Output Feedback Discrete SMC Design For Quadratic Buck DC-DC Converter

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Abstract— **The purpose of this study is to design an output feedback sliding mode control for Quadrature Buck Converter(QBC) whose popularity has increased over the last decade owing to the increasing Maximum Power Point Tracking(MPPT) applications and growing power quality concerns in the industry. QBC is non-minimum phase and discontinuous system thanks to the switching components which makes it challenging to design a controller. The plant in Continuous Conduction Mode(CCM) is modeled by state-space averaging method. Output Feedback Sliding Mode Controller which is capable of controlling the plants with non-minimum phase characteristics is designed for the QBC in the face of process line voltage and load variations. The performance of the ODSMC controlled QBC during changing load and supply voltage is examined by means of numerical simulations that are done in Matlab/Simulink. Based on the results that are presented, the considerable disturbance rejection is achieved.**

Keywords—QBC; ODSMC.

I. Introduction

QBC is one type of Buck Converter with a high transformation ratio which is especially used in automotive industry and industrial power transformation. The use of DC-DC converters in general has increased over the last couple of decades due to the improvement of manufacturing process of more efficient power switches and increasing industrial power conversion regulations regarding Total Harmonic Distortion(THD) and power quality [1]. QBC is a reducing type dc-dc converter whose state-space model is described by a 4^{th} order discontinuous nonlinearity due to the switching components in the circuit [2]. In this study, the linear model of the plant was obtained by using the state-space averaging method however the method called circuit averaging method is also commonly used for the circuits that include switching components [3].

One of the most challenging issue with a control of a DC-DC converter circuit is to design a controller capable of regulating the output voltage in the presence of change in the input voltage and current that is drawn in the load side. These disturbances can be handled by a robust control scheme [4]. Discrete output feedback control employed in applications where the matched uncertainties present problems such as aerospace and underwater vehicles. ODSMC control scheme is capable of mitigating the effects of the mentioned disturbances on the nominal operation of the converter [5]. Generally conventional Sliding Mode Control(SMC) has its limits if the plant is non-minimum phase and also require some type of state estimators. The controller can stabilize the plant which has the non-minimum characteristics with the help of the additional compensator dynamics [6].

This paper is arranged as follows, the converter nonlinear model is presented and the linear model using state space averaging method is derived in section II, design procedure of the controller is presented and the selection of the parameters that are needed is argued in section III. Finally, numerical simulations that are performed in MATLAB/SIMULINK for the different operating conditions of the plant are presented in section IV.

II. System Modeling

QBC converter can be considered as cascaded Buck converter, because of that its transformation ratio is D^2, where D is the steady state duty cycle parameter. It is only capable of step down operations. It is used to distribute the supplied DC source to the electronic devices that require lower voltage level [7]. The QBC is illustrated in Fig 1.

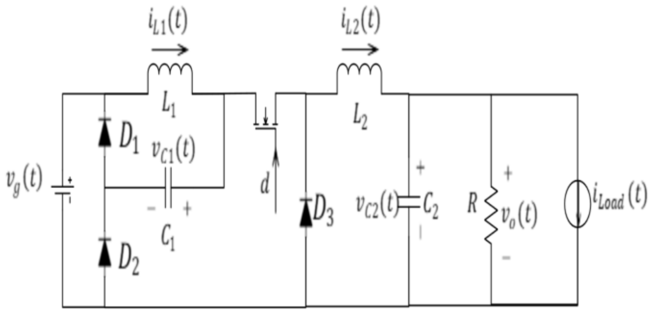

Fig. 1 Quadratic Buck Converter Circuit Diagram.

