Power Quality Assessment of Table Based Direct Power Control for Active Front-end Rectifiers

Amit Kumar
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
contact.amit.ele@gmail.com

Gopalakrishna Srungavarapu
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
gopal@nitrkl.ac.in

Abstract— **The objective of this study is to investigate the various switching tables for performance enhancement of three-phase Pulse Width Modulated (PWM) rectifiers controlled by Direct Power Control (DPC). This study includes different lookup tables such as fast, slow regenerative fast and regenerative slow along with Noguchi's conventional lookup table. DPC has portrayed the benefits of simplicity, faster response, elimination of current controllers, and better sensitivity to variations in system parameters and load changes. The lookup table is the heart of this control technique. Hence, it is extremely vital to do in-depth investigation and analysis of switching tables to ensure optimal performance of DPC. With a view of this many pieces of research have been carried out but nowhere power quality of various lookup tables were analyzed at a single place, and optimal table concern with the power quality is justified. In our work, we have considered various lookup tables collectively from literature and their power quality analysis has been done for performance study of three phase PWM rectifiers controlled by DPC using MATLAB Simulink.**

Keywords— *Direct power control; pulse width modulation; switching table; total harmonic distortion; direct torque control*

I. INTRODUCTION

The utilization area of three-phase PWM rectifiers are expanding rapidly, thereby has not restricted to industries rather helping in various applications also [1-3]. These fields are renewable energy systems, active power filters, motor drives requiring regeneration operation, voltage source converter transmission, smart grid, micro-grid, power condition and transmission equipment [1, 4]. PWM rectifiers have numerous advantages over passive diode rectifiers such as bidirectional power flow, lesser Total Harmonic Distortion (THD) in the line current, nearly unity power factor and better regulation of dc link voltage with downsized capacitor [5, 6]. Nowadays, with the rapid utilization of PWM rectifier, its control becomes very crucial. In this respect, various control techniques have been proposed for better control and to enhance the performance of PWM rectifiers. Hence, they can be categorized into different groups based on the application of current loop controllers or power controllers and their principles [1, 6]. Voltage Oriented Control (VOC), a classical control method of PWM rectifier which takes into account the orientation of current vector with reference to the line voltage vector [6]. Erstwhile, the current control loops ensure the dynamic and static performance of VOC and decoupled control are achieved through current controllers [6, 7]. Hence, its

performance highly depends on the inner current control and fine tuning of PI controller. To control the PWM rectifiers, DPC is a useful alternative [8]. During, 1998, Toshihiko Noguchi et. al. introduced DPC for grid connected three-phase PWM rectifier [9]. Their advantages include simplicity, faster response, elimination of current controllers, and better sensitivity to variations in system parameters [9-11]. The performance of DPC is better under transient conditions because of the absence of inherent current controllers and PWM modulator. It is based on the instantaneous power theory [12, 13], and analogous to Direct Torque Control (DTC) of AC drives. In DPC, active and reactive powers are controlled directly by using a bang-bang controller. The switching states of the PWM rectifier are decided on the basis of this predefined lookup table [14, 15]. The errors between the reference active & reactive powers to its feedback value followed by hysteresis controllers and voltage vector position are the inputs to the switching table [16-18]. Therefore, we posit lookup table as the heart of this control technique. Our study considers, power quality analysis of various lookup tables of DPC, optimality of the lookup table for enhanced power quality performance and this is justified using MATLAB Simulink results. Lookup tables have divided into two groups based on the divisions of the voltage vector space. There are six sector based lookup tables & twelve sector based lookup tables, out of which only twelve sector based tables are considered in our analysis for direct power control of PWM rectifiers. This is because twelve sector based tables have better resolution as compared to six sector based tables and hence the better performance. DPC algorithm with conventional switching table (Noguchi's table) has a significant impact on the research community [15-20]. Therefore, it is considered as a benchmark for new DPC algorithms. We also consider the conventional lookup table to support the performance comparison. The performance of each switching table is compared with conventional twelve division based DPC. Fast, slow, regenerative slow and regenerative fast lookup tables [19, 20] with twelve sectors based DPC are analyzed, and their performance is compared with power quality point of view. [21]. This provides the clear insights of the lookup table performance for DPC of three phase PWM rectifiers concern with the power quality in a better way. In section II, the mathematical background for direct power control of PWM rectifier is demonstrated. In section III, simulation results are presented and discussed in details concerning the objective of this work. Finally, in section IV, some important remarks are presented briefly.

