Study of AC Line Voltage Disturbance on the Direct Power Controlled PWM Rectifier

H.Azizi A.Vahedi GH. Papi
Power Engineering Department
Iran University of Science &Technology

Abstract: In resent years because of the increasing amount of electronic equipment and nonlinear loads, disturbances and harmonic pollution in power systems have been widely increased. These undesired phenomena have undesired influence on the control and automatic equipment, such as motor drives, resulting in reduced reliability and availability. usuall motor drives utilize voltage and current source converter. Because of limitation and weakness of these converters against disturbances, some new topologies are presented in advanced drive such as DPC – PWM rectifier. Thanks to well known capabilities of DPC-PWM rectifier, such as robustness, improved power factor, good dynamic, etc, classical converter's problem can be overcome. In this paper performance of this rectifier under disturbed line voltage is investigated. For this purpose a DPC-PWM rectifier is simulated under unbalance and symmetrical / asymmetrical voltage sags. Then the results are compared to the conventional rectifiers.

Keywords: Direct power control, voltage sag, imbalance voltage

1 Introduction

Today voltage and current source inverter are widely used in electrical motor drives. In this drives, DC voltage or current are usually obtained by using rectifiers with phase control and line commutation converter. This type of rectifiers is the most used method in industrial applications. The most important disadvantages of classical rectifiers are: low order current harmonics generation on the AC line, lagging displacement factor establishment to the utility grid that in its turn consume an important amount of reactive power, unidirectional power transmission and large DC link filter [1,2,3]. Besides, new limit has been applied by standards such as IEEE519-1992 and IEC 61000-3-2/IEC 6100-3-4 that indicate the current harmonic limits of power electronic converters [4,5,6] .To overcome these problems in past few years PWM rectifiers are presented. Thanks to well known capabilities such as power regeneration, low harmonic input current, sinusoidal input current wave form, high total power factor, controlled dc-link voltage, small filter, 4-quadrant operation (bidirectional power transmission). Because of these features, they become more and more popular in industry application [3,4]. There are several control strategies to control PWM rectifier such as: Voltage oriented control (VOC) in which an internal current loop guarantees the high dynamics operation [7,8,9]. This method largely depends on the quality of the applied current control strategy. Another control strategy is direct power control (DPC) that is based on the instantaneous active & reactive power control loops and there is no need to PWM modulator block. because the converter switching state are appropriately selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power, therefore the key point for implementation of DPC strategies is a correct and fast estimation of the active and reactive line power[5]. In DPC method, the error of estimated instantaneous active and reactive power is influence by switching state and total line impedance (AC side inductance and motor cable inductance for long cable) Another new method of PWM rectifier control is virtual flux direct power control (VF-DPC) and virtual flux voltage oriented (VF-VOC) method based on a duality with the PWM inverter-fed induction motor where the estimated flux signal is used in the control system [7]. each of previous methods have some practical advantage and disadvantage. In this paper the control methods of PWM rectifier will be interdicted. Then the direct power control PWM rectifier (DPC) based on the space vector modulation is discussed. At first performance of the Direct Power Control (DPC –PWM rectifier) is studied under balanced voltage condition. As line voltage disturbance has a undesirable effect on industrial speed control drive, it is important to study the performance of these converter in this condition. For this purpose a DPC method is implemented in MATLAB/SIMULINK environment. Base on simulation result DPC-PWM rectifier performance under unbalance and symmetrical voltage sage is discussed.

2 The PWM rectifier structure

Fig.2 shows a single-phase equivalent circuit of the PWM rectifier system shown in fig.1. R, L represent the line inductor, $\underline{U}_S$ is the line voltage and $\underline{U}_L$ is the bridge converter voltage controllable from the DC-side depends on the modulation index and DC voltage level [1,2,3].

