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Power Quality Improvement by Direct Power Control of Active Front End Rectifier

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Active fronts End Rectifiers (AFE) are used as a powerful tool for Harmonic Mitigation. This paper proposes a new development of Direct Power Control (DPC) in AFE Rectifier technologies that are utilized to mitigate harmonics in utility power lines. In this paper, Voltage Oriented Control (VOC) based Direct Power control (DPC) of three phases PWM Rectifier with reduced input harmonics and improved power factor is presented. In the proposed Direct Power Control based on Voltage Oriented Control scheme, instantaneous active and reactive powers provided by harmonic component of input currents are directly controlled using predefined switching table with 12 switching states. A complete simulation model is developed using MATLAB/Simulink in order to test the performance of VOC based DPC of PWM rectifier and compared with SVPWM based AFE Rectifier. Results show effective harmonic compensation at front end for DPC based PWM rectifier and the current THD is 3.3% which is well below the IEEE standards. Also almost unity power factor is achieved with significant power ripple reduction and more sinusoidal grid current can be observed in DPC.

Keywords: Direct Power Control, Total Harmonic Distortion, Pulse Width Modulated Rectifier, Voltage Oriented Control.

Introduction

Researches in three-phase PWM rectifiers has grown rapidly due to some of their important application areas, which includes renewable energy systems (wind turbines and photovoltaic), power condition and transmission equipments (flexible ac transmission systems, voltage source converter transmission, active power filter), motor drives requiring regeneration operation, and micro grid [1,12]. Various methods have been proposed to achieve power control of PWM rectifiers.VOC decomposes the grid currents into active and reactive power components and regulates them using linear Proportional Integral (PI) controllers[2]. Space Vector Modulation (SVM) is employed in voltage oriented control to synthesis the reference rectifier voltage vector. This helps to achieve good steady and dynamic responses, but the performance of VOC relies heavily on the internal current control loop and fine tuning of PI controller. DPC is another kind of high performance control strategy for PWM rectifier the basic principle of DPC is similar to Direct Torque Control (DTC) in motor drives. It directly selects the desired voltage vector from a predefined switching table, according to the grid voltage position (or virtual flux position) and the errors between the reference power (active/reactive) and feedback values. In DPC, internal current control loop and PWM modulator blocks are eliminated due to the instantaneous errors between the reference and estimated values of active and reactive power, the converter switching states are appropriately selected by a switching table. Therefore, for implementation of the DPC system fast estimation of the active and reactive line power is necessary. This paper presents Power Control of PWM Rectifier where the estimated voltage signal is used in the control system. The VOC based DPC of AFE rectifier system has the following advantages over conventional SVPWM Rectifier [3].

- Compared to the conventional SVPWM technique, there is lower sampling frequency, a simpler voltage and power estimation algorithm, easy implementation of the unbalanced and distorted line voltage compensation to obtain sinusoidal line currents.
- Compared to SVPWM technique, in VOC based DPC current control loop is eliminated and replaced with hysteresis controller and hence better power quality is achieved.

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The DPC-SVM with constant switching frequency uses closed-loop power control, which eliminates steady-state error.

Principle of Direct Power Control (DPC)

In DPC, the control of PWM rectifier is done by estimating the real and reactive powers [4,5]. The estimated power is then compared with the reference power. Reference real power is obtained by the voltage control loop as shown in Fig. 1. Reference reactive power is kept zero in order to obtain unity power factor and sinusoidal grid current.

This error value is then used to select the particular voltage vector from the predefined switching table. In this paper, the power estimation is done by using the input voltage and input current. Also inner current control loop using PI is eliminated and replaced with hysteresis comparator.

Model of Active Front End (AFE) Rectifier

In the following model, the AC voltage is assumed as a balanced three phase supply. The voltage equation of the rectifier in the *a-b-c* frame can be expressed as

$$e = L\frac{di}{dt} + Ri + v \qquad \dots (1)$$

Model of PWM rectifier in a-b-c frame,

$$v_n = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix} \begin{bmatrix} v_{am} \\ v_{bm} \\ v_{cm} \end{bmatrix}$$