As seen from the Fig. 1 the plant is 4^{th} order since there are 2 inductances and 2 capacitances. The presence of 2 switch components leads the system to have discontinuous nonlinear characteristics. Since there are 2 switching elements there are 4 combinations. However, for simplicity the combinations where the component are both in conduction and cut-off mode at the same time are usually ignored. These valid 2 combinations are called large signal modes and they are averaged by weighting by the corresponding duration. The resulting state space model, also known as averaged large signal model is used to obtain the steady state values of the each state variable and using those variables, the small signal model is obtained. Small signal model, is a dynamic model and represents the behavior of the small signal components of the states where the small signal in this context is defined as the deviation from the determined steady state value. These procedures are explained in this section by determining the state space model of the each mode based on the position of the switches [8],[9].. When the transistor is in conduction mode, the state space model is represented as,

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{1}{L_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_2} \end{bmatrix} \begin{bmatrix} v_g \\ i_{Load} \end{bmatrix} \tag{1}$$

When the transistor is in cut-off mode, the state space model is given as,

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2} \\ \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_2} \end{bmatrix} \begin{bmatrix} v_g \\ i_{Load} \end{bmatrix} \tag{2}$$

Averaged large state space model is determined by averaging those state space representation in (1) and (2) with weighting by d, duty cycle parameter, and can be found as,

$$\frac{d}{dt}\begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & \frac{1}{L_2}d & -\frac{1}{L_2} \\ \frac{1}{C_1} & -\frac{1}{C_1}d & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ v_1 \\ v_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1}d & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_2} \end{bmatrix} \begin{bmatrix} v_g \\ i_{Load} \end{bmatrix} \tag{3}$$

where the states i_1, i_2, v_1 and v_2 are called large signals. They are composed of both a steady state which has a time derivative of zero and a small signal which is the deviation from the corresponding steady state [10],[11].

For instance, d, being one of the large signals in the averaged large signal model, can be found as,

$$d = D + \Delta d \tag{4}$$

Substituting every large signal in (3), with their small signal and steady state component and also using the fact that time derivative of every steady state component is zero, small signal model of the plant can be found in state space form and is given as,

$$\frac{d}{dt}\begin{bmatrix} \Delta i_1 \\ \Delta i_2 \\ \Delta v_1 \\ \Delta v_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & \frac{1}{L_2}D & -\frac{1}{L_2} \\ \frac{1}{C_1} & -\frac{1}{C_1}D & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2} \end{bmatrix} \begin{bmatrix} \Delta i_1 \\ \Delta i_2 \\ \Delta v_1 \\ \Delta v_2 \end{bmatrix} + \begin{bmatrix} \frac{V_g}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} [\Delta d] + \begin{bmatrix} \frac{1}{L_1}(D) & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{C_2} \end{bmatrix} \begin{bmatrix} \Delta v_g \\ \Delta i_{Load} \end{bmatrix} \tag{5}$$

This model is illustrated as block diagram in Fig 2,

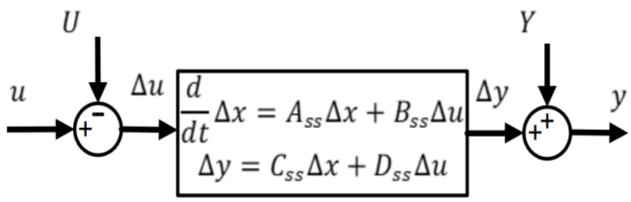

Fig. 2 Small Signal representation.

The steady state values of the converter also specifies the operating condition of the plant is given in TABLE I,

TABLE I. OPERATING POINT

V_{in}	$42\,V$	R	$5\,\Omega$
V_{out}	$12\,V$	C_1	$28\,\mu F$
L_1	$400\,\mu H$	C_2	$96\,\mu F$
L_2	$150\,\mu H$	f_{sw}	$100\,kHz$

By substituting these parameters the small signal model is found numerically. Discrete model is required for ODSMC. It is determined by using the sampling period of $T_s = 10\,\mu s$ and is given as,

$$x_p(k+1) = \begin{bmatrix} 0.6 & 0.19 & -0.19 & 0.04 \\ 0.52 & 0.43 & 0.23 & -0.47 \\ 2.71 & -1.26 & 0.32 & 0.48 \\ 0.18 & 0.73 & 0.14 & 0.54 \end{bmatrix} x_p(k) + \begin{bmatrix} 11.06 \\ 12.64 \\ -1.875 \\ 6.55 \end{bmatrix} u(k) \quad (6)$$

$$y_p(k) = [0 \quad 0 \quad 0 \quad 1] x_p(k)$$

III. CONTROLLER DESIGN

In the previous section the discrete time state space model of the plant is derived.