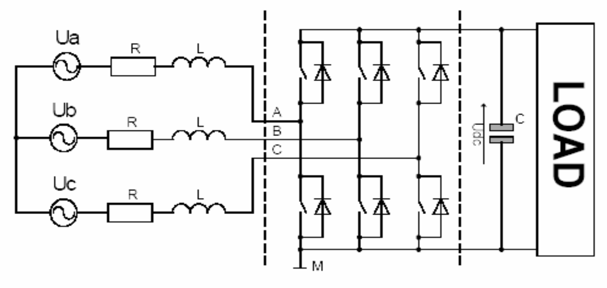

Fig.1 structure of PWM- rectifier

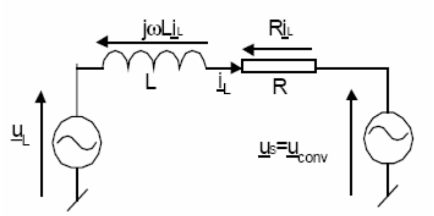

Fig.2 Single-phase equivalent circuit of the PWM rectifier

The voltage equation for this single phase ircuit can be written as:

$$\begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} \qquad (1)$$

for the balanced three-phase voltage we can write PWM rectifier equation in stationary coordinates.

$$U_L = \begin{bmatrix} U_{L\alpha} \\ U_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{\frac{3}{2}} \end{bmatrix}\begin{bmatrix} U_{ab} \\ U_{bc} \end{bmatrix} \qquad (2)$$

$$i_L = \begin{bmatrix} i_{L\alpha} \\ i_{L\alpha} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 3/2 & 0 \\ \frac{\sqrt{3}}{2} & \sqrt{3} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \end{bmatrix} \qquad (3)$$

Also we can write PWM rectifier equation in synchronous rotating coordinates(R is neglected):

$$\begin{bmatrix} U_{Ld} \\ U_{Lq} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} + \omega\begin{bmatrix} -i_{Lq} \\ i_{Ld} \end{bmatrix} + \begin{bmatrix} U_{sd} \\ U_{sq} \end{bmatrix} \qquad (4)$$

The equation 4 can be transformed to vector form in synchronous d-q coordinates defining derivative of current as:

$$L\frac{d\,\underline{i}_{Ldq}}{dt} = \underline{u}_{L_{dq}} - j\omega L\,\underline{i}_{Ldq} - \underline{u}_{sdq} \qquad (5)$$

fig.3 shows the relationship between the six active vectors of input voltage in PWM rectifier and direction and rate of current vector movement.

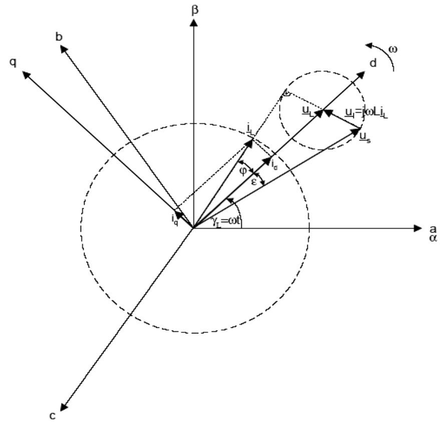

Fig. 3. Relationship between the six active vectors and current vector movement.

Another voltage estimation based control strategy called direct power control (DPC) that is based on the instantaneous active & reactive power control loops and no PWM modulator block. In this method the converter switching state are appropriately selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power. Hence the key point for implementation of DPC strategies is a correct and fast estimation of the active and reactive line power [5].

3 DPC Method Equations

In this section the operation of the DPC method is discussed and simulated. Fig.4 shows the block diagram of the DPC system and motor drive [5,7]. In this system the instantaneous active and

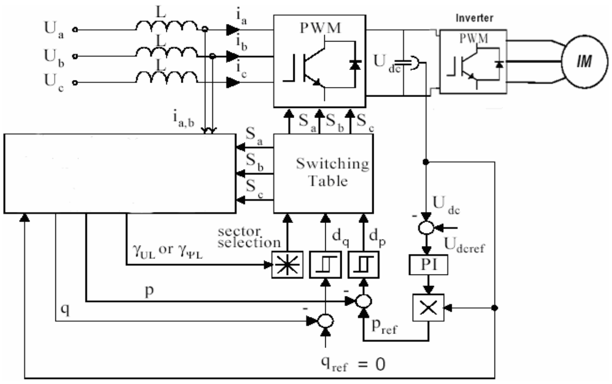

Fig.4. Block scheme of DPC method

reactive power are estimated by the eqs. 8, 9. In this equation i_a, i_b, i_c are the ac-line measured current and the s_a, s_b, s_c are the switching state of the converter. This two equation require knowledge of the line inductance L [7].