II. PRINCIPLE OF DIRECT POWER CONTROL OF PWM RECTIFIER

A. Mathematical modeling of voltage source rectifier

The schematic diagram of PWM rectifier is shown in Fig.1 where, three phase source voltages e_a, e_b and e_c, line inductances L and line resistors R are connected with the voltage source rectifier. i_a, i_b, i_c and v_a, v_b, v_c are the input currents and input voltages of the voltage source rectifier respectively. ω is the three phase source frequency and R_L is the load resistance. The mathematical equation for the PWM rectifier in matrix form can be represented by equation (1) as given below,
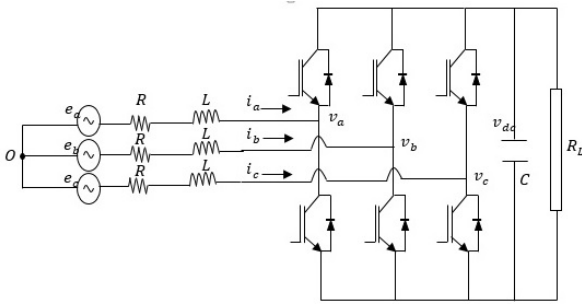

Fig. 1. Schematic diagram of three-phase PWM rectifier

$$[e_{abc}] = R[i_{abc}] + Lp[i_{abc}] + [v_{abc}] \tag{1}$$

$$[f_{abc}]^T = [f_a \quad f_b \quad f_c]$$

where, [f may be voltage or current]

$$\text{Let,} \quad [A] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

The equation (1) can be transformed into stationary reference frame by following expression (2) as described below,

$$f_{\alpha\beta} = [A]f_{abc} \tag{2}$$

Multiply equation (1) $[A]$ by,

$$[A][e_{abc}] = R[A][i_{abc}] + L[A]p[i_{abc}] + [A][v_{abc}] \tag{3}$$

Equation (3) is simplified by substituting equation (2) as

$$[e_{\alpha\beta}] = R[i_{\alpha\beta}] + Lp[i_{\alpha\beta}] + [v_{\alpha\beta}] \tag{4}$$

The instantaneous active and reactive power in stationary reference frame can be written as equation (5) and (6),

$$P = e_\alpha i_\alpha + e_\beta i_\beta \tag{5}$$

$$q = e_\beta i_\alpha - e_\alpha i_\beta \tag{6}$$

Equation (5) and (6) can be written in matrix form as given below,

$$[Pq] = [B][i_{\alpha\beta}] \tag{7}$$

where, $[Pq]^T = [P \quad q]$ and $[B] = \begin{bmatrix} e_\alpha & e_\beta \\ e_\beta & -e_\alpha \end{bmatrix}$

Further, the line voltage vector can be simplified as below,

$$e = e_\alpha + je_\beta = e\cos(\omega t + \phi) + ie\sin(\omega t + \phi)$$

$$\frac{de}{dt} = -\omega e_\beta + j\omega e_\alpha \tag{8}$$

From equation (4)-(7),

$$[e_{\alpha\beta}] - [v_{\alpha\beta}] = [R + Lp]i_{\alpha\beta} = [R + Lp][B]^{-1}[Pq]$$

$$= R[B]^{-1}[Pq] + L[[pB^{-1}][Pq] + B^{-1}[p[Pq]]] \tag{9}$$

Again, by simplifying the equation (9) considering equation (7), we will get

$$L \begin{bmatrix} \dfrac{dP}{dt} \\ \dfrac{dq}{dt} \end{bmatrix} = \begin{bmatrix} K - v_\alpha e_\alpha - e_\beta v_\beta \\ -v_\alpha e_\beta + e_\alpha v_\beta \end{bmatrix} - R \begin{bmatrix} P \\ q \end{bmatrix} - L\omega \begin{bmatrix} q \\ -P \end{bmatrix} \tag{10}$$

$$\text{where, } K = e_\alpha^2 + e_\beta^2$$

Equation (10) describes the rate of change of instantaneous active and reactive powers for three phase voltage source rectifier. From the equation (10), it is also clear that the rate of power variations are dependent on source voltages, current, power value, and system parameters

