$|\tilde{d}| < \rho \tag{30}$$

Taking into consideration inequality in (30), one can easily show that

$$\frac{dV}{dt} \leq -ke^2 + |e|\rho - \frac{\rho^2 e^2}{|\rho||e|+\epsilon} \tag{31}$$

$$\frac{dV}{dt} \leq -ke^2 + \epsilon\left[\frac{|e|\rho}{|e|\rho+\epsilon}\right] \tag{32}$$

$$\frac{dV}{dt} \leq -ke^2 + \epsilon \tag{33}$$

Using (25), we can obtain

$$\frac{dV}{dt} \leq -2kV + \epsilon \tag{34}$$

Solution of the differential equation in (34) is

$$V \leq V(0)e^{-2kt} + \frac{\epsilon}{2k}[1 - e^{-2kt}] \tag{35}$$

From (35) it is obvious that error signal converges exponentially to a boundary near zero. So it is proved that origin point, $e = 0$ is globally ultimately bounded.

VII. SIMULATION RESULTS

In order to demonstrate the performance of the proposed controller and observer given in (7) and (14), various numerical simulations are conducted on the full bridge dc/dc converter dynamic models illustrated in (1) and (2) using simulation environments in Gebze Technical University. The model parameters are shown in Table 1.

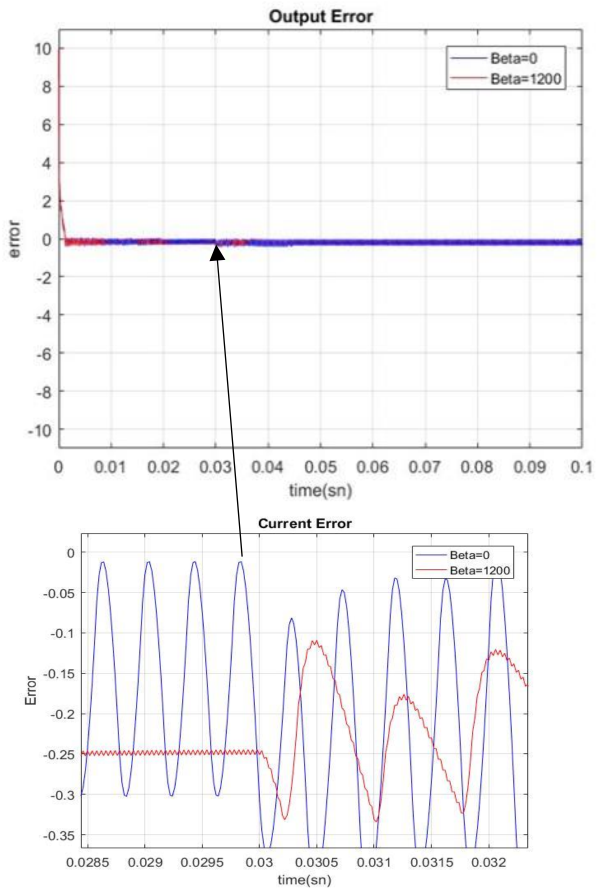

Fig. 2 Super Twisting Algorithm-Current Error Under Load Change

TABLE I
PARAMETERS OF THE FULL BRIDGE DC/DC CONVERTER

Parameters	Values	Units
Transformation Rate (n)	19/6	-
Output Inductance (L)	0.8	mH
Primary Voltage (V)	400	V
Internal Resistance Of Diode (r_d)	0.6	Ω
Internal Resistance Of Inductor (r_l)	6.23	Ω
Nominal Load Resistance ($\hat{R}$)	2	Ω
Output Capacitance (C)	2000	µF
Mosfet On Resistance (R_{on})	5	mΩ
Diode Forward Voltage	0.7	V
Load Change(ΔR)	1	Ω
i_{Ld}	10	A

For this numerical study the converter control, sampling and switching frequencies have been set to 50kHz. During the simulation studies we chose the super twisting control parameters, k=23000 and α=3459.5 and observer parameters $K = 40000$ and α=20. At 0.03 s a step change in the load value is applied, according to the quantity in Table 1. The current tracking error performance illustration, the controller effort comparison for the super twisting controller and traditional PI regulator are given in Figures 2 and 5, respectively whereas Figure 6 and Figure 7 present a comparison of current tracking performances of STA and PI regulators under no load change and load change respectively. Figure 4 demonstrates output current profile when STA is applied to the converter model under load change and Figure 3 depicts observer performance with STA.