$$P = L\left(\frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c\right) + U_{dc}\left(S_a i_a + S_a i_a + S_a i_a\right) \quad (8)$$

$$q = \frac{1}{\sqrt{3}}\left(3L\left(\frac{di_a}{dt} i_c - \frac{di_c}{dt} i_a\right) - U_{dc}\left[S_a(i_b - i_c) + S_b(i_c - i_a) + S_a(i_a - i_b)\right]\right) \quad (9)$$

the ac-line current are measured and the values of the active and reactive power are estimated by eqs.8,9 and then the line voltage can easily be calculated from the equation 3.

$$\begin{bmatrix} u_{l\alpha} \\ u_{l\beta} \end{bmatrix} = \frac{1}{i_{l\alpha} + i_{l\beta}} \begin{bmatrix} i_{l\alpha} & -i_{l\beta} \\ i_{l\beta} & i_{l\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (10)$$

fig.5 shows the instantaneous active power, reactive power and ac voltage estimator block:

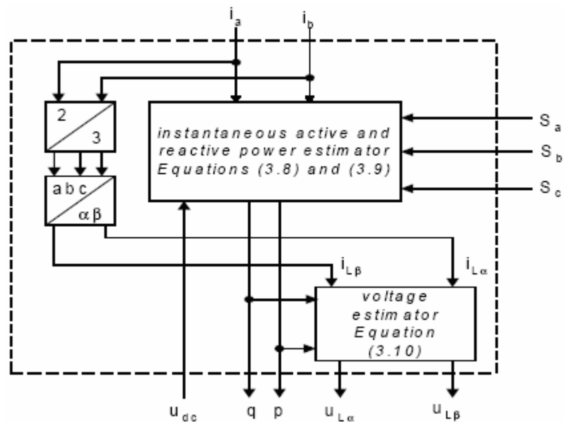

Fig. 5 Instantaneous active and reactive power estimation

In this system the active and reactive power are estimated at each time (as shown in fig.5).The digitized output signal of the reactive and active power controller are defends as:

$$d_q = 1 \; for q < q_{ref} - H_q \quad (11)$$

$$d_q = 0 \; for q > q_{ref} + H_q \quad (12)$$

where H_q and H_p are the hysteresis band. Table I shows the switching table for DPC control .

Table 1.switching table for 12 sectors

d_p	d_q	Sector A	Sector B
0	**1**	**VB**	**V7**
0	**0**	**V0**	**V0**
1	**1**	**VB**	**VB**
1	**0**	**VA**	**VA**

VA=V1(100),V2(110), V3(010), V4(011), V5(001), V6(101)
VB=V6(101),V1(100), V2(110), V3(010), V4(011), V5(001)
V0=V0(000),V7(111)

Fig. 6 shows the 12sector voltage plane for switching table.

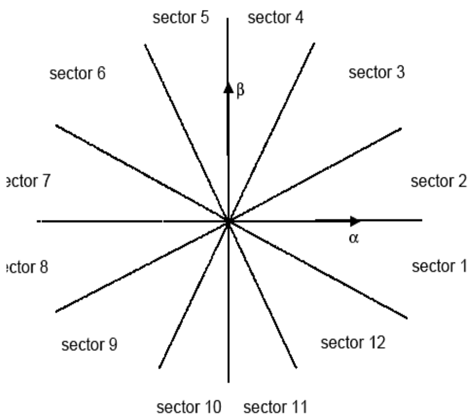

Fig. 6. Voltage plane with 12 sectors

Region of the voltage is divided in to twelve sectors, the area between adjoining vectors contain two sectors. Sector A is located closer to UA and sector B closer to UB.
To study the operation of the voltage based direct power controlled rectifier, this system is simulated in SIMULINK/MATLAB environment. The simulation results are obtained under different conditions and are compared to the conventional diode rectifier.

4 Balanced voltage condition

The dc link voltage variation, when step change applied to Vdc_{ref} (from 380 to 480 volt) is shown in fig.7. Fig.8 shows the active and reactive power in ac line side when the step change is happened. To obtain a unity power factor in AC line side the reference value of reactive power is set to zero. as shown in this figure active power change so that the dc link voltage be regulated. As shown in this figure the reactive power is approximately equal to zero.