The controller is designed based on the small signal model of the plant which was derived in section II. The control strategy can be explained as follows. The controller produces the small signal component of actuator signal by processing the small signal part of the output signal that is measured. This small signal actuator signal, Δd is incremented by its state space value, D to obtain actuator signal, d which is modulated by the PWM block at the frequency of 100 kHz. The modulated d signal is applied to do gate of the switch in the DC-DC converter. This process is illustrated by the block diagram given in Fig 3.

In this section the controller algorithm is explained and the determination of the required parameters is discussed.

As it can be seen from the block diagram, the controller has one input variable that is available to manipulation, the other 2 input signals, v_g and i_{Load} are seen in the figure are the disturbances and the important purpose of the controller is to maintain a stable performance even in the case of varying of those parameters. Another interesting aspect of this problem is to consider the changing of the plant components which is beyond the scope of this study. Sliding Mode Control is a type of nonlinear control and has attracted the researchers' attention due to its ability to suppress the disturbances that affect the plant from the same channel of actuator signals. These types of disturbances are generally called matched uncertainties and are assumed to be unknown but bounded by certain physical constraints [12].

A discrete state space model is given as,

$$x_p(k+1) = G_p x_p(k) + H_p\big(u(k) + \xi(k)\big) \quad (7)$$
$$y_p(k) = C_p x_p(k)$$

where $x_p \in \mathbb{R}^n, u \in \mathbb{R}^m, y \in \mathbb{R}^p$ are the state, input and output vectors belonging to the plant respectively. $G_p \in \mathbb{R}^{nxn}, H_p \in \mathbb{R}^{nxm}, C_p \in \mathbb{R}^{pxn}$ are state matrices that denote state transition matrix, input and output distribution matrices respectively. ξ denotes matched uncertainty.

First design step of SMC is to determine a set, which is known as sliding manifold, that the state vector is meant to be driven onto the set and it is tried to be confined within a close neighborhood of this set by controller action. After determining such a set, next step is to guarantee that the states will remain on that set and converge to the desired point despite mentioned disturbances [13]. The sliding manifold can be represented as,

$$\mathcal{S} = \{x_p \in \mathbb{R}^n : S(x_p) = 0\} \quad (8)$$

where the function S is used to define the set and it can be chosen as a linear function. As it can be seen from the expression that statement assumes the availability of the plant states and because of that this control strategy cannot be employed for the non-minimum phase systems [14]. To overcome these issues output feedback type controller known as ODSMC which requires more calculations is studied. The next step of designing a ODSMC is to define a new fictitious plant which is represented by the system matrices (G_p, H_p, L_p) where $L_p \in \mathbb{R}^{pxn}$ is defined as the output distribution matrix of the fictitious model [15]. To simplify the determination of the controller parameters, a coordinate transformation is required and leads to a canonical form whose state matrices are given as,

$$\widehat{G_p} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix}, \widehat{H_p} = \begin{bmatrix} 0 \\ H_2 \end{bmatrix}, \widehat{L_p} = [0 \quad T] \quad (9)$$

where $x_1 \in \mathbb{R}^{n-m}, G_{11} \in \mathbb{R}^{(n-m)x(n-m)}, H_2 \in \mathbb{R}^{mxm}$ and $T \in \mathbb{R}^{pxp}$ is an orthogonal matrix. The controller is mainly designed to regulate the output voltage. However, there might be some applications at which this output voltage is set to a different value. For the purpose of reference tracking integrator is introduced, whose dynamics represented as,

