Control Strategies for Three Phase PWM Rectifier using Space Vector Modulation: Part-I

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Abstract: This paper explains the control strategies for three phase PWM rectifier using space vector modulation (SVM).The virtual flux based Direct Power Control (VF-DPC) which eliminates the line voltage measurements, active filtering function along with direct power control and conventional Voltage Oriented Control (VOC) in rotating coordinates with a novel line voltage estimator are studied, modeled and simulated. The steady state performances of these strategies are observed by measuring Total Harmonic Distortion (THD). From the simulations it is found that virtual flux based direct power control and active filtering function methods exhibits several features such as a simple algorithm, good dynamic response, and constant switching frequency. The details of mathematical modeling and simulations of all the three methods are presented in this thesis. This paper is organized as three parts.

Keywords: **Pulse Width Modulation Rectifier, Space Vector Modulation, Voltage Oriented Control, Direct Power Control, Active Filtering.**

1. INTRODUCTION

1.1 Introduction

The increase in use of electronic equipments such as computers, radio set, printers, TV sets, etc., acts as nonlinear loads, are source of current harmonics, which leads to increase in reactive power and power losses in transmission lines. The harmonics also cause electromagnetic interference and, sometimes, dangerous resonances. They have negative influence on the control and automatic equipment, protection systems, and other electrical loads, resulting in reduced reliability and availability. Moreover, non-sinusoidal currents produce non sinusoidal voltage drops across the network impedances, so that a non-sinusoidal voltage appears at several points of the mains. It brings out overheating of line, transformers and generators due to the iron losses.

Reduction of harmonic content in line current to a few percent allows avoiding most of the mentioned problems. Restrictions on current and voltage harmonics maintained in many countries through IEEE 519-1992 and IEC 61000-3-2/IEC 61000-3-4 standards, are associated with the popular idea of clean power. Methods for limitation and elimination of disturbances and harmonic pollution in the power system have been widely investigated by many researchers. These techniques based on passive components, mixing single and three-phase diode rectifiers, and power electronics techniques as: multipulse rectifiers, active filters and PWM rectifiers (Fig. 1.1).
They can be generally divided as:

- Harmonic reduction of already installed non-linear load;
- Harmonic reduction through linear power electronics load installation;

A) Harmonic reduction of already installed non-linear load
B) Harmonic reduction through linear power electronics load installation

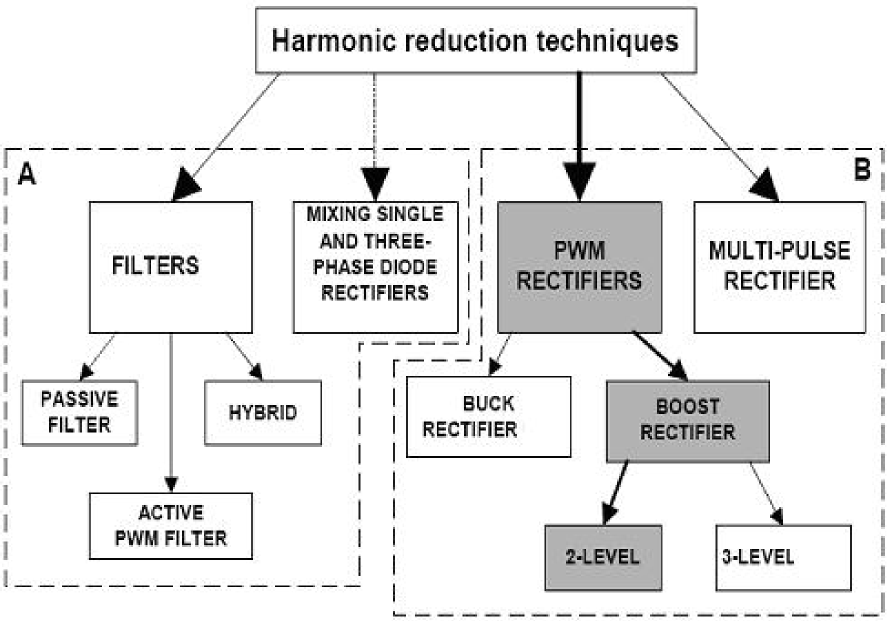

Fig. 1.1 Most popular three-phase harmonic reduction techniques of current

Traditional method of current harmonic reduction involves passive filters LC, parallel-connected to the grid. Filters are usually constructed as series-connected legs of capacitors and chokes. The number of legs depends on number of filtered harmonics (5th, 7th, 11th, and 13th). The advantages of passive filters are simplicity and low cost. The disadvantages are:

- Each installation is designed for a particular application (size and placement of the filters elements, risk of resonance problems),
- High fundamental current resulting in extra power losses,
- Filters are heavy and bulky.

