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Adaptive Robust Control of DC/AC Converter for Renewable Energy Applications Using Discrete Sliding Mode

U. M. Mate[1], V. N. Pande[2], Shailaja Kurode[3]

[1,2,3]Department of Electrical Engineering, College of Engineering, Pune, Weilsey Road, Shivajinagar, PIN-411005, Maharashtra State, India

Abstract: **This paper proposes an adaptive robust control strategy for voltage source dc/ac converter interfaced with the grid for harnessing renewable energy using discrete sliding mode control (DSMC). In the proposed method, the Euler's first order approximation method is used for obtaining the discrete plant model. This model retains matched uncertainties to matched uncertainties. The proposed approach uses adaptive control to get fast convergence without overshoot. The explicit adaptive nature of the control law ensures lower control energy. The power quality is improved with a smaller total harmonic distortion. The proposed method rejects the system disturbances and uncertainties. Use of stationary reference frame avoids the rotating co-ordinate transformation and the angular information of grid voltage or virtual flux is not required. Extra current loops are not needed which leads to simple design. Further, the performance of the proposed algorithm is compared with the conventional look up table (LUT), DPC method and the superiority of the proposed controller is exhibited.**

Keywords: **Discrete sliding mode control, direct real and reactive power regulation, dc to ac converters, renewable energy applications.**

1. INTRODUCTION

Due to increasing penetration of renewable energy systems [1] like wind, solar photovoltaic, fuel cells etc. there has been significant rise in the application of the three phase dc/ac voltage source converter interfaced with the grid. Traditionally the control of three phase dc/ac converter connected to the grid is based on vector control methods [2]. The performance of vector controlled scheme largely depends on the accuracy of current decoupling, the design of the current controllers and the tuning of PI parameters. Direct Torque Control (DTC) scheme for electrical machines was developed [3] as an alternative to the classic vector control method. Based on the principles of DTC, an alternative control approach, namely direct power control (DPC) was developed for the grid connected VSC with look up table technique (LUT-DPC)[4],[5],[6]. The appropriate switching signals are selected from a predefined look up table by a switching rule based on the instantaneous errors in the active and reactive powers and the angular position of the converter terminal voltage [4] or the virtual flux vector estimated based on the dc link voltage and converter switching states,[5] or obtained from the integration of converter terminal voltage measured with voltage transducers [6]. The main drawback of LUT-DPC is the variable switching frequency which give rise to dispersed harmonic spectrum of the line currents. This makes the design of the line filters quiet difficult. Thus, a DPC approach with PWM resulting in constant switching frequency was proposed in [7], [8]. The methods necessitate complicated online calculations and are not robust to system parameter variations [9]. Robustness is an important issue. Sliding mode control has been reported in the literature as a robust control strategy. It has been proven as a robust control method for non linear uncertain system. Moreover, it is simple to implement [10]. But it is accomplished with the undesirable phenomenon of chattering which limits its practicability [11]. Discontinuity in the control causes chattering which leads to wear and tear of the actuators [12],[11]. This drawback is rectified by introducing the idea of existence of quasi-sliding mode for discrete time systems [13]. Also, most control systems exploit a digital computer and computer controlled systems are now prevalent in engineering practice. The discrete sliding mode approach is for three phase inverter connected to the grid is proposed in [14]. The author used model that are obtained using discretization method. This may result in converting matched uncertain system to unmatched one. Unmatched uncertainty further affects the performance of the system.

In the proposed method, we use the Euler's first order approximation model. This model retains the matched uncertainties to matched uncertainties. It results in a desirable performance. The proposed approach uses adaptive control to get fast convergence without overshoot. The explicit adaptive nature of the control law ensures lower control energy. The power quality is improved with a smaller total harmonic distortion, improving the transient response. At the same time, it rejects the system disturbances.