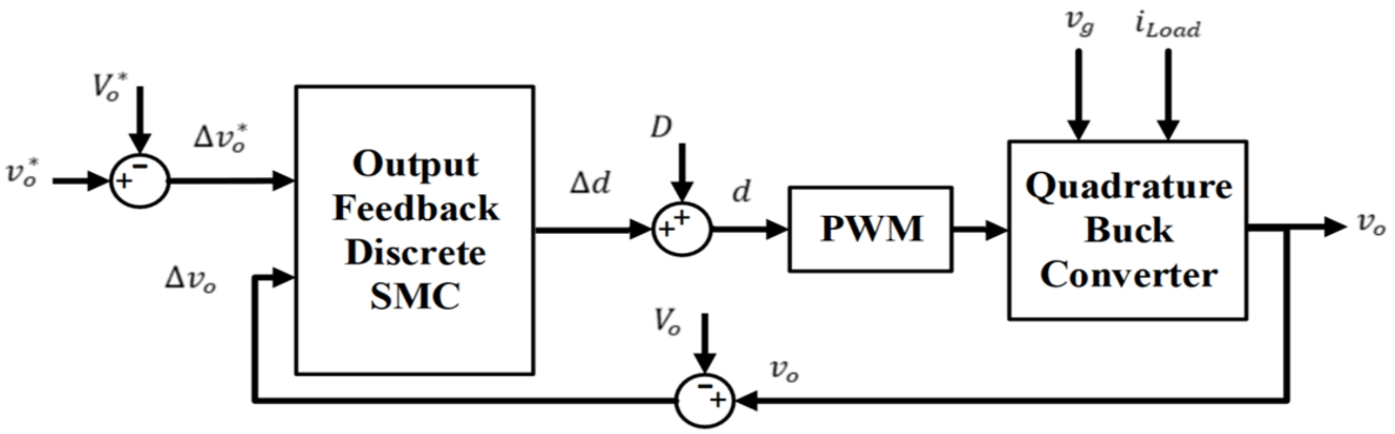

Fig. 3. Block diagram of ODSMC strategy

$$x_r(k+1) = x_r(k) + T_s\left(r(k) - C_P x_p(k)\right) \quad (10)$$

where $x_r, r \in \mathbb{R}^p$ and T_s are the state variable of the integrator dynamic equation, the reference signal to be tracked and the sampling period respectively. This dynamic equation is illustrated by the block diagram in fig 4,

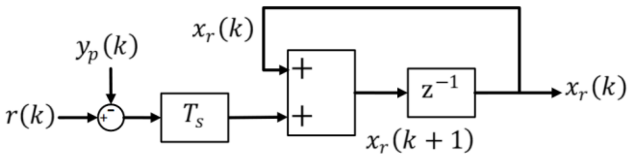

Fig. 4. Integrator sub-block diagram

Another block which is called compensator is added to the controller, because the plant poses invariant zeros. The compensator dynamics are given by,

$$x_c(k+1) = \Phi x_c(k) + \Gamma_1 y + \Gamma_2 x_r + \Gamma_3 r \quad (11)$$

where x_c is compensator state variable and $\Phi, \Gamma_1, \Gamma_2, \Gamma_3$ are the design parameters that are yet to be chosen. The compensator is illustrated by the block diagram in Fig 5.