$$\text{with } e_{an} + e_{bn} + e_{cn} = 0 \qquad \dots (2)$$

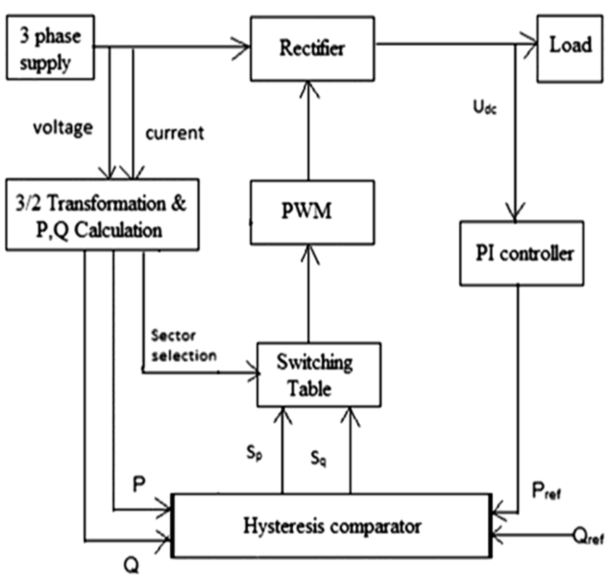

Fig. 1—Block diagram of VOC based DPC of PWM Rectifier

The differential equation for the *dc* side of the rectifier can be expressed as

$$C\frac{dV_{dc}}{dt} = i_{dc} - i_{Rdc} \qquad \dots (3)$$

Model of AFE rectifier in synchronously rotating frame is given in [6]. In VOC, the unity power factor condition is met when the line current vector is aligned with the phase voltage vector. Line current and line voltage vector is given by [2]

$$i = i_d + ji_q \text{ and } v = v_d + jv\_q \qquad \dots (4)$$

In DPC, real and reactive powers are calculated using line currents, dc-link voltage, and previous switching states. To achieve unity power factor condition, the reactive power should be zero. Using two hysteresis comparators and by the identification of previous sector next switching states are selected from the switching table. Design of AFE Rectifier is based on the design formulae using which the inductor and capacitor values are calculated. The value of the inductor and capacitor values are obtained based on the design given in [11].

Control Principle

The voltage control loop is implemented using PI controller. The reference real power is obtained using PI controller[6] and the reference reactive power is made zero in order to achieve unity power factor. In the proposed technique, the inner current control loop is eliminated. Instead Power control is implemented using hysteresis comparator[7]. The errors between the powers are given to hysteresis controller. The output of hysteresis controller is digitized to signals S_p and S_q according to bandwidth BW_p and BW_q. Condition for Hysteresis controller is given in Table 1. Based on the digitized output obtained from the hysteresis controller, particular voltage vector is selected from the predefined switching table. The selected switching state is used to control the AFE rectifier.

Switching Table

Each voltage vector when applied to the converter causes a change in active and reactive power value. Therefore depending on the previous sector and error

Table 1—Hysteresis Condition

Condition	Output
$P_{ref} - P_{act} \geq BW_p$	S_p=1
$P_{ref} - P_{act} \leq -BW_p$	S_p=0
$Q_{ref} - Q_{act} \geq BW_q$	S_q=1
$Q_{ref} - Q_{act} \leq -BW_q$	S_q=0

conditions, particular voltage vector is selected from the switching table[8]. Active and reactive power equations in d-q coordinates are given by,

$$p = v_d i_d + v_q i_q \qquad \ldots (5)$$

$$q = v_q i_q - v_d i_d \qquad \ldots (6)$$

Based on the hysteresis comparator output, a particular voltage vector is selected. In this paper, a twelve state switching table is implemented in order to reduce THD and to obtain unity power factor[9,10]. The voltage plane is divided into 12 sectors. The possible location of space vector is obtained from the sector. The voltage vectors of the switching table is given by, V_1=100, V_2=110, V_3=010, V_4=011, V_5=001, V_6=101, V_7=111, V_8=000. Table 2 shows the switching table for Voltage Oriented Control based Direct Power Control.

Simulation Results and Discussion

The proposed VOC based DPC of three phases AFE rectifier is simulated in MATLAB/Simulink and the results are compared with the conventional SVPWM technique. Fig. 2 shows the input single phase voltage and current waveform of VOC based DPC respectively. The reference dc voltage was changed from 500V to 760 V which was tracked instantly at 0.05s as shown in Fig. 3. The input current waveform of the active front end rectifier is in phase with that of the supply voltage waveform thus achieving unity power factor. Fig. 3 shows the DC output voltage of the VOC based DPC. Fig. 3 shows the reactive power of VOC based DPC and it could be observed that the reactive power drawn is zero. Fig. 4 shows the THD of input current of VOC based DPC scheme and the THD of proposed method is found to be 3.3% which is well below the IEEE-519 Standards while the current THD of conventional SVPWM based AFE rectifier system is 29.85%. In the proposed technique, voltage ripples, current ripples and power ripples are less with good dynamic response when compared to SVPWM based PWM rectifier. In DPC, power factor is unity while in SVPWM technique, power factor is found to be 0.75.