The outline of the paper is as follows. The principles of the direct power control strategy for grid connected ac/dc converter are illustrated in Section 2 of the paper. Section 3 envisages the design of the proposed discrete sliding mode controller. Section 4 discusses the performance based on results of the proposed DSMC based DPC algorithm in comparison with the conventional LUT-DPC. Section 5 narrates the conclusions.

2. PRINCIPLES OF DIRECT POWER CONTROL STRATEGY FOR DC/AC CONVERTERS CONNECTED TO THE GRID

The three phase inverter is used to feed the power from renewable energy source to the grid. It is assumed that the input DC voltage derived from the renewable energy applications is maintained constant. To simplify the calculations, the three phase quantities of the converter are transformed to α-β quantities. The principles of DPC for grid-connected dc/ac converter in stationary reference frame are described in [10]. Figure 1 shows the simplified equivalent circuit of the grid connected dc to ac converter in the stationary reference frame. In Figure 1, $U_{g\alpha\beta}$ represents grid voltage vector in stationary reference frame, $V_{g\alpha\beta}$ is converter voltage vector in stationary reference frame, $I_{g\alpha\beta}$ represents converter current vector in stationary reference frame, L_g is line inductance, R_g is line resistance. As seen from Figure 1, the relationship between the supply voltage, converter voltage, and line current is given by

$$U_{g\alpha\beta} = R_g I_{g\alpha\beta} + L_g \frac{dI_{g\alpha\beta}}{dt} + V_{g\alpha\beta} \quad (1)$$

The instantaneous real and reactive power from the converter to the grid can be found from the standard formula as

$$P_g + jQ_g = -1.5 U_{g\alpha\beta} \hat{I}_{g\alpha\beta} \quad (2)$$

Where Pg and Qg are output real and reactive powers respectively. Simplifying, we get

$$P_g = -1.5\left(u_{g\alpha} i_{g\alpha} + u_{g\beta} i_{g\beta}\right) \quad (3)$$

$$Q_g = -1.5\left(u_{g\beta} i_{g\alpha} - u_{g\alpha} i_{g\beta}\right) \quad (4)$$

Where $u_{g\alpha}$ and $u_{g\beta}$ are instantaneous grid voltages and $i_{g\alpha}$ and $i_{g\beta}$ are instantaneous grid currents in stationary reference frame.

Substituting values from equation (1) to equation (4), we get

$$\frac{dP_g}{dt} = -\frac{3}{2L_g}\left[\left(u_{g\alpha}^2 + u_{g\beta}^2\right) - \left(u_{g\alpha} v_{g\alpha} + u_{g\beta} v_{g\beta}\right)\right] - \frac{R_g}{L_g} P_g - \omega_1 Q_g \quad (5)$$

$$\frac{dQ_g}{dt} = -\frac{3}{2L_g}\left[-\left(u_{g\beta} v_{g\alpha} - u_{g\alpha} v_{g\beta}\right)\right] - \frac{R_g}{L_g} Q_g - \omega_1 P_g \quad (6)$$

Equations (5) and (6) represent the dynamic plant model. The objective is to device the discrete sliding mode control for the system using the dynamic plant model, which is exhibited in the next section.

3. DESIGN OF PROPOSED DISCRETE SLIDING MODE CONTROL BASED DPC SCHEME

The design of the proposed algorithm equipped with adaptive reaching law is illustrated in the following subsections.

3.1 Discrete representation of the system model:

The plant model must be necessarily represented in discrete form to devise a discrete control.