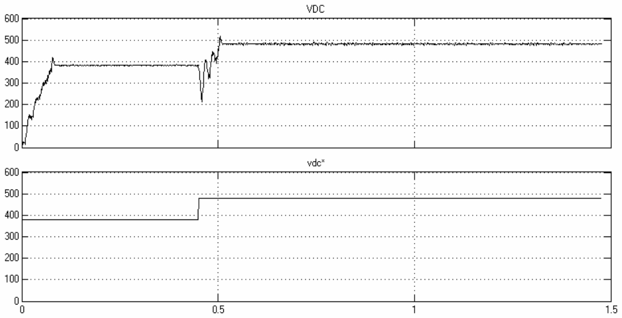

Fig.7 Dc link voltage for step 380 to 480 step change in reference

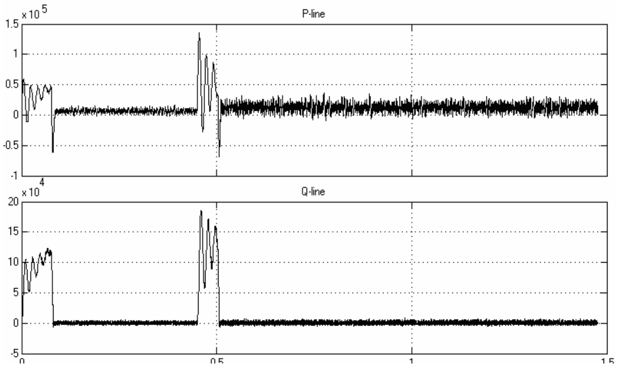

Fig.8 Active and reactive time variation after step change (q=0)

figures 9 to 11 show the effect of load variation on the performance of system. As shown in these figures this control strategy regulate the DC link voltage when the load change. the amplitude of the line current and the line side active power change in this condition. The reactive power will be unchanged and equal to zero.

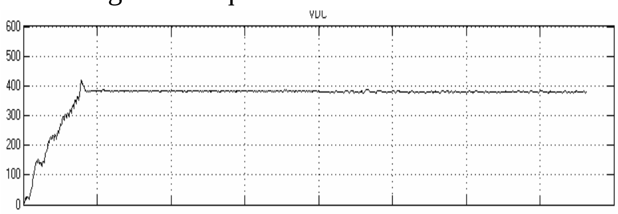

Fig.9 Dc –link voltage variation with change in load

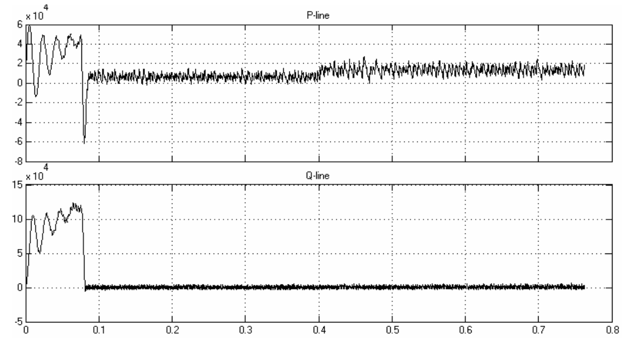

Fig.10 Variation in active and reactive power with change in load

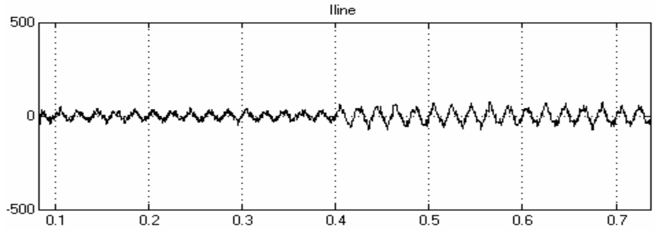

Fig.11 Variation in current with change in load

in spite of conventional rectifier that inject low order harmonic to the grid, the DPC-PWM rectifier because of use high frequency switching, only generate high order harmonic that can be cancel by using a small size filter. Fig.12, show the harmonic content of AC line current in the steady state condition for DPC-PWM rectifier for same resistive load.

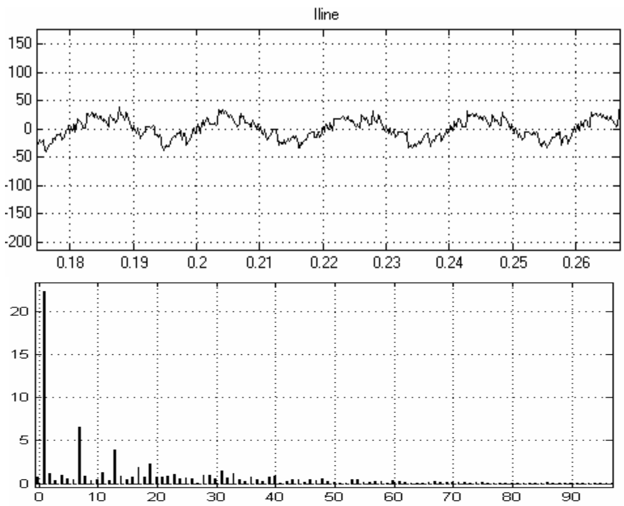

Fig.12 PWM rectifier input current and its harmonic content

5 Unbalanced voltage condition

To study the performance of DPC method under different disturbed ac line voltage, 2 conditions are considered beside the balanced voltage condition:

- Voltage unbalance in amplitude and phase
- Three phase and two phase voltage sag

5.1 Voltage unbalance in amplitude and phase

The Voltage unbalance affects the DC link voltage of conventional rectifiers and cause to undesired operation of industrial loads. As shown in fig.13 amplitude Voltage unbalance lead to considerable voltage drop on DC bus of diode rectifier. To assessment the DPC-PWM rectifier in this condition the simulation performed under amplitude and phase Voltage unbalance conditions. As shown in figures 14-15 , compared to the conventional diode rectifier, the PWM rectifier properly regulate the DC link voltage under this conditions.

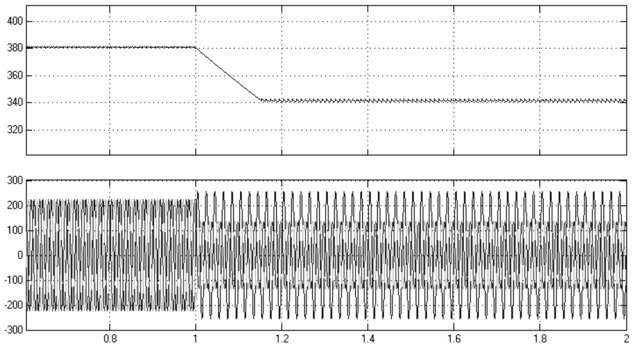

Fig.13 AC and DC side voltage for diode rectifier with input voltage: $V_a = 230$, $V_b = 125$, $V_c = 120$

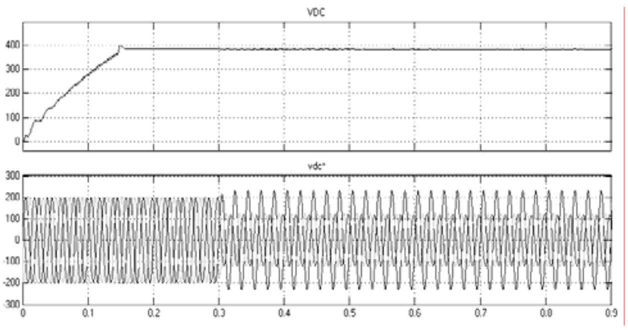

Fig.14 AC and DC side voltage for PWM rectifier with input voltage: $V_a = 230$, $V_b = 125$, $V_c = 120$

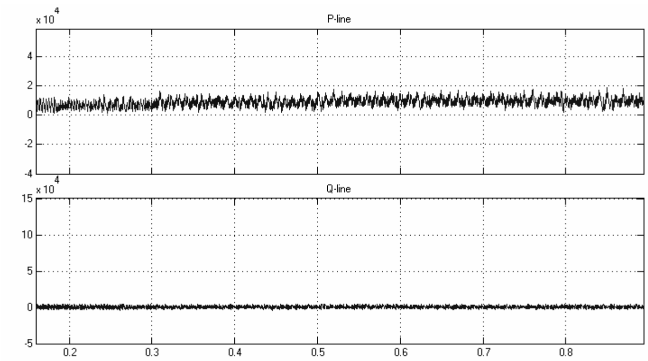

Fig.15 Active and reactive input power for PWM rectifier with input voltage: $V_a = 230$, $V_b = 125$, $V_c = 120$

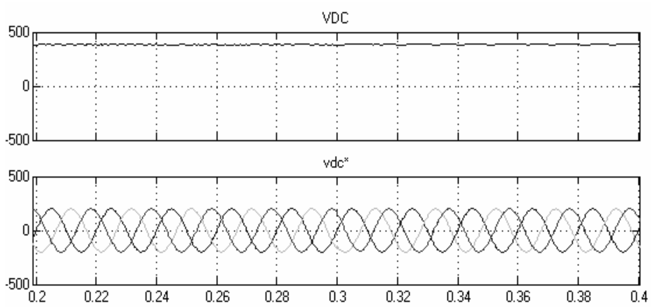

Fig. 16 AC and DC side voltage for PWM rectifier with input voltage phase angle: $\theta_a = 0$, $\theta_b = -140$, $\theta_c = 140$