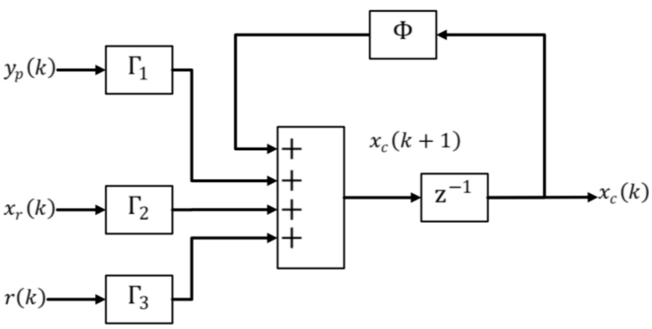

Fig. 5. Compensator sub-block diagram

When the states are on the sliding surface, compensator parameters can be found as,

$$\begin{aligned} \Phi &= G_{11} - \Omega T G_{21} - G_{21}K_1 + LTG_{22}K_1 \\ \Gamma_1 &= \Omega \\ \Gamma_2 &= -G_{12}K_r + \Omega T G_{22}K_r \\ \Gamma_3 &= -G_{12}S_r + \Omega T G_{22}S_r \end{aligned} \quad (12)$$

where $K_1 \in \mathbb{R}^{mx(n-m)}, K_r, S_r \in \mathbb{R}^{mxm}, \Omega \in \mathbb{R}^{(n-m)xm}$ are the parameters that are used to represent the sliding manifold.

After adding the compensator and integrator dynamics to the plant and augmented state space model can be represented as,

$$\begin{aligned} x_a(k+1) &= G_a x_a(k) + H_a\left(u(k) + \xi(k)\right) \\ &\quad + H_r r(k), \\ y_a(k) &= C_a x_a(k) \end{aligned} \quad (13)$$

where $G_a \in \mathbb{R}^{(2n-m+p)x(2n-m+p)}, H_a \in \mathbb{R}^{(2n-m+p)xm}, H_r \in \mathbb{R}^{(2n-m+p)xp}$. Augmented state is represented as,

$$x_a = \begin{bmatrix} x_c \\ x_r \\ x_1 \\ x_2 \end{bmatrix} \quad (14)$$

After the establishment of the augment system, the control law can be written as,

$$\begin{aligned} u(k) = &-(FC_aG_a^{-1}H_a)^{-1}\left(FC_a x_a(k)\right. \\ &\left. + (FC_aG_a^{-1}H_r + F_2S_r)r(k)\right) \end{aligned} \quad (15)$$

where $F \in \mathbb{R}^{mxm}$ is another design parameter that is expressed in terms of the variables mentioned before and is given as,

$$F = F_2[K_1\Phi \quad K_1\Gamma_2 + K_r \quad K_1\Gamma_1 - K_rT_s + T^T] \quad (16)$$

where $F_2 \in \mathbb{R}^{mxm}$ is constant that has no effect on the performance directly. However, it is required to satisfy the constraints that is related to the reaching condition that is given as,

$$FC_a = H_a^T P_a G_a \quad (17)$$

where $P_a \in \mathbb{R}^{(2n-m+p)x(2n-m+p)}$ is a positive definite that is necessary to guarantee that the designed controller satisfies the sliding mode reaching condition. To determine if the controller satisfies the reaching condition, the energy like Lyapunov function is defined as,

$$V_a(k) = x_a(k) P_a x_a(k)^T \tag{18}$$

where V_a is a positive and decreasing function of the augmented state vector.

The other controller parameters K_1, K_r and Ω is determined after a specific coordinate transformation of the augmented system [16]. The change of coordinates is made by using the transformation matrix that is given by,

$$\tilde{T} = \begin{bmatrix} I_{n-m} & -I_{n-m} & 0 & 0 \\ 0 & I_{n-m} & 0 & 0 \\ 0 & 0 & I_m & 0 \\ 0 & K_1 & K_r & I_m \end{bmatrix} \tag{19}$$