Consider τ as sample time. The dynamic system model of equations (5, 6) is expressed utilizing Euler's first order approximation as

$$\frac{dP_g}{dt} = \frac{P_g(k+1) - P_g(k)}{\tau} \qquad (7)$$

and $\frac{dQ_g}{dt} = \frac{Q_g(k+1) - Q_g(k)}{\tau}$ (8)

Where k is sampling instant. The equations (7) and (8) are combined in a matrix form as below

$$\begin{bmatrix} \frac{P_g(k+1) - P_g(k)}{\tau} \\ \frac{Q_g(k+1) - Q_g(k)}{\tau} \end{bmatrix} = -\frac{3}{2L_g}\begin{bmatrix} u_{g\alpha}^2(k) + u_{g\beta}^2(k) \\ 0 \end{bmatrix} + \frac{3}{2L_m}\begin{bmatrix} u_{g\alpha}(k) & u_{g\beta}(k) \\ u_{g\beta}(k) & -u_{g\alpha}(k) \end{bmatrix}\begin{bmatrix} v_{g\alpha}(k) \\ v_{g\beta}(k) \end{bmatrix}$$

$$+\begin{bmatrix} -\frac{R_g}{L_g} & -\omega_1 \\ \omega_1 & -\frac{R_g}{L_g} \end{bmatrix}\begin{bmatrix} P_g(k) \\ Q_g(k) \end{bmatrix} \quad (9)$$

Simplifying the above equation, we get

$$\begin{bmatrix} P_g(k+1) \\ Q_g(k+1) \end{bmatrix} = -\frac{3\tau}{2L_g}\begin{bmatrix} u_{g\alpha}^2(k) + u_{g\beta}^2(k) \\ 0 \end{bmatrix} + \frac{3\tau}{2L_m}\begin{bmatrix} u_{g\alpha}(k) & u_{g\beta}(k) \\ u_{g\beta}(k) & -u_{g\alpha}(k) \end{bmatrix}\begin{bmatrix} v_{g\alpha}(k) \\ v_{g\beta}(k) \end{bmatrix}$$

$$+\begin{bmatrix} -\frac{R_g}{L_g}\tau + 1 & -\omega_1\tau \\ \omega_1\tau & -\frac{R_g}{L_g}\tau + 1 \end{bmatrix}\begin{bmatrix} P_g(k) \\ Q_g(k) \end{bmatrix}$$

$$= L_\tau + M\tau v_{g\alpha\beta}(k) + [N\tau + 1]\begin{bmatrix} P_g(k) \\ Q_g(k) \end{bmatrix} \qquad (10)$$

Where

$$L = -\frac{3}{2L_g}\begin{bmatrix} u_{g\alpha}^2(k) + u_{g\beta}^2(k) \\ 0 \end{bmatrix} \qquad (11)$$

$$M = \frac{3}{2L_m}\begin{bmatrix} u_{g\alpha}(k) & u_{g\beta}(k) \\ u_{g\beta}(k) & -u_{g\alpha}(k) \end{bmatrix} \qquad (12)$$

$$N = \begin{bmatrix} -\frac{R_g}{L_g} & -\omega_1 \\ \omega_1 & -\frac{R_g}{L_g} \end{bmatrix} \qquad (13)$$

Equation (10) represents the system dynamic equations in discrete form. Here $P_g(k)$, $Q_g(k)$, $P_g(k+1)$, $Q_g(k+1)$ are the states of the system. $v_{g\alpha}$ and $v_{g\beta}$ are the control inputs.

3.2 Development of the controller:

Sliding surface s is described as $s \in {}^{m\times n}$ where m is number of inputs and n number of states. Since we have two control inputs $v_{g\alpha}$ and $v_{g\beta}$, we select two sliding surfaces as shown below.

$$s_1(k) = P_g^*(k) - P_g(k) = e_p(k) \qquad (14)$$

$$s_2(k) = Q_g^*(k) - Q_g(k) = e_q(k) \qquad (15)$$

Where $P_g{}^*(k)$ is the active power reference and $Q_g{}^*(k)$ is the reactive power reference.