As can be seen from the simulation results the control and observer effort with STA controller contains some high-frequency components. Our experience with the STA controller have shown that, one has to be very careful while tuning this type of observer and controller, especially dealing with β term and combinations of k and controller parameter α.

In Fig.8, Fig.9 and Fig.10 error and control signals are illustrated when robust controller in (27) is applied to the full bridge converter. Value of control parameters are $k = 10500$, $\rho = 220, \hat{d} = 12$. Desired current value is constant 10 A. Sampling and switching frequencies are same, 50kHz.

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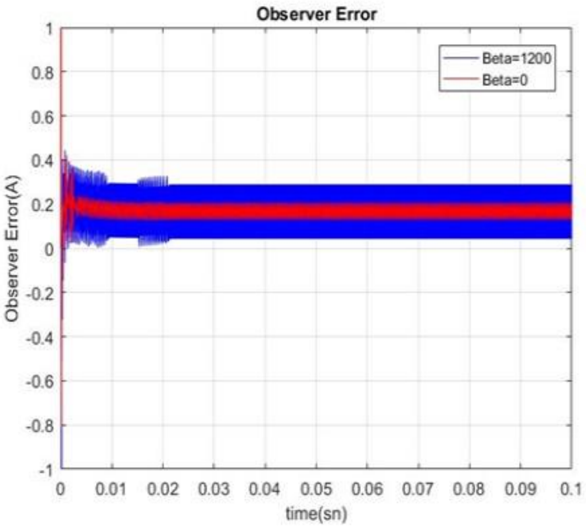

Fig.3 Observer Error With Super Twisting Algorithm

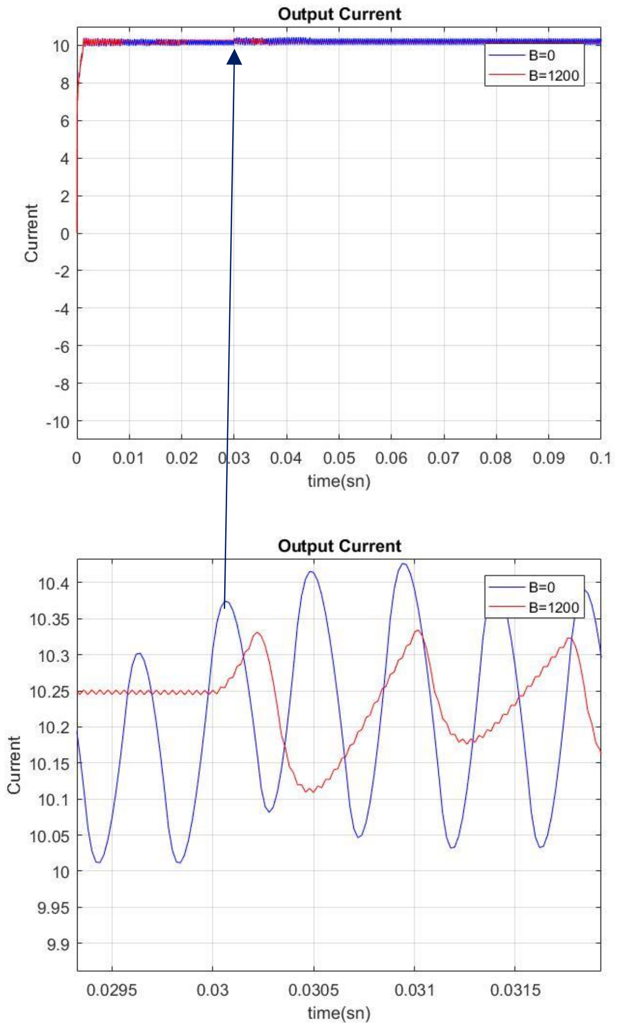

Fig.4 Output Current (Super Twisting Algorithm)