B. Direct power control of voltage source rectifier

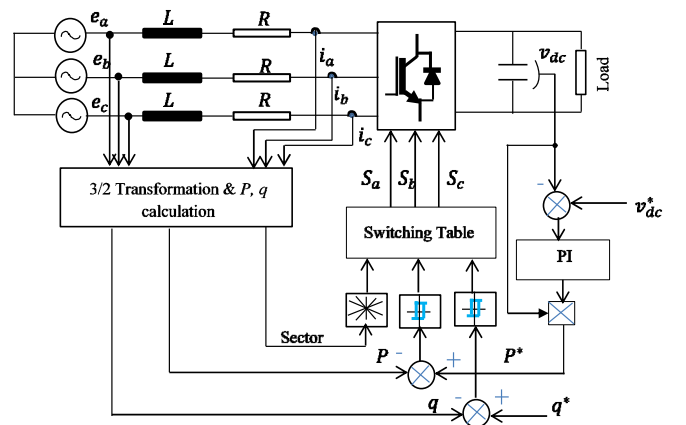The schematic diagram for the control of voltage source rectifier is shown in Fig.2.

Fig. 2. Schematic diagram of DPC of voltage source rectifier.

In this control scheme the dc link voltage is controlled through PI controller, it takes the error in dc link voltage from its reference to generate the reference current. Further, generated reference current is multiplied by the dc link voltage to generate reference active power (P^*). The reference reactive power (q^*) is kept to zero, to ensure unity power factor operation. The instantaneous active and reactive powers are calculated by the sensed three phase voltages and currents. These calculated powers are compared with their respective power references and given to the hysteresis controller followed by switching table to generate the control signals for voltage source rectifier.

III. SIMULATION RESULTS AND DISCUSSIONS

All the investigated switching tables are taken from [9, 14, 16, 19] and parameters considered for simulation is given in Table1 of Appendix-A. The performance of switching table highly depends on the sampling frequency. Therefore, the complete analysis is carried out with different sampling frequency along with various switching tables such as Noguchi's table, fast table, and slow table, regenerative slow table and regenerative fast table. Since all the simulation results are of similar type, so only a few results are presented, and their performance has been compared on bar charts for various power quality parameters.
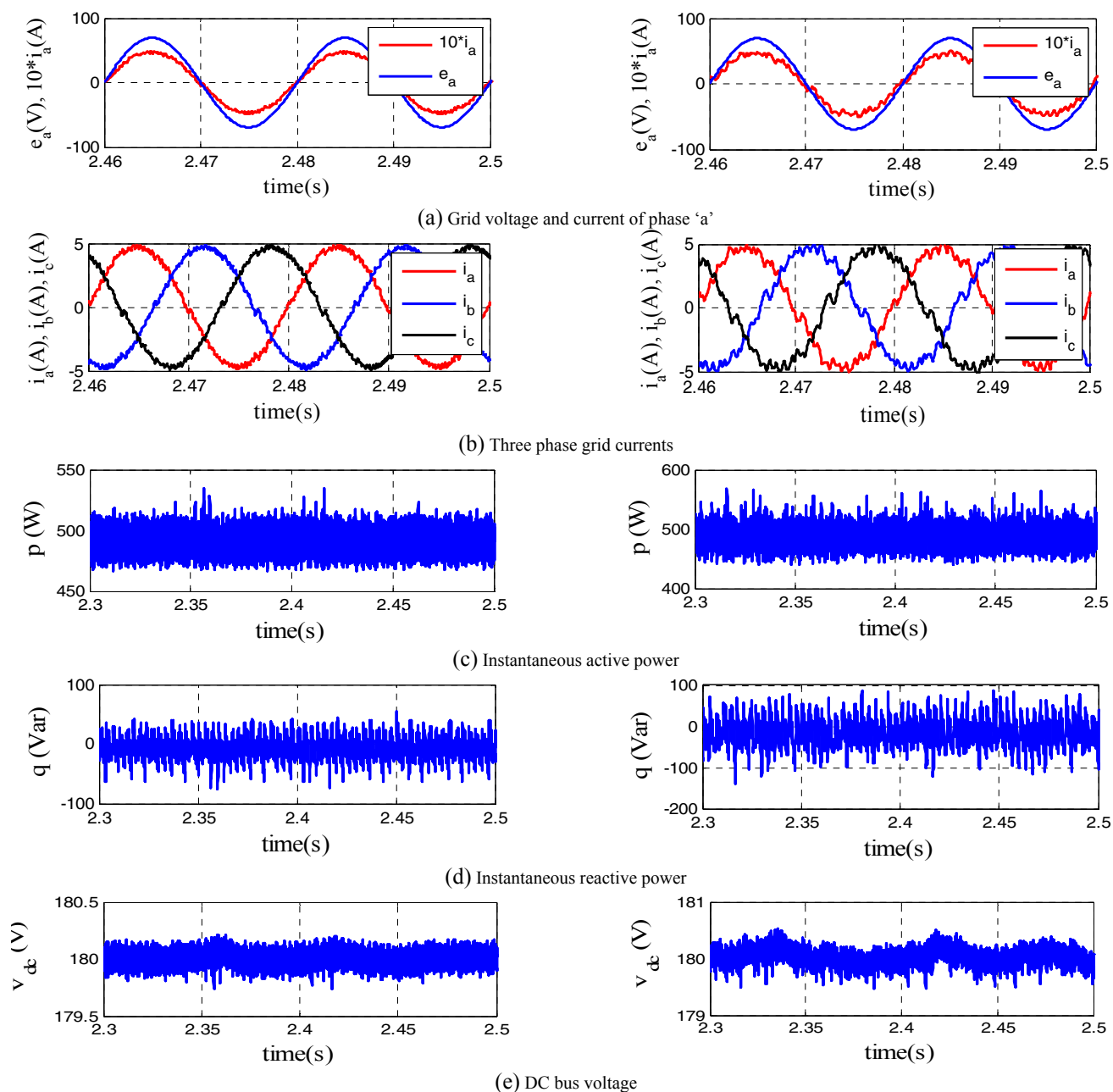