$P(k)$ and $Q_g(k)$ are the active and reactive power outputs at k^{th} sampling instant respectively. At $(k+1)^{th}$ sampling instant,

$$s_1(k+1) = e_p(k+1) = P_g^*(k+1) - P_g(k+1) \qquad (16)$$

$$s_2(k+1) = e_q(k+1) = Q_g^*(k+1) - Q_g(k+1) \qquad (17)$$

Since the reference real and reactive powers are constant, $P_g^*(k) = P_g^*(k+1)$ and,

$Q_g^*(k) = Q_g^*(k+1)$. To get DSMC based controller the values of $P_g\ (k+1)$ and $Q_g\ (k+1)$ from equation 10 are substituted in the equation of sliding surfaces $s_1(k+1)$ and $s_2(k+1)$.

$$\begin{bmatrix} s_1(k+1) \\ s_2(k+1) \end{bmatrix} = \begin{bmatrix} P_g^*(k+1) \\ Q_g^*(k+1) \end{bmatrix} - L\tau - M\tau v_{g\alpha\beta}(k) - [N\tau + 1] \begin{bmatrix} P_g(k) \\ Q_g(k) \end{bmatrix} \quad (18)$$

The discrete model of the system in terms of the sliding surfaces is expressed by Equation (18). The adaptive reaching law [15] is given by the following expression:

$$s_1(k+1) = {k_1}^1 s_1(k) \quad (19)$$

Where $${k_1}^1 = \left(\beta_1 \exp\left(\frac{-1}{|s_1(k)|}\right) + \beta_2\right) \quad (20)$$

where β_1 and β_2 are constants and they are governed by the following rules as given below. $\beta_1 > 0$, $\beta_2 > 0$ and $(\beta_1 + \beta_2) <1$ and also, $\beta_2 < \beta_1$ Similarly, for the second sliding surface, the adaptive reaching law is

$$s_2(k+1) = {k_2}^1 s_2(k) \quad (21)$$

Where $${k_2}^1 = \left(\beta_3 \exp\left(\frac{-1}{|s_2(k)|}\right) + \beta_4\right) \quad (22)$$

β_3 and β_4 follow the similar rules as for β_1 and β_2 By substituting equation (19),(20) and (21),(22) into equation (18) and simplifying we get the control law as given below.

$$v_{g\alpha\beta}(k) = M^{-1} \left\{ \frac{1}{\tau} \begin{bmatrix} P_g^* - {k_1}^1 s_1(k) \\ Q_g^* - {k_2}^1 s_2(k) \end{bmatrix} - L - \frac{1}{\tau}[N\tau + 1] \begin{bmatrix} P_g(k) \\ Q_g(k) \end{bmatrix} \right\} \quad (23)$$

Equation (23) represents the necessary control. Figure 3 shows the schematic diagram of the DSMC based DPC for grid connected dc/ac converter Remark: In the context of DSMC, it is ensured that the trajectories should be on the surface. The closed loop dynamics during sliding is decided by the dynamics of the surfaces. It is therefore essential to have the stable surfaces. If the control ensures sliding on the stable surface, it implies closed loop stability. The sliding surface s1 and s2 are chosen as s1(k) = Pg∗(k)−Pg(k)=0 and s2(k)=Qg∗(k)-Qg(k)=0, which are stable by design. The control based on the adaptive reaching law is ensuring the trajectories to be on the surface at every sampling instant. This implies that the system as a whole is closed loop stable.

4. RESULTS AND DISCUSSIONS

Extensive simulation studies are carried out for checking the system performance of the proposed DMC based DPC algorithm using Matlab Simulink. Figures demonstrate the simulation results for the system with the proposed controller. The electrical parameters of the dc/ac converter system are as given below.

Rated power 40 kVA, line to line rms voltage 400 V, line inductance 4 mH, converter dc link voltage 700 V, ac supply frequency 50 Hz, SPWM switching frequency 6 kHz. The control parameters of the DSMC strategy are selected as $\beta_1 = 0.84$, $\beta_2 = 0.1$, $\beta_3 = 0.6$ and $\beta_4 = 0.1$

Transient response:

To analyze transient performance of the DSMC based DPC, detailed simulation study is carried out. The power reference is chosen as +30 KW (transport of active power from the converter to the network) and +10 KVAR (capacitive) respectively. Figure 3 displays the transient responses for the proposed DSMC based DPC approach.