Table 2—Switching Table for DPC

S_p	S_q	Sector 1	2	3	4	5	6	7	8	9	10	11	12
1	0	6	8	1	7	2	8	3	7	4	8	5	7
	1	8	8	7	7	8	8	7	7	8	8	7	7
0	0	6	1	1	2	2	3	3	4	4	5	5	6
	1	1	2	2	3	3	4	4	5	5	6	6	1

Table 3—System Parameters

Line resistance	10 Ω
Line inductance	1 mH
DC-bus capacitor	400 μF
Load resistance	100 Ω
Load inductance	1 mH
Line to line voltage	239.6 V
Line voltage frequency	50 Hz
DC voltage	760 V
Hysteresis bandwidth	0.05
Switching frequency	5 kHz
Sampling frequency	20 kHz
Supply frequency	50 Hz

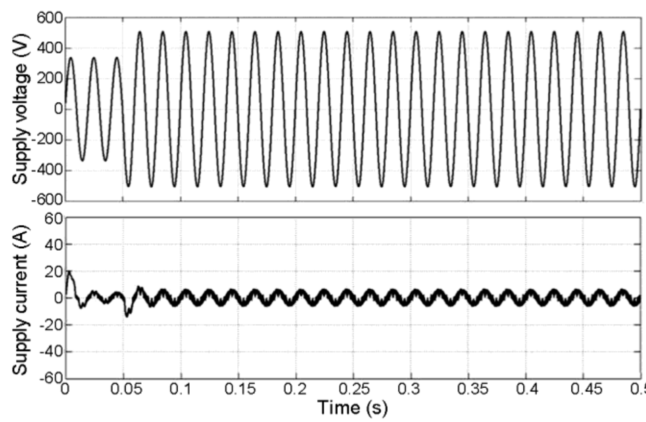

Fig. 2—Single phase Input voltage and current waveform

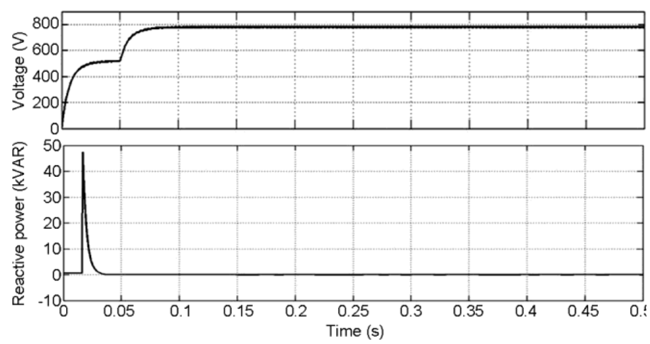

Fig. 3—DC Output voltage and Reactive power of VOC based DPC

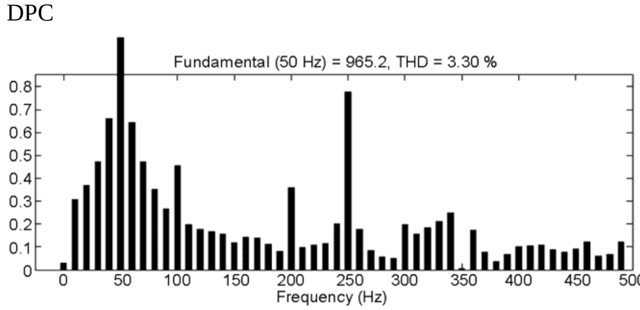

Fig. 4—THD of input current of VOC based DPC

Hence in the VOC based DPC power ripples are less and power factor is improved compared to conventional SVPWM Rectifier. From the performance analysis of VOC based DPC and conventional SVPWM Rectifier, it is clear that, VOC based DPC has better performance than conventional SVPWM Rectifier.

Conclusion

This paper has presented the implementation of VOC based DPC of three phase PWM rectifier. The main objective of proposed strategy is to improve power factor, to reduce the THD and to obtain the sinusoidal line currents. In the proposed system, instantaneous active and reactive power control is done using switching table. Simulation result shows that the proposed VOC based DPC with improved switching table is more advantageous compared to conventional SVPWM technique. The power ripples in the proposed method is 2% whereas it is 8% in conventional SVPWM. The power factor of SVPWM rectifier is 0.75 whereas unity power factor is achieved in the proposed method. The THD of the conventional method is 29.85% whereas it is only 3.3% for the proposed method which is well below the IEEE standards. In the proposed technique, reactive power is zero and hence sinusoidal line currents are obtained. Also THD has been reduced to 3.30% and power factor is unity. Finally the simulation results have verified the validity of the proposed DPC and are compared with SVPWM Rectifier and have proven excellent performance with regard to power ripples, power factor and harmonic compensation.

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