(a) Grid voltage and current of phase 'a'

(b) Three phase grid currents

(c) Instantaneous active power

(d) Instantaneous reactive power

(e) DC bus voltage

Fig. 3. All the above results are analyzed at $T_s = 33.33\mu s$ and $T_s = 65\mu s$ respectively for Noguchi's table

(a) Grid voltage and current of phase 'a'

(b) Three phase grid currents

(c) Instantaneous active power

(d) Instantaneous reactive power
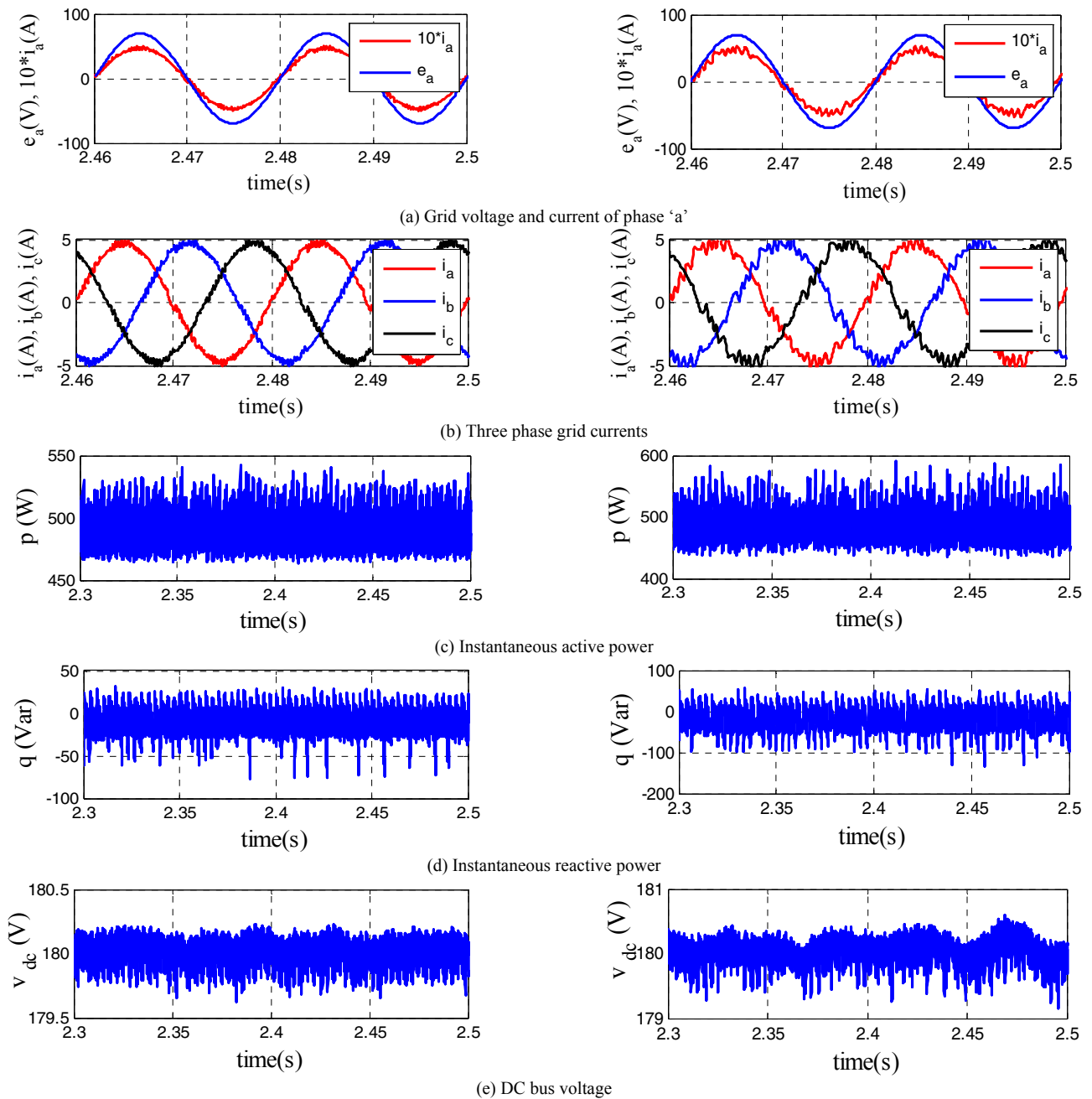

(e) DC bus voltage

Fig. 4. All the above results are analyzed at $T_s = 33.33\mu s$ and $T_s = 65\mu s$ respectively for slow switching table

Fig4. Show the similar analysis as Fig3. But the switching table is replaced by slow switching table. All other table results are skipped here because their power quality performance is poor as compared to this two lookup (Slow and Noguchi's) tables. But power quality performance bar characteristic is presented for each table with different sampling frequencies. Fig5 and Fig.6 shows the active and reactive power ripple for various switching tables at different sampling frequency. Fig7 and Fig.8 represents the dc bus voltage ripple and total harmonic distortion respectively. At last Fig.9 is shown, which depicts the average switching frequency for various tables at different sampling frequencies. From the simulation results it is found that the Noguchi's table has least active power ripple (3.7853W) and dc bus voltage ripple (0.0256V) as compared to all other switching tables at $T_s = 10\mu s$ and at all other sampling