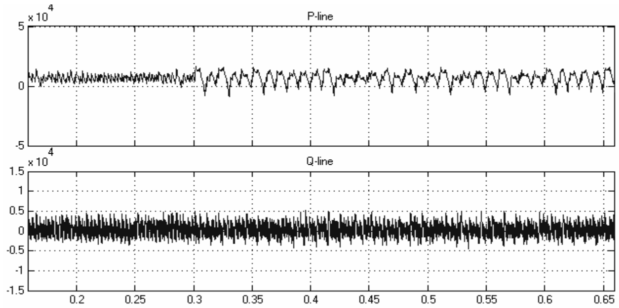

Fig. 17 Active and reactive input power for PWM rectifier with input voltage phase angle: $\theta_a = 0$, $\theta_b = -140$, $\theta_c = 140$

The simulation result under phase angle imbalance illustrated in Fig.16-17. The phase angle imbalance in input voltage accrue after t=0.3sec.

5.2 Three phase voltage sag

Voltage sags, are normally caused by faults on transmission and distribution systems. According to IEEE Std. 1159, a voltage sag is defined as “a decrease in rms voltage or current at power frequency for duration of 0.5 cycle to 1 minute” [11]. In diode rectifier depend on the sag magnitude, the sag duration and the steady state load, the DC bus voltage falls during voltage sag condition(fig 18), wich in turn affects the response of electrical drives and this can significantly affect the industrial process that use them. In PWM rectifier the control loop guaranties the DC-link voltage regulation in different conditions. Fig 19-20 shows the simulation result when a symmetrical three phase voltage sag occur in AC line side. As shown in these figures, in start of voltage sag, during and after voltage sag recovered the DC voltage remain unchanged.

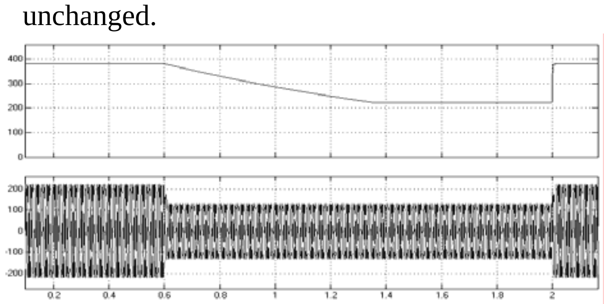

Fig. 18 AC and DC side voltage for PWM rectifier with a symmetrical three phase voltage sag occur in AC side

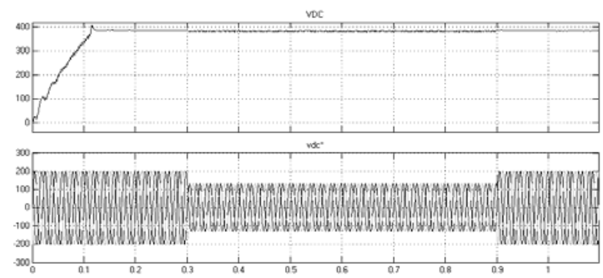

Fig.19 AC and DC side voltage for PWM rectifier with a symmetrical three phase voltage sag (from 200 V to 130 V) occur in AC side

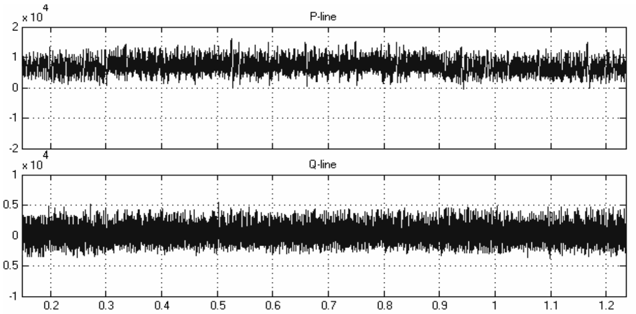

Fig. 20 Active and reactive input power for PWM rectifier with a symmetrical three phase voltage sag (200-130) occur in AC side