In case of diode rectifier, the simpler ways to harmonic reduction of current are additional series coils used in the input or output of rectifier (typical 1-5%).

The other technique, based on mixing single and three-phase non-linear loads, gives a reduced THD because the 5th and 7th harmonic current of a single-phase diode rectifier often are in counter-phase with the 5th and 7th harmonic current of a three-phase diode rectifier. The power electronics techniques are use of multipulse rectifiers. Although easy to implement, possess several disadvantages such as: bulky and heavy transformer, increased voltage drop, and increased harmonic currents at non-symmetrical load or line voltages.

An alternative to the passive filter is use of the shunt active PWM filter, which displays better dynamics and controls the harmonic and fundamental currents. Active filters (AF) are mainly divided into two different types: the active shunt filter (current filtering) as shown in fig.1.2 and a PWM (active) rectifier fig.1.3.

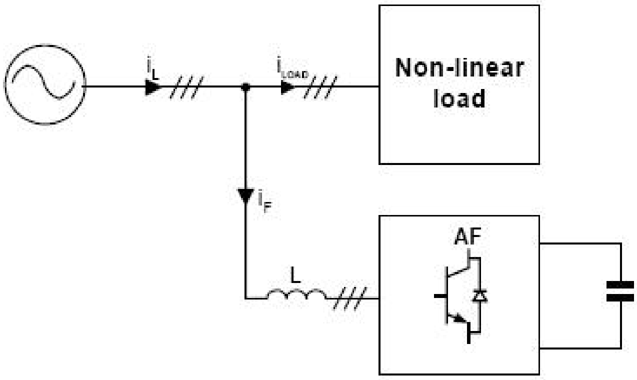

Fig. 1.2 Three-phase shunt Active filter

The three-phase two-level shunt AF consists of six active switches and its topology is identical to three phase PWM converter. The Active Filter represents a controlled current source i_F which added to the load current i_{Load} yields sinusoidal line current i_L (Fig. 1.2). Active filter provides:

- Compensation of fundamental reactive components of load current,
- Load symmetrization (from grid point of view),
- Harmonic compensation much better than in passive filters.

In spite of the excellent performance active filters possess certain disadvantages such as complex control, switching losses and EMC problems. For reduction of these effects, a small low-pass passive filter between the line and the AF is necessary.

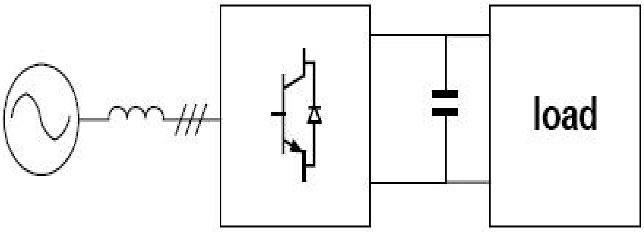

Fig.1.3 PWM rectifier

The other current harmonic reduction technique is a PWM (active) rectifier (Fig.1.3). PWM rectifiers can be configured as a voltage source output (Fig.1.4a) and a current source output (Fig. 1.4b). Voltage source configuration is a boost rectifier (increases the voltage) works with fixed DC voltage polarity, and the current source configuration is a buck rectifier (reduces the voltage) operates with fixed DC current flow.

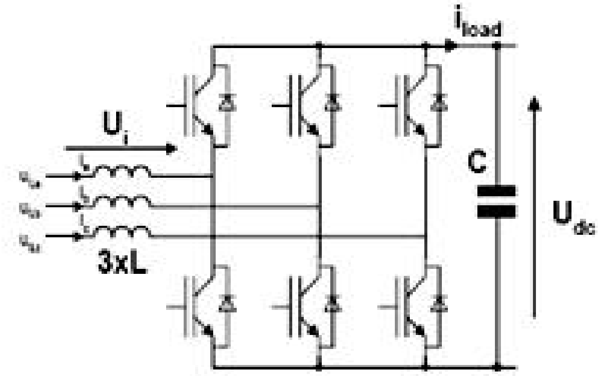

Fig. 1.4 (a) Boost topology of PWM rectifier

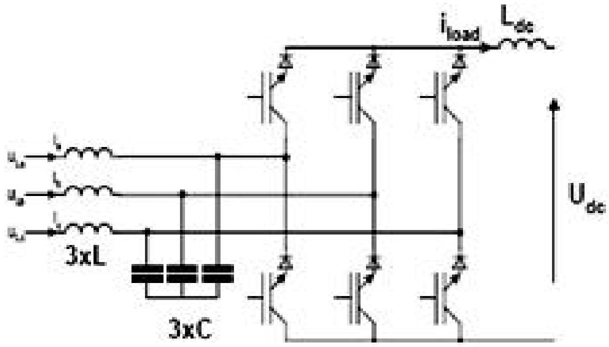

Fig. 1.4 b) Buck topology of PWM rectifier

Important features of PWM rectifiers are:

- Bi-directional power flow,
- Nearly sinusoidal input current,
- Regulation of input power factor to unity,
- Low harmonic distortion of line current (THD below 5%),
- Adjustment and stabilization of DC-link voltage (or current),
- Reduced capacitor (or inductor) size due to the continues current.

Furthermore, it can be properly operated under line voltage distortion and notching, and line voltage frequency variations.

Similar to the PWM shunt active filter, the PWM rectifier has a complex control structure and the efficiency is lower than the diode rectifier due to extra switching losses. A properly designed low-pass passive filter is needed at the front end of the PWM rectifier to limit EMI.

1.2 Scope of the Project

In this thesis a detailed investigations of different control strategies for boost type of three-phase bridge PWM rectifiers has been presented. Modeling and simulation of control strategies for three phase boost rectifier such as Voltage Oriented Control (method based on indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector), Direct Power Control (method based on instantaneous direct active and reactive power control) and Direct Power Control with Active Filtering technique are presented and compared their performance with respect to Total Harmonic Distortion (THD), dynamic response and parameter sensitivity. From the analysis of simulations of all these control strategies, it is found that control strategy based on virtual flux (Direct Power Control), instead of the line voltage vector orientation (Voltage Oriented Control) provides lower harmonic distortion of line current and leads to line voltage sensorless operation.

2. PWM RECTIFIER

2.1. Introduction

As it has been observed for recent decades, an increasing part of the generated electric energy is converted through rectifiers, before it is used at the final load. In power electronic systems, especially, diode and thyristor rectifiers are commonly connected in the front end of DC-link power converters as an interface with the AC line power (grid) as shown in Fig. 2.1. The rectifiers are nonlinear in nature and, consequently, generate harmonic currents in to the AC line power. The high harmonic content of the line current and the resulting low power factor of the load causes a number of problems in the power distribution system like:

- Voltage distortion and electromagnetic interface (EMI) affecting other users of the power system,
- Increasing volt ampere ratings of the power system equipment (generators, transformers, transmission lines, etc.).

Therefore, governments and international organizations have introduced new standards (IEEE 519 and in IEC 61000-3) which limit the harmonic content of the current drawn from the power line by the rectifiers. As a consequence a great number of new switch-mode rectifier topologies that comply with the new standards have been developed. In the area of variable speed AC drives, it is believed that three-phase PWM boost AC/DC converter will replace the diode rectifier. The resulting topology consists of two identical bridge PWM converters (Fig. 2.4). The line-side converter operates as rectifier in forward energy flow, and as inverter in reverse energy flow. In further discussion assuming the forward energy flow, as the basic mode of operation the line-side converter will be called as PWM rectifier. The AC side voltage of PWM rectifier can be controlled in magnitude and phase so as to obtain sinusoidal line current at unity power factor (UPF). Although such a PWM rectifier/inverter (AC/DC/AC) system is expensive, and the control is complex, the topology is ideal for four-quadrant operation. Additionally, the PWM rectifier provides DC bus voltage stabilization and can also act as active line conditioner (ALC) that compensates harmonics and reactive power at the point of common coupling of the distribution network. However, reducing the cost of the PWM rectifier is vital for the competitiveness compared to other front-end rectifiers. The cost of power switching devices (e.g. IGBT) and digital signal processors (DSPs) are generally decreasing and further reduction can be obtained by reducing the number of sensors. Sensorless control exhibits advantages such as improved reliability and lower installation costs.

2.2. PWM Rectifier Topologies

A voltage source PWM inverter with diode front-end rectifier is one of the most common power configuration used in modern variable speed AC drives (Fig. 2.1). An uncontrolled diode rectifier has the advantage of being simple, robust and low cost. However, it allows only unidirectional power flow. Therefore, energy returned from the motor must be dissipated on power resistor controlled by chopper connected across the DC link. The diode input circuit also results in lower power factor and high level of harmonic input currents. A further restriction is that the maximum motor output voltage is always less than the supply voltage. Equations (2.1) and (2.2) can be used to determine the order and magnitude of the harmonic currents drawn by a six-pulse diode rectifier:

$$h=6k\pm 1 \quad k=1, 2, 3..... \tag{2.1}$$

$$\frac{I_h}{I_1}=\frac{1}{h} \tag{2.2}$$

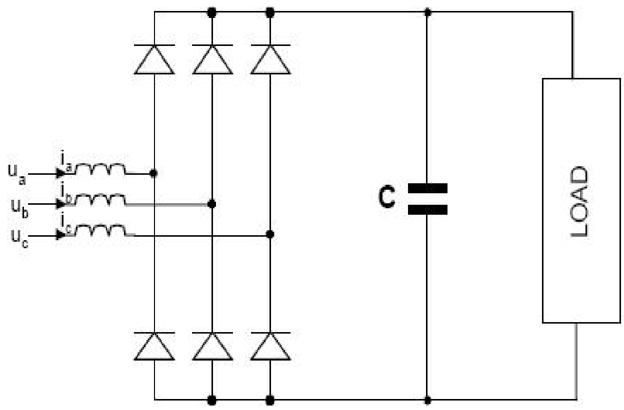

Fig. 2.1 Diode Rectifier

Harmonic orders as multiples of the fundamental frequency, 5th, 7th, 11th, 13th etc., with a 50 Hz fundamental, corresponds to 250, 350, 550 and 650 Hz, respectively. The magnitude of the harmonics in per unit of the fundamental is the reciprocal of the harmonic order: 20% for the 5th, 14% for the 7th, etc. Equations (2.1) and (2.2) are obtained from the Fourier series for an ideal square wave current (critical assumption for infinite inductance on the input of the converter). Equation (2.1) is fairly good description of the harmonic orders generally encountered. The magnitude of actual harmonic currents often differs from the relationship described in (2.2). The shape of the AC current depends on the input inductance of converter. The ripple current is equal 1/L times the integral of the DC ripple voltage. With infinite inductance the ripple current is zero and the input current is flat-top wave. (Fig. 2.2d).

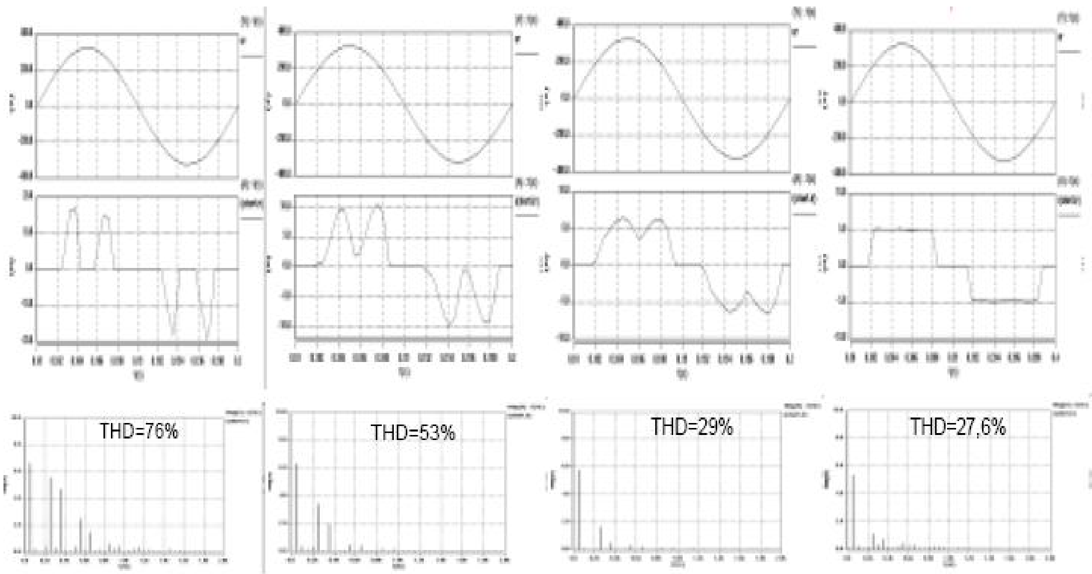

Fig. 2.2 Simulation results of diode rectifier at different input inductance (from 0 to infinity)

Besides six-pulse bridge rectifier, few other rectifier topologies are available. Some of them are presented in Fig. 2.3. The topology of Fig. 2.3(a) presents simple solution of boost type converter with a possibility to increase DC output voltage. This is an important feature for Adjustable Speed Drives (ASD) giving maximum motor output voltage. The main drawback of this boost converter topology is stress on the components, low frequency distortion of the input current. The topologies Diode rectifier with PWM regenerative braking rectifier Fig. 2.3(b) and Diode rectifier with PWM active filtering rectifier Fig. 2.3 (c) uses a PWM rectifier modules with a very low current rating (20-25% level of rms current compared with (e) topology). Hence they have a low cost potential provide only possibility of regenerative braking mode Fig. 2.3 (b) or active filtering Fig. 2.3 (c). Fig. 2.3 (d) presents 3-level converter called Vienna rectifier. The main advantage of this topology is low voltage drop across switch. Fig. 2.3 (e) represents a PWM reversible rectifier which is most popular topology used in ASD, UPS. This universal topology has the advantage of using a low cost three-phase power module with a bi-directional energy flow capability but it suffers from high per-unit current ratting, poor immunity to shoot-through faults, and high switching losses.

Table 2.1 Features of three-phase rectifiers

feature / topology	Regulation of DC output voltage	Low harmonic distortion of line current	Near sinusoidal current waveforms	Power factor correction	Bi-directional power flow	Remarks
Diode rectifier	-	-	-	-	-	
Rec(a)	+	-	-	+	-	
Rec(b)	-	-	-	-	+	
Rec(c)	-	+	+	+	-	UPF
Rec(d)	+	+	+	+	-	UPF
Rec(e)	+	+	+	+	+	UPF

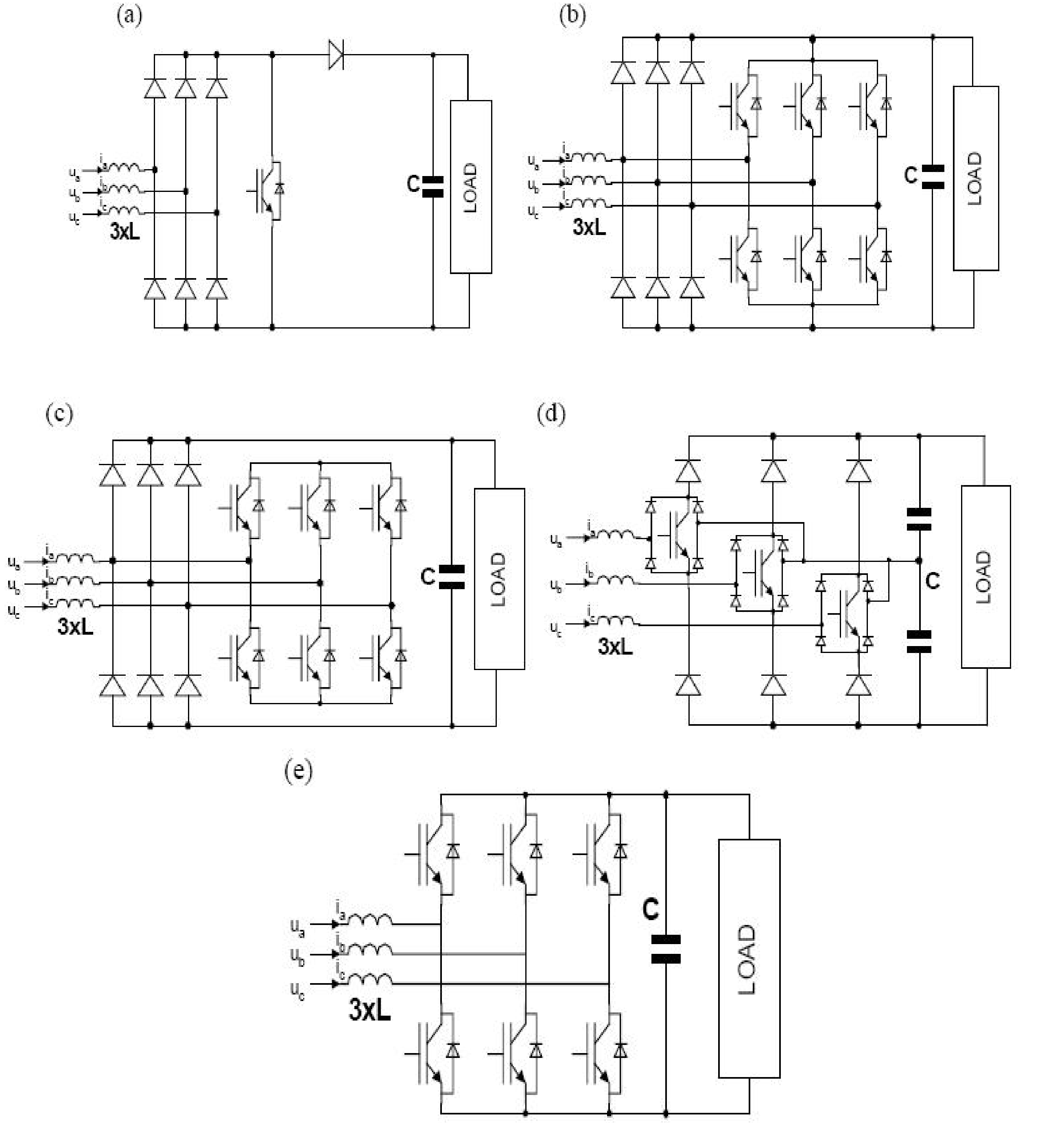

Fig.2.3 Basic topologies of switch-mode three-phase rectifiers: a) Simple boost-type converter; b) Diode rectifier with PWM regenerative braking rectifier; c) Diode rectifier with PWM active filtering rectifier; d) Vienna rectifier (3. level converter); e) PWM reversible rectifier (2 Level converter)

In the PWM reversible rectifier topology, used in *DC* distributed Power System (Fig. 2.5) or AC/DC/AC converter (Fig. 2.4). Where AC power is converted into *DC* using three-phase PWM rectifier. It provides *UPF* and low current harmonic content. The converters connected to the DC-bus provide further desired conversion for the loads, such as adjustable speed drives for induction motors (*IM*) and permanent magnet synchronous motor (*PMSM*), DC/DC converter, multidrive operation, etc.
AC/DC/AC configuration has following features:

- the motor can operate at a higher speed without field weakening (by maintaining the DC-bus voltage above the supply voltage peak),
- common mode voltage decreases by one-third compared to conventional configuration due to the simultaneous control of rectifier – inverter (same switching frequency and synchronized sampling time may avoid common mode voltage pulse because the different type of zero voltage (*U0,U7*) are not applied at the same time) ,

- the response of the voltage controller can be improved by fed-forward signal from the load what gives possibility to minimize the DC link capacitance while maintaining the DC-link voltage within limits under step load conditions.

Fig. 2.5 shows the Multidrive operation of the PWM Rectifier.

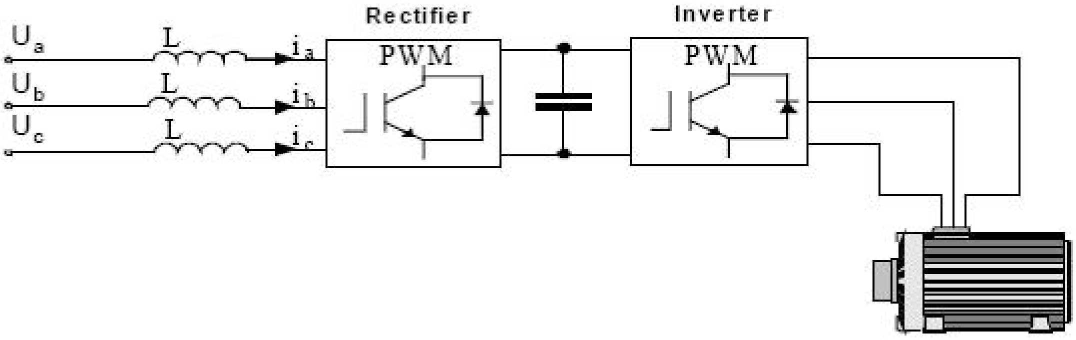

Fig. 2.4 AC/DC/AC converter

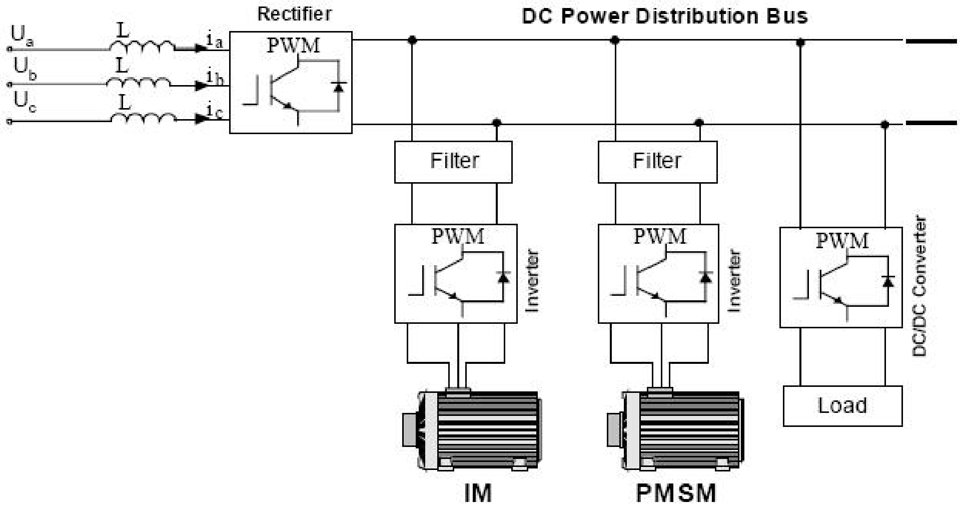

Fig. 2.5 DC distributed Power System

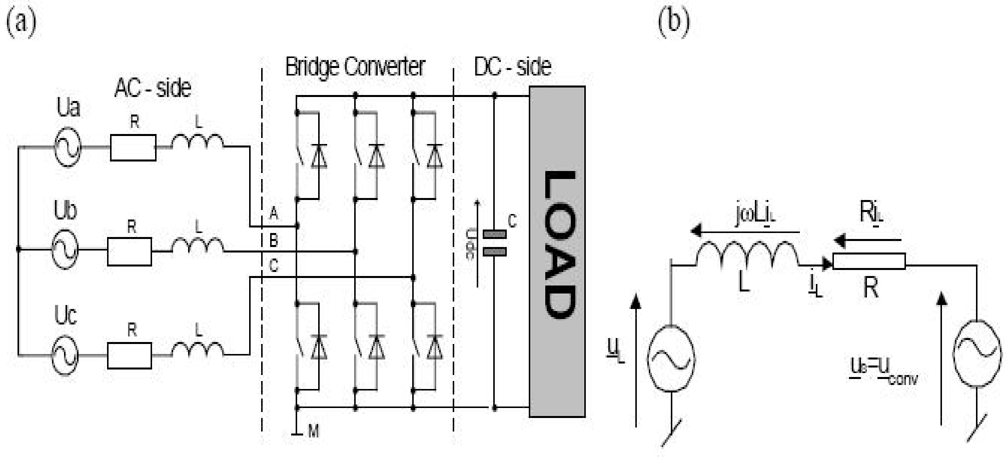

Fig. 2.6 (a) Three-phase PWM rectifier for bi-directional power flow.
(b)Single-line diagram of the PWM rectifier

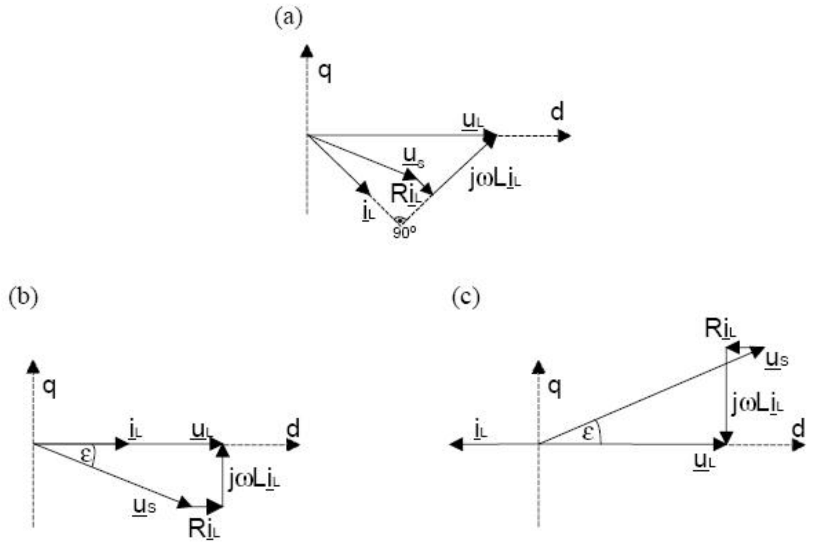

Fig. 2.7 (a) General Phasor diagram of the PWM rectifier
(b) Rectification at unity power factor (c) Inversion at unity power factor

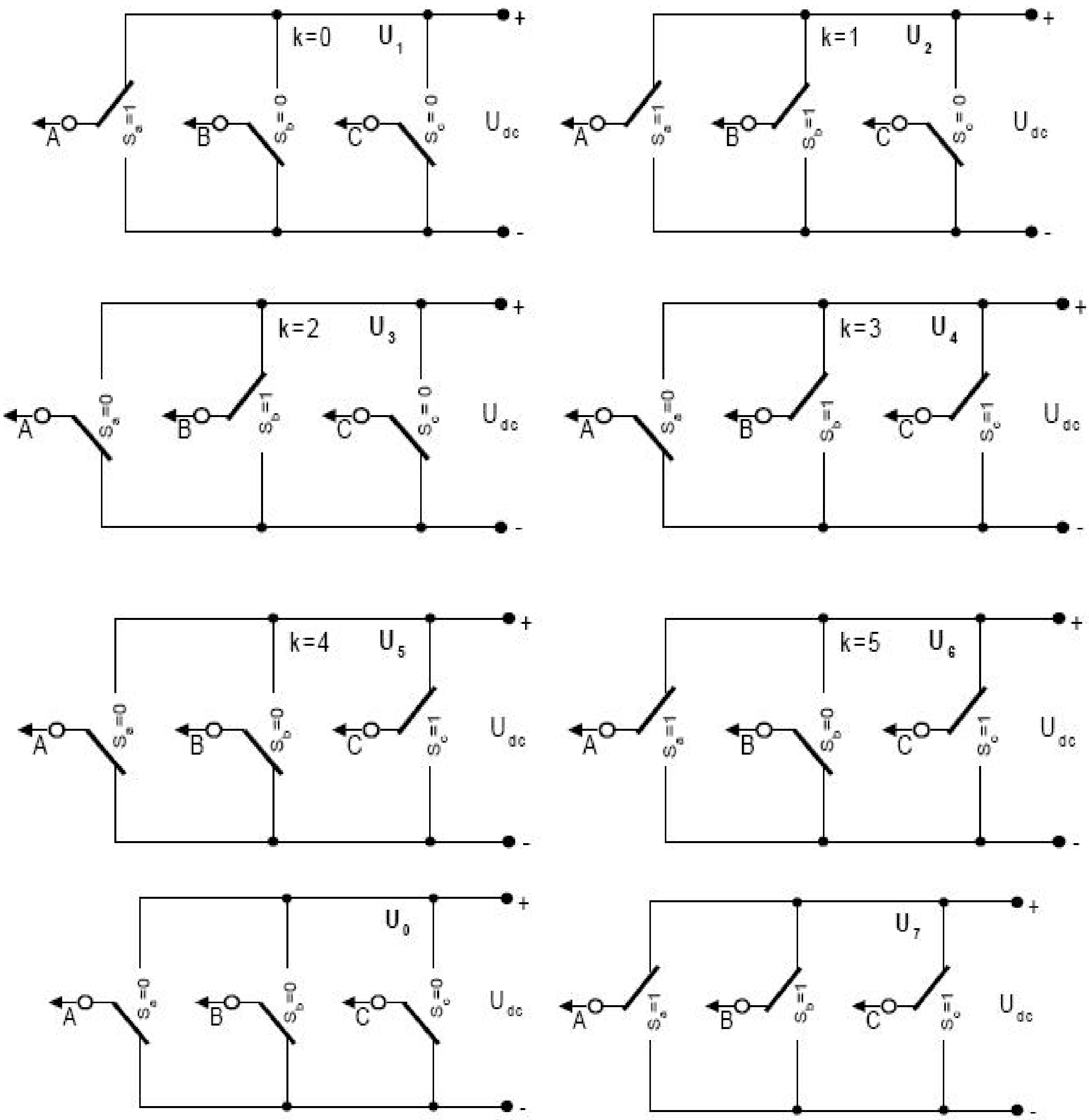

Fig. 2.8 Switching states of PWM bridge converter

2.3 Operation of the PWM Rectifier

Fig. 2.6 (b) shows a single-line diagram of the rectifier circuit presented in Fig.2.6 (a). U_L is the line voltage and U_S is the bridge converter voltage controllable from the DC-side. Magnitude of U_S depends on the modulation index and DC voltage level.

Inductors connected between input of rectifier and supply lines are integral part of the circuit. It brings current source character of input circuit and provide boost feature of converter. The line current i_L is controlled by the voltage drop across the inductance *L* interconnecting two voltage sources (line and converter). It means that the inductance voltage u_l equals the difference between the line voltage u_L and the converter voltage u_S. When we control phase angle ε and amplitude of converter voltage u_S, we control indirectly phase and amplitude of line current. In this way average value and sign of *DC* current is subject to control which is proportional to active power conducted through converter. The reactive power can be controlled independently with shift of fundamental harmonic current I_L in respect to voltage U_L. Fig. 2.7 presents the phasor diagrams for normal operation, rectification and regenerating when unity power factor is required. This figure shows that the voltage vector u_S is higher during regeneration (up to 3%) then rectifier mode. It means that these two modes are not symmetrical. Bridge converter (Fig. 2.6a) consists of three legs with *IGBT* transistor or, in case of high power, *GTO* thyristors. The bridge converter voltage can be represented with eight possible switching states (Fig. 2.8 six-active and two-zero) described by equation:

$$u_{k+1}=2/3u_{dc}e^{jk\pi/3} \quad \text{for} \quad k= 0\ldots\ldots\ldots.5 \qquad (2.3)$$

2.3.1 Mathematical description of the PWM Rectifier

The basic relationship between vectors of the PWM rectifier is presented in Fig. 2.9. From this representation, three phase 120 degree time displaced voltages are transformed into stationary and synchronously rotating reference frames.