periods. But slow switching table has least THD (1.47%) and reactive power ripple (5.8146 Var) as compared to all other tables at $T_s = 10\mu s$ and at all other sampling periods. This can also be observed from bar charts. Hence it is advisable to use Noguchi's table or slow switching table to obtain better power

quality performance for DPC of active front end rectifiers. We observed that with the increase of sampling frequency the power quality performance of the tables are improved but at the same time its hardware implementation became costly. Hence, it is very crucial to obtain the optimal sampling frequency along with the improvement in power quality performance. In this work, we found that at sampling frequency of $F_s = 30kHz$ the THD, ripples in active power, reactive power and dc bus voltage is coming under considerable limits for Noguchi's lookup table and slow lookup table. At 30 kHz, sampling frequency active power ripple and reactive power ripple for best two tables i.e. Noguchi's table and slow table is observed as 12.7862W &15.3317W and 21.8013Var and 18.2345Var respectively. Again, total harmonic distortion and dc bus voltage ripple for Noguchi's table and slow table tables are obtained as 4.97% & 4.72% and 0.0892V & 0.1070V respectively. Since, THD at this sampling frequency is coming below 5% which is following the IEEE-519 standards, hence it can be considered as optimal sampling frequency, considering the cost of implementation and power quality both at a time.
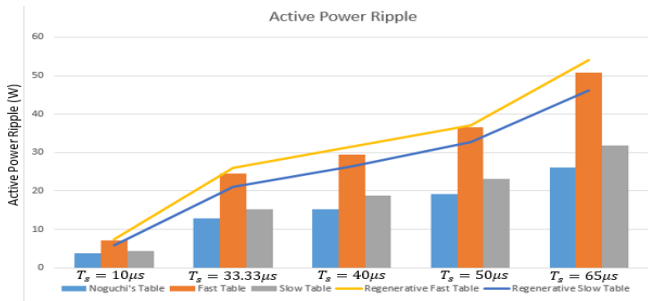