Considering the control law that is given in (15), the transformed close loop system matrix is determined to be,

$$\tilde{G}_c \coloneqq \tilde{G} - \tilde{H}\left(F\tilde{L}\tilde{H}\right)^{-1} F\tilde{C} \tag{20}$$

and whose eigenvalues must lie inside the unit circle. This coordinate transformation facilitates the parameter determination and results with $\tilde{G}_c$ in (20) the transformed close loop state matrix $\tilde{G}_c$ can be expressed as,

$$\tilde{G}_c = \begin{bmatrix} G_{11} - \Omega T G_{21} & 0 & * \\ * & \tilde{G}_m & * \\ 0 & 0 & 0 \end{bmatrix} \tag{21}$$

Since $\tilde{G}_c$ has a block diagram form, the problem of determining whether the matrix is stable or not can be reduced to determining the stability of these 3 lower dimensional matrices [17]. One of these matrices, $\tilde{G}_m$ can be written as,

$$\tilde{G}_m = \begin{bmatrix} G_{11} & 0 \\ -T_s T G_{21} & I_m \end{bmatrix} - \begin{bmatrix} G_{12} \\ -T_s T G_{22} \end{bmatrix} \begin{bmatrix} K_1 & K_r \end{bmatrix} \tag{22}$$

By using that equality, K_1 and K_r can be selected such that $\tilde{G}_m$ is stable. Another matrix design freedom Ω is chosen such that the matrix $G_{11} - \Omega T G_{21}$ is stable [18].

For the QBC, the controller parameters were selected such that the $max(|\lambda(G_{11} - \Omega T G_{21})|) = 0.87$ and $max\left(\left|\lambda(\widetilde{G_m})\right|\right) = 0.35$. Matlab software is utilized during the mentioned pole placement operations.

Resulting from the assigned poles, controller parameters are determined to be,

$$\Omega = \begin{bmatrix} 0.7992 \\ 0.375 \\ 2.9888 \end{bmatrix} \quad K_1 = \begin{bmatrix} 0.1675 \\ -0.0505 \\ -0.5498 \end{bmatrix}^T \tag{23}$$
$$K_r = 36.095 \qquad S_r = 1.2$$

Lastly the whole control scheme is illustrated in Fig 6.

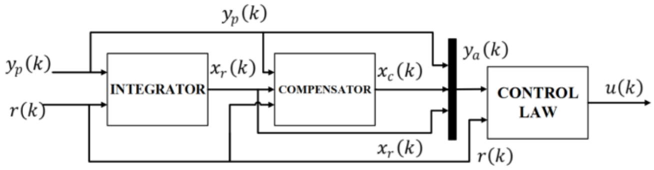

Fig. 6. Compensator sub-block diagram

IV. SIMULATION RESULTS

In the previous sections, the plant is modelled and discrete time small signal representation is derived based on the operating point that is presented in the table I. Controller is designed based on that model. To assess the performance of the ODSMC, overall system is simulated in Matlab/Simulink environment. To test the robustness, the disturbance signals were applied during the operation. Applied input voltage and current that is drawn by the resistive load waveforms are given in the Fig 7 and Fig 8 respectively. The performance of the controller can be illustrated by the output voltage waveform that is given in Fig 9. As it can be seen from the Fig 9, the ODSMC is successful in maintaining the stable operation in the face of applied disturbances. In addition to the disturbances, ODSMC achieves reasonable performance during the changing output voltage reference that indicates a robust performance.