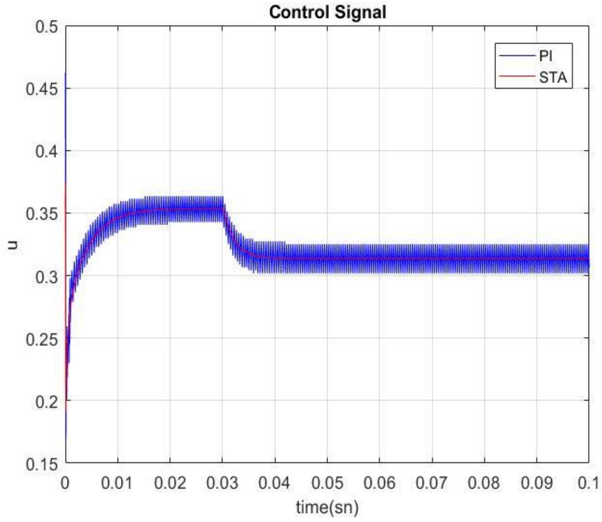

Fig. 5 Super Twisting Algorithm and PI Regulator Control Signal Comparison Under Load Change

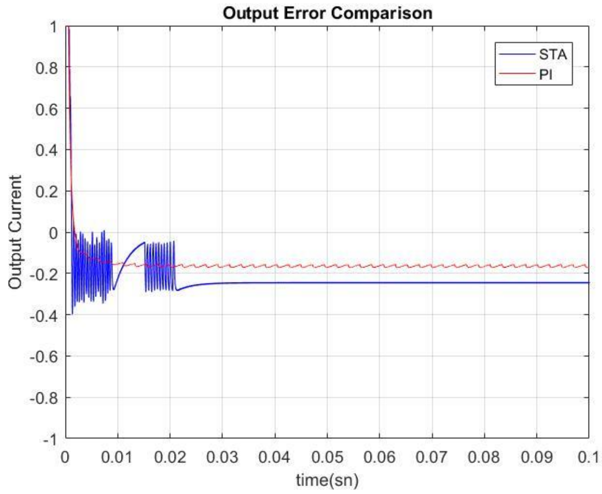

Fig.6 PI and STA Output Current Tracking Comparison

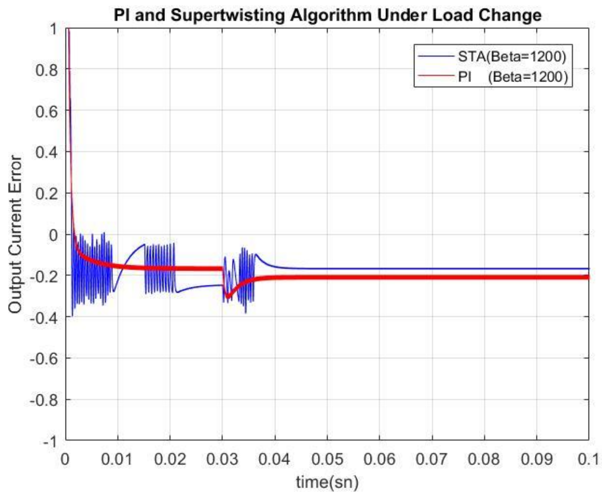

Fig.7 PI and STA Output Current Tracking Comparison (Under Load Change)