As seen from Figure 3, the active and reactive power references are followed very smoothly and the line current waveform is also very much sinusoidal with very less distortions. The peak overshoot in the active power is 3.2 percent and the rise time is 1 ms only with the proposed method. The smaller rise time along with the lesser percentage overshoot is achieved on account of the adaptive reaching law utilized in the proposed DSMC based DPC scheme.

The coefficient of s(k) in the adaptive reaching law of equation determines how fast the convergence takes place. The convergence rate is kept small initially when s(k) (i.e. the error) is high. Subsequently When the s(k) decreases, the coefficient of s(k) is kept increasing. This philosophy of variation in the convergence (leading to small rise times) occurs simultaneously.

Steady state response:

To study steady state behavior of the proposed DSMC based DPC controller simulations are per- formed with step changes in active power reference value for the proposed DSMC based DPC method. Figure 4 displays the system for LUT DPC and DSMC based DPC where active power reference is step changed from 10 kw to 20 kw (transfer of active power from converter to the network) at 0.1 s and then to 30 kw at 0.2 s. The reactive power was maintained at a constant value of 10 KVAR (capacitive). Figure 4 depicts the system behavior with the proposed DSMC based DPC. It is clearly revealed from figure 4 that the stepped active and reactive power reference commands are tracked very smoothly. Figure 5 shows harmonic spectrum of the grid currents for the proposed DSMC based DPC algorithm. Figure 5 shows that the total harmonic distortion with the proposed DSMC based DPC approach is 0.70 percent only.

Robustness analysis:

Behavior with the disturbance:

To test the robustness of the controller, the behavior with disturbances is required to be analyzed. Grid voltage sag is one of such disturbances. The simulation results with grid voltage sag of fifteen percent are displayed in Figure 6. The active power reference is changed from 10 kw to 20 kw at 0.1 s and then to 30 kw at 0.2 s and again to 40 kw (transfer of real power from converter to the network) at 0.3 s. The reactive power reference is stepped from 0 to -10 kVAR (inductive) at 0.05 s and then further from -10 kVAR (inductive) to 10 kVAR (capacitive) at 0.15 s and then from +10 kVAR (capacitive) to +5 kVAR (capacitive) at 0.25 s. Figure 6 clearly indicates that the active and reactive powers track their reference commands satisfactorily inspire of the existence of grid voltage sag. Similar results are obtained in case of grid voltage unbalance also, when voltage in one of the three phases of the network is reduced by 10 percent.

Behavior with parametric errors:

To check the performance of the controller in presence of the line inductance error, simulation studies are carried out. The simulations are performed for the following conditions:

(i) With reduction in line inductance Lg by 25 percent

(ii) With increase in value Lg to 150 percent of its original value and

(iii) With no error in the line inductance.

It is revealed from the simulation results displayed in Figure 7. That the results with no parameter error, with 25 percent error and with +50 percent error are in close agreement with each other. Similar results are obtained for the real power also. These are not displayed here due to space limitations. Therefore, the proposed controller exhibits excellent robust performance.

5. CONCLUSION

Adaptive robust control of dc/ac converters for renewable energy applications using discrete sliding mode has been investigated in this paper. Extra current loops are eliminated and tuning of PI controller parameters in vector control methods is not required. The intrinsic adaptive nature of the control law demands less initial control efforts inspite of large initial error and subsequently when the error reduces, control efforts gradually increase without shooting at any instant of time. This has resulted into fast transient response with no overshoot as compared to the conventional method.

Thus the results with the proposed DSMC based DPC algorithm are very much encouraging.

REFERENCES

[1] J. Hu, Y. He, L. Xu, B. W. Williams, Improved control of dfig systems during network unbalance using pi-r current regulators, IEEE Trans. Ind. Electron. 56 (2) (2009) 439–451.

[2] V. Pedro, G. D. Marques, Dc voltage control and stability analysis of pwm-voltage-type re- versible rectifier, IEEE Trans. Ind. Electron. 45 (2) (1998) 263–273.

[3] Takahashi, T. Noguchi, A new quick-response and high-efficiency control strategy of an in- duction motor, IEEE Trans. Ind. Appl. IA-22 (5) (1986) 820–827.

[4] T. Noguchi, H. Tomiki, S. Kondo, , I. Takahashi, Direct power control of pwm converter without power-source

voltage sensors, IEEE Trans. Ind. Appl. 34 (3) (1998) 473–479.

[5] M. Malinowski, M. P. Kazmierkowski, S. Hansen, F. Blaabjerg, G. D. Marques, Virtual-flux- based direct power control of three-phasepwm rectifiers, IEEE Trans. Ind. Appl. 37 (4) (2001) 1019–1027.

[6] D. Zhi, L. Xu, B. W. Williams, Improved direct power control of grid-connected dc/ac convert- ers, IEEE Trans. Power Electron. 24 (5) (2009) 1280–1292.

[7] M. Malinowski, M. Jasinski, M. Kazmierkowski, Simple direct power control of three- phasepwmrectifier using space-vectormodulation (dpc-svm), IEEE Trans. Ind. Electron. 51 (4) (2004) 447–454.

[8] G. Abad, M. A. Rodriguez, J. Poza, Two-level vsc-based predictive torque control of doubly fed induction machine with reduced torque and flux ripples at low constant switching frequency, IEEE Trans. Power. Electron 23 (3) (2008) 1050–1061.

[9] P. Antoniewicz, M. P. Kazmierkowski, Virtual-flux-based predictive direct power control of ac/dc converters with online inductance estimation, IEEE Trans. Ind. Electron 55 (12) (2008) 4381–4390.

[10] J. Hu, L. Shang, Y. He, Z. Q. Zhu, Direct active and reactive power regulation of grid-connected dc/ac converters using sliding mode control approach, IEEE Trans. on Power Electron. 26 (1) (2011) 210–222.

[11] V. Utkin, H. Lee, Chattering problem in sliding mode control systems, Proceedings of the 2006 International Workshop on Variable Structure Systems Alghero, Italy.

[12] C. Edwards, S. Spurgeon, Sliding mode control:theory and applications, london:Taylor and francis.

[13] C. Miloslavjevic, General conditions for the existence of a quasi-sliding mode on the switch- ing hyperplane in discrete variable structure systems, Automaion and Remote Control, 1985 46 (679684).

[14] S. Huseinbegovic, B. Perunicic-Draenovic, N. Hadimejlic, Discrete-time sliding mode direct power control for grid connected inverter with comparative study, IEEE 23rd International Symposium on Industrial Electronics (ISIE) (2014) 582–590.

[15] S. Kurode, B. Bandopadhyay, P. Gandhi, Output feedback control for slosh free motion: A sliding mode approach, Lambert Academic Publishing.

APPENDIX – A

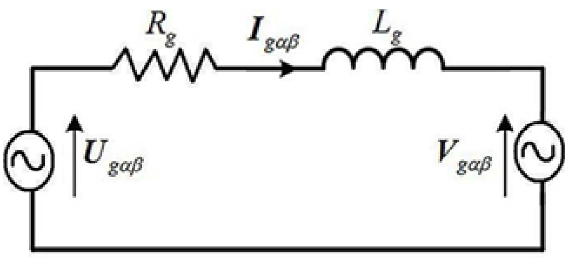

Figure 1: Equivalent circuit of the grid-connected dc/ac converter in stationary reference frame

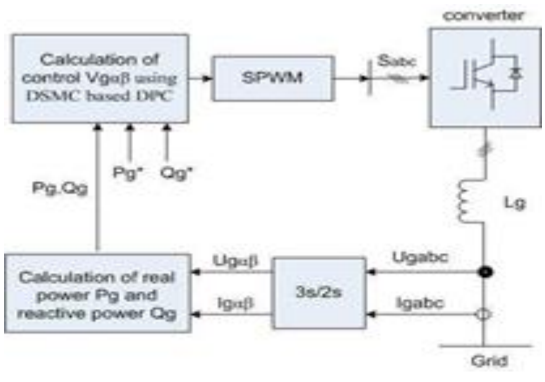

Figure 2: Schematic diagram of DSMC-DPC for a grid-connected dc/ac converter

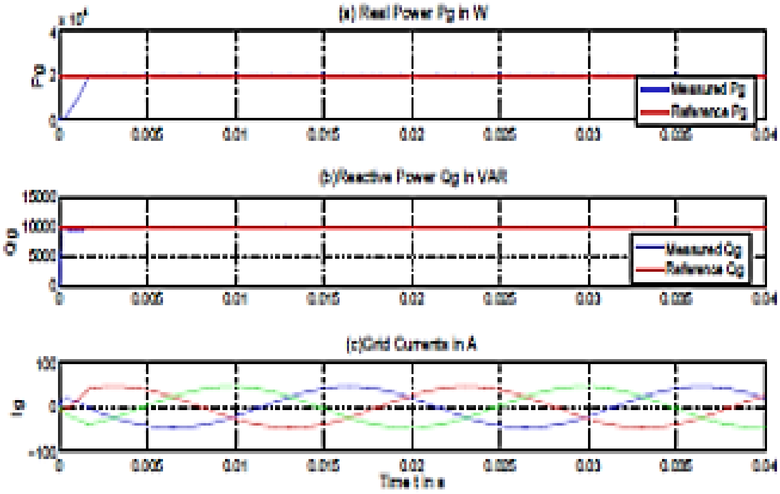

Figure 3: Transient response for step change in real power reference (a) Real Power (W), (b) Reactive Power (Var) and (c) Three phase line currents (A) with the proposed DSMC based DPC

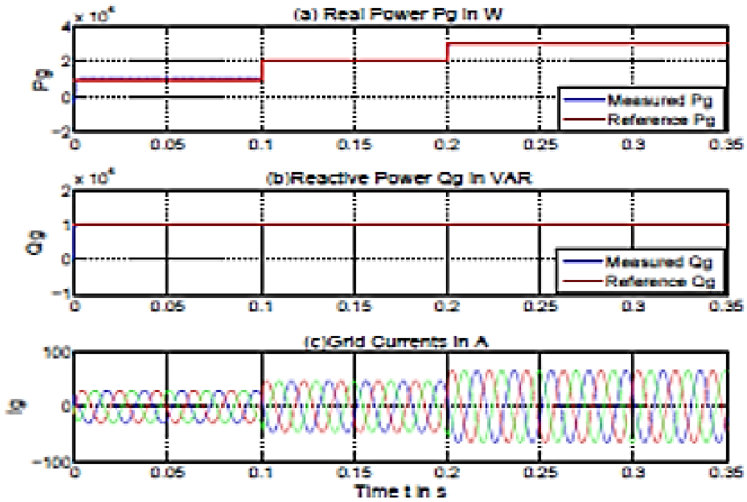

Figure 4: Simulation results with step change in real power reference (a) Real Power (W), (b) Reactive Power (Var) and (c) Three phase line currents (A) with the proposed DSMC based DPC

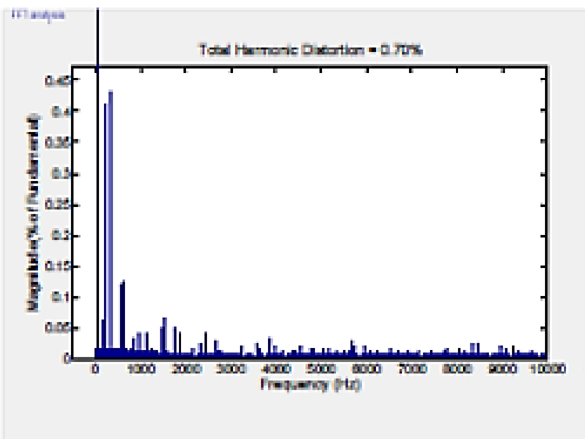

Figure 5: Grid current harmonics with the proposed DSMC based DPC

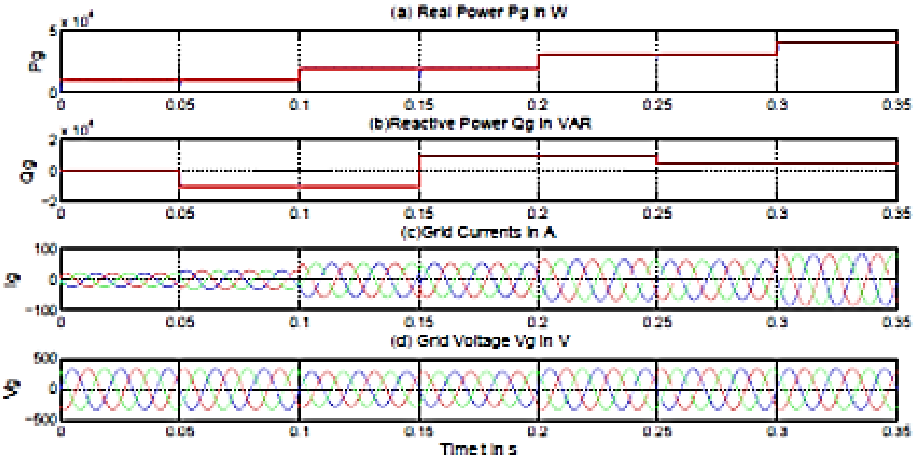

Figure 6: Simulation results with minus fifteen percent disturbance added in the grid voltage from 0.1 seconds to 0.2 seconds associated with step changes in real and reactive power references (a) Real Power (W), (b) Reactive Power (Var) and (c) Three phase line currents (A) with the proposed DSMC based DPC with the proposed DSMC based DPC

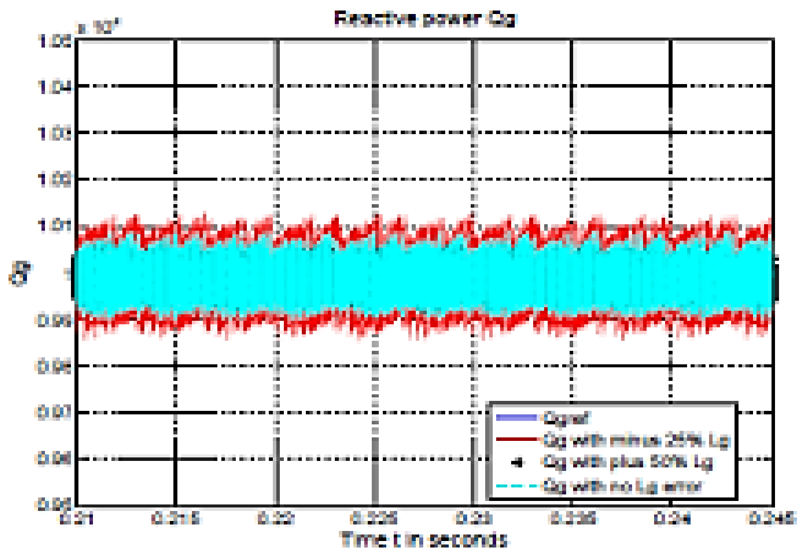

Figure 7: Simulation results with line inductance errors for reactive power(W) with the proposed DSMC based DPC