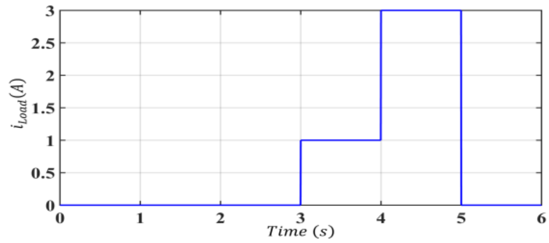

Fig. 7. Load current disturbance

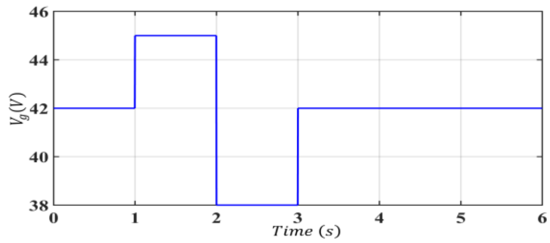

Fig. 8. Input voltage disturbance

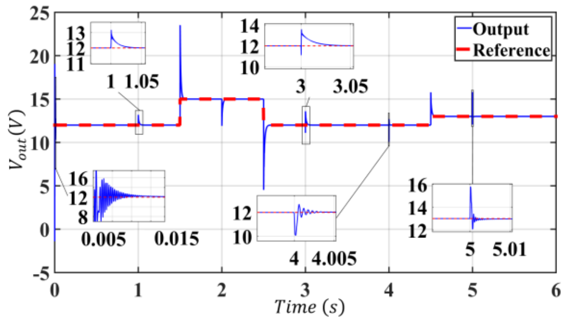

Fig. 9. Comparison of output and reference output voltage

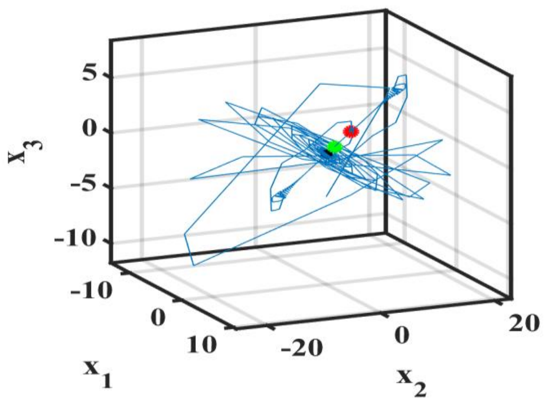

Fig. 10. Evolution of three of the states in state space

To illustrate the sliding mode control action, in Fig 10 three of the four states are drawn in 3 dimension. It is also seen that the control action that is used is discrete from the evolution of the states. At $t = 0, t = 1.5$ and $t = 2.5$ the states converge the corresponding desired point that is highlighted by black, red and green circles respectively.

V. Conclusions and Future Work

In this paper, the small signal state space model of QBC has been derived. An ODSMC is designed and its key parameters have been found after choosing the new pole locations of the augmented system. For the sake of constraining the internal states of the converter, the new poles have been placed in a certain neighborhood of the current poles. The design procedure of the controller and its implementation in the plant in question has been discussed thoroughly. Finally, the results of the numerical simulations that take place in Matlab/Simulink have been given and interpreted. As it can be seen from the previous section, ODSMC is capable of regulating the output voltage in a wide range of operating conditions.

References

[1] S. Yong, J. Zhijian and C. Xu, "Three-level DC-DC converter: Four switches Vsmax=Vin/2, TL voltage waveform before LC filter," 2006 37th IEEE Power Electronics Specialists Conference, Jeju, 2006, pp. 1-4.doi: 10.1109/pesc.2006.1711781Y. Kang and J. K. Hedrick, "Linear Tracking for a Fixed-Wing UAV Using Nonlinear Model Predictive Control," in *IEEE Transactions on Control Systems Technology*, vol. 17, no. 5, pp. 1202-1210, Sept. 2009.

[2] F. L. de Sá, C. V. B. Eiterer, D. Ruiz-Caballero and S. A. Mussa, "Double Quadratic Buck Converter," 2013 Brazilian Power Electronics Conference, Gramado, 2013, pp. 36-43.Y. Shen, "Research on chattering and limit cycle adjusting for output feedback SMC based on frequency domain analysis," *The 26th Chinese Control and Decision Conference (2014 CCDC)*, Changsha, 2014, pp. 2465-2469.

[3] A. P. Hu, "Modeling a contactless power supply using GSSA method," 2009 IEEE International Conference on Industrial Technology, Gippsland, VIC, 2009, pp. 1-6.