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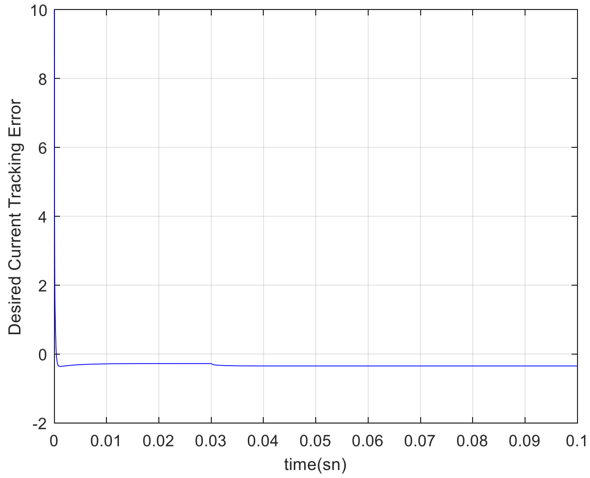

Fig. 8 Robust Controller Desired Trajectory Tracking Performance

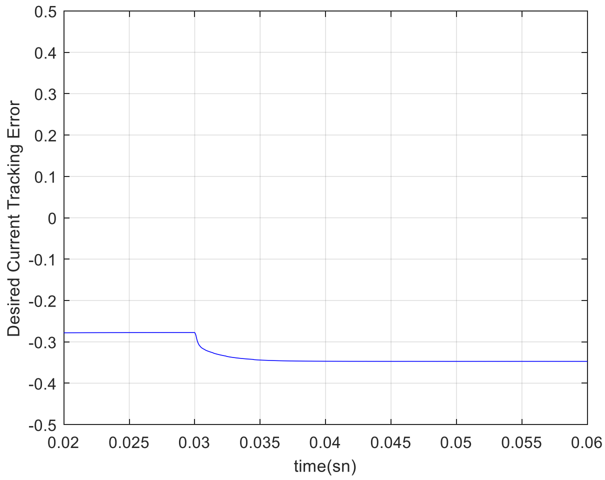

Fig.9 Robust Controller Desired Trajectory Tracking Performance Under Load Change

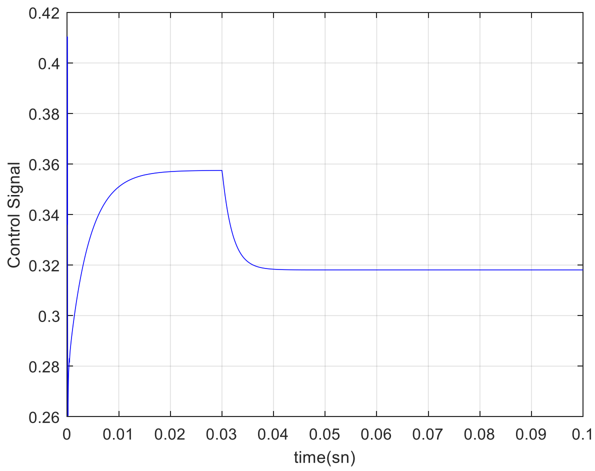

Fig.10 Robust Controller Control Signal Trajectory Under Load Change

VIII. CONCLUSIONS

In this paper, we have presented a new controller approach for the current control of a kind of full bridge dc/dc converter. Despite the parametric uncertainties in the system dynamics (C, L, load etc.), the proposed control approach guarantees ultimate boundedness. The overall analysis is supported by Lyapunov based arguments. Our simulation studies showed that proposed methodology is as effective as the PI regulator under unknown load changes. Moreover, proposed novel observer structures have sufficiently fast response and do not require any known system parameter or require only load data. To compare the proposed method with a nonlinear robust controller, we designed a high frequency robust controller for the mathematical model of the system in [2]. As it can be seen in Fig. 9 robust controller has faster response than PI and STA, although steady state error slightly higher. Notice that robust controller simulations are realized as all signals are measurable. In the view of aforementioned issues, the main advantage of the designed controller/observer can be summarized as:

- The controller requires only voltage measurement across the output component (load or capacitor), reduces total design cost and increases reliability.
- Having fast response under load changes.
- Different from the past works on control of dc/dc converters actual observer input $\beta\tanh(\tilde{x}_2)$ is designed and dependency on the model parameters is eliminated.

All of these aspects show the realisticity and applicability of the designed controller/observer for the real time applications.

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