Fig. 5. Active power ripple for various lookup tables
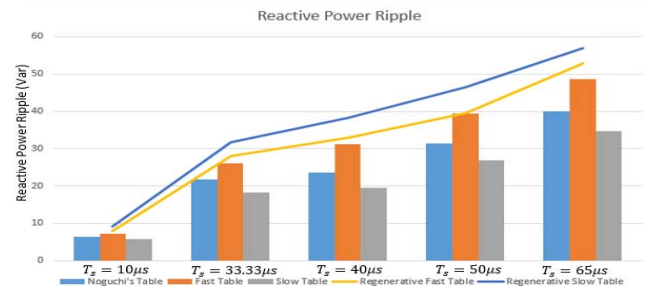

Fig. 6. Reactive power ripple for various lookup tables
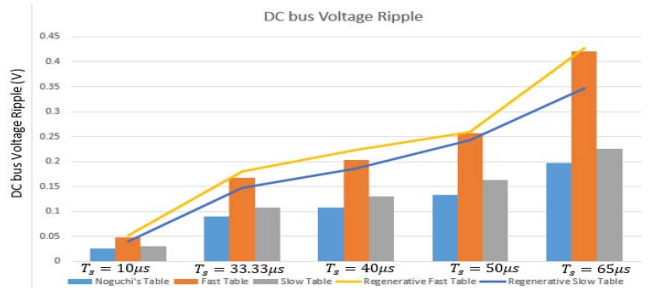

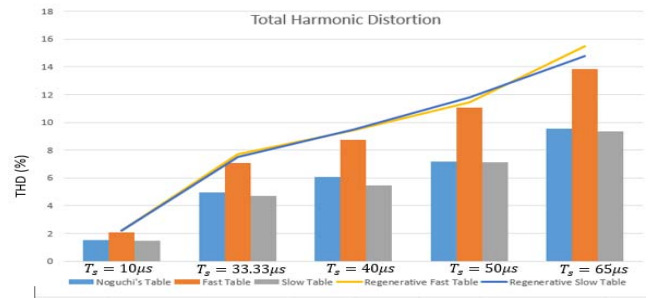Fig. 7. DC bus voltage ripple for various lookup tables

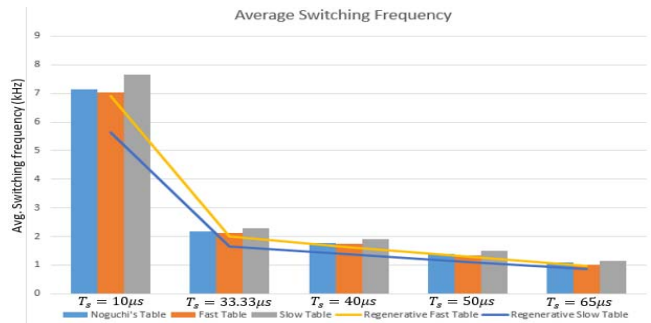Fig. 8. THD for various lookup tables

Fig. 9. Average switching frequency for various tables

IV. CONCLUSION

In this research work in-depth investigation is carried out for various switching tables at different sampling frequencies. From the analysis optimal table and optimal sampling frequency is decided, by considering the ease of implementation cost and power quality performance. Nagouchi table and slow switching table have the superior performance than other lookup tables. Also, in all the cases the power factor is found nearly unity.

REFERENCES

[1] Z. Yongchang, L. Zhengxi, Z. Yingchao, X. Wei, P. Zhengguo, and H. Changbin, "Performance Improvement of Direct Power Control of PWM Rectifier With Simple Calculation," *IEEE Trans. Power Electron.*, vol. 28, no. 7, pp. 3428–3437, 2013.

[2] D. A. Khaburi and A. Nazempour, "Design and simulation of a PWM rectifier connected to a PM generator of micro turbine unit," *Sci. Iran.*, vol. 19, no. 3, pp. 820–828, 2012.

[3] A. M. Razali and M. a. Rahman, "Performance analysis of three phase PWM rectifier using direct power control," *IEEE Int. Electr. Mach. Drives Conf.*, pp. 1603–1608, 2011.

[4] H. Jingjing, Z. Aimin, C. Xiaoju, Z. Hang, W. Jianhua, "A novel direct power control strategy of double hysteresis and multiple switching table for rectifiers," *in Proceedings Int.. Conf. on Adv. Power System Auto. Prot. (APAP) Beijing China*, 36-41, 2011.