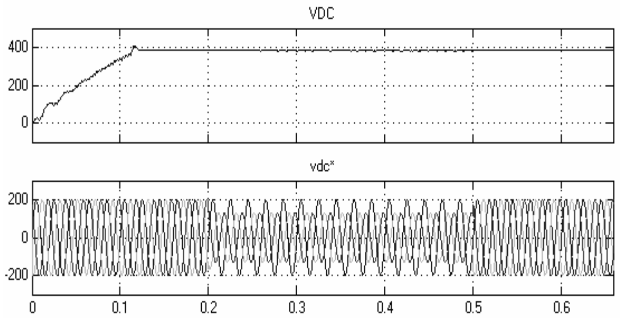

Fig. 21 AC and DC side voltage for PWM rectifier with a two phase voltage sag (200 V to 120 V) occur in AC side

Similar study for single phase, two phase and other type of voltage sags show that this rectifier has good performance against these voltage sags.

6 Conclusion

Thanks to the advantage of DPC-PWM rectifier, this rectifier is widely considered in new advanced drive systems. As the line voltage, usually is disturbed in distribution system, in this paper the performance of the DPC-PWM system under balanced voltage is studied as well as under amplitude and phase unbalance, three And two phase voltage sag . Simulation results show that, by using a DPC/PWM rectifier, not only the DC-link voltage has been regulated but also the power quality index is improved. The simulation results show DPC/PWM rectifier has a good performance for %35 three phase %40 two phase and %60 single phase(not shown) voltage sag. Also several Amplitude and phase unbalanced voltage condition simulated and shown that the rectifier is robust against unbalanced voltage. In each case Simulation result show that appropriate performance for DPC/PWM rectifier is not accessible when the line voltage disturbance is very large. In this case The DC-link capacitor, the input boast rector and PI regulator effect on performance of rectifier. Hence this rectifier has very god operation in normal disturbed voltage that It is an important advantage of this rectifier particularly in drive system that the operation of drive should be robust in line voltage distribution condition.

References:

[1] Marian P.Kazmierkowski, "Control strategies for PWM rectifier/inverter-fed induction motors" ,IEEE conference, Volume: 1 , Page(s): TU15 -TU23 vol.1 , june2000

[2] D.Rendusara, P.Enjeti, "A method to reduce common mode& different mode dv/dt the motor terminals in PWM rectifier/PWM inverter Type adjustable speed drive systems", APEC, Volume: 2 , Page(s): 1010 -1016 vol.2 ,1998

[3]Xiong Jian,Kang Yong, Duan Shan Xu, Zhang Kai ,Chen Jian ,"simplified control circuit of three phase PWM rectifier"1999,IEEE

[4]G.D.Marques ;"A PWM rectifier control system with DC current control based on the space vector modulation and stabization" Power Electronics and Variable Speed Drives, 1998. Seventh International Conference on (Conf. Publ. No. 456) Published: 1998 , Page(s): 74 -79

[5]M. M. Marian, P.Kazmierkowski , A. Tryznadlowski," Direct power control with virtual flux estimation for three-phase PWM rectifiers" Industrial Electronics, 2000. ISIE 2000. Proceedings of the 2000 IEEE International Symposium on Published: 2000 Volume: 2 , Page(s): 442 -447 vol.2

[6]M.Malinowski,F.B. Marian, P.Kazmierkowski "Sensorless Control Strategies for PWM rectifier", APEC2000, Vol. 2 , PP. 832 -838

[7]M.M. Marian, P.Kazmierkowski, F. Blaabjerg "Virtual-flux based direct power control of three-phase PWM rectifier" ,IEEE, VOL.37, NO.4 , july/august 2001

[8]Shimizu. T, Fujita. T, Kimura. G, Hirose. J, ”A unity power factor PWM rectifier with DC ripple compensation”, , IEEE Trans on Industrial Electronics , Aug. 1997, Vol. 44 4 , PP. 447 -455

[9]W. C. Lee, T. J. Kweon, D. S. Hyun, T.K.Lee ,“ A novel control of three-phase PWM rectifier using single current sensor”, PESC , Vol. 1 , PP. 515 -520, 1999

[10] J. K. Yong, D. S. Xu, Z. Kai, C. Jian ,"Simplified control circuit of three phase PWM rectifier", APEC, Vol. 1, PP. 229 -233

[11]IEEE Recommended Practice on Monitoring Electric Power Quality. IEEE Std. 1159