[4] P. Ramesh, K. R. Lekshmi and A. Joseph, "Control of DC-DC converter and inverter for stand-alone solar photovoltaic power plant," 2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Mumbai, 2014, pp. 1-6.

[5] A. Argha, L. Li, S. W. Su and H. Nguyen, "Robust output-feedback discrete-time sliding mode control utilizing disturbance observer," 2015 54th IEEE Conference on Decision and Control (CDC), Osaka, 2015, pp. 5671-5676.

[6] A. Argha, L. Li, S. Su and H. Nguyen, "Stabilising the networked control systems involving actuation and measurement consecutive packet losses," in IET Control Theory & Applications, vol. 10, no. 11, pp. 1269-1280, 7 18 2016.

[7] Y. Chen, Z. Zhong and Y. Kang, "Design and Implementation of a Transformerless Single-Stage Single-Switch Double-Buck Converter With Low DC-link Voltage, High Step-Down, and Constant Input Power Factor Features," in IEEE Transactions on Power Electronics, vol. 29, no. 12, pp.

[8] X. Du, L. Zhou and H. M. Tai, "Double-Frequency Buck Converter," in IEEE Transactions on Industrial Electronics, vol. 56, no. 5, pp. 1690-1698, May 2009.

[9] A. Sel, U. Gunes, O. Elbir and C. Kasnakoglu, "Comparative analysis of performance of the SEPIC converter using LQR and PID controllers," 2017 21st International Conference on System Theory, Control and Computing (ICSTCC), Sinaia, 2017, pp. 839-844.

[10] N. Bottrell, M. Prodanović and T. C. Green, "Analysed small signal state-space model of an active rectifier," 45th International Universities Power Engineering Conference UPEC2010, Cardiff, Wales, 2010, pp. 1-6.

[11] G. D. Demetriades and H. P. Nee, "Small-signal analysis of the half-bridge soft-swithing uni-directional converter employing extended state-space averaging," 2008 IEEE Power Electronics Specialists Conference, Rhodes, 2008, pp. 385-391.

[12] J. Mu, X. G. Yan, S. K. Spurgeon and Z. Mao, "Generalized Regular Form Based SMC for Nonlinear Systems With Application to a WMR," in IEEE Transactions on Industrial Electronics, vol. 64, no. 8, pp. 6714-6723, Aug. 2017.

[13] Z. Haoyu, Y. Gang, Z. Lidan, M. Boshan and L. Dongdong, "Sliding mode control based on six-phase PMSM speed control system," IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, 2017, pp. 8819-8824.

[14] A. S. Sagar, P. D. Shendge and S. M. Vaitheeswaran, "Attitude control of fixed wing UAV using Multiple Sliding Surface," 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, 2016, pp. 1-6.

[15] Mohamad Riduwan Md Nawawi, Chong Shin Horng, Mohd Ruzaini Hashim and A. N. Hanaffi, "Development of output feedback Sliding Mode Control for nonlinear system with disturbance," 2011 IEEE International Conference on Control System, Computing and Engineering, Penang, 2011, pp. 495-499.

[16] N. Khalid and A. Y. Memon, "Output feedback stabilization of an Inertia Wheel Pendulum using Sliding Mode Control," 2014 UKACC International Conference on Control (CONTROL), Loughborough, 2014, pp. 157-162.

[17] E. Gatavi, A. R. Husain, A. H. Shirdel and M. N. Ahmad, "On the design of output feedback sliding mode control for a class of uncertain system," 2011 Fourth International Conference on Modeling, Simulation and Applied Optimization, Kuala Lumpur, 2011, pp. 1-4.

[18] N. O. Lai, C. Edwards and S. K. Spurgeon, "On Output Tracking Using Dynamic Output Feedback Discrete-Time Sliding-Mode Controllers," in IEEE Transactions on Automatic Control, vol. 52, no. 10, pp. 1975-1981, Oct. 2007.