[5] M. Malinowski, M. P. Kazmierkowski, and a M. Trzynadlowski, "A comparative study of control techniques for PWM rectifiers in AC adjustable speed drives," *IEEE Trans. Power Electron.*, vol. 18, no. 6, pp. 1390–1396, 2003.

[6] Z. Boudries, D. R. Ziani, " Study of decoupling direct power control of a PWM rectifier using space vector modulation,"Arabian Journal of Science and Engineering, Springer, vol.38, pp. 875-882, 2013.

[7] A. Bouafia, J. P. Gaubert, F. Krim, " Analysis and design of new switching table for direct power control of three-phase PWM rectifier,"

in Proceedings of 13th Power Elect.and Motion Control Conference, EPE-PEMC, 703-709, 2008.

[8] J. Hu and Z. Q. Zhu, "Investigation on switching patterns of direct power control strategies for grid-connected DC-AC converters based on power variation rates," IEEE Trans. Power Electron., vol. 26, no. 12, pp. 3582–3598, 2011.

[9] T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi, "Direct power control of PWM converter without power-source voltage sensors," IEEE Trans. on Industry Applications, vol. 34, no.3, pp. 473-479,1998.

[10] R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems. 2010.

[11] J. Hu, J. Zhu, D. G. Dorrell, "In-depth study of direct power control strategies for power converters," IET Power Electronics, vol. 7, no.7, pp. 1810-1820, 2014.

[12] T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi, J. Katsumara," Instantaneous active and reactive power control of PWM converter by using switching table," Trans. of Institute of Electrical Engineers, Japan vol. 116, no. 2, pp. 222-223, 1996.

[13] T.Ohnishi, "Three-phase PWM converter/inverter by means of instantaneous active and reactive power control," in Proceedings of IEEE, IECON '91 Kobe, Japan , pp. 819-824, 1991.

[14] A. Baktash, A. Vahedi, M. A. S. Masoum, "Improved switching table for direct power control of three-phase PWM rectifier," in Proceedings of Australasian Universities Power Engineering Conference (AUPEC), pp. 1-5, 2007.

[15] B. Gong, K. Wang, F. Meng, J. You, Y. Luo, A comparative study on switching tables of direct power control for voltage source rectifier, in Proceedings of IEEE International Conference on Mechatronics and Automation (ICMA) Tianjin China ,pp. 1978-1983, 2014.

[16] J. Alonso-Martinez, J. E. Carrasco, S. Arnaltes, "Table-based direct power control: A critical review for micro-grid applications," IEEE Trans. on Power Elect., vol. 25, no. 12, pp. 2949-2961,2010.

[17] Zhang, C. Qu, Z. Li, Y. Zhang, "Mechanism analysis and experimental study of table-based direct power control," Proceedings of International Conference on Electrical Machines and System (ICEMS), pp. 2213-2218, 2013.

[18] G. Escobar, A. Stankovic, J. Carrasco, E. Galvan, R. Ortega, "Analysis and design of direct power control (DPC) for a three-phase synchronous rectifier via output regulation subspaces," IEEE Trans. Power Electron, vol. 18, no. 3,pp. 823-830,2003.

[19] J. G. Norniella, J. M. Cano, G. A. Orcajo, C. H. Rojas, J. F. Pedrayes, M. F. Cabanas, M. G. Melero, "Multiple switching tables direct power control of active front-end rectifiers," IET Power Electronics, vol. 7, no. 6, pp. 1578-1589,2014.

[20] J. Rodriguez, J. Dixon, J. Espinoza, J. Pontt, P. Lezana, "PWM regenerative rectifiers: state of the art," IEEE Trans. on Industrial Electronics, vol. 52, no. 1,pp. 5-22, 2005.

[21] J. G. Norniella, J. M. Cano, G.A. Orcajo, "Optimization of direct power control of three-phase active rectifiers by using multiple switching tables," Proceedings of International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada, Spain ,2010.

APPENDIX-A

TABLE I. SYSTEM PARAMETERS

System Parameters		Value
Equivalent series resistance	R	0.56Ω
Line inductance	L	19.5mH
DC-bus capacitor	C	$1100\mu\text{F}$
Load resistance	R_L	68.6Ω
Line to line voltage	E	85V
Line frequency	f	50Hz
DC-bus voltage	V_{dc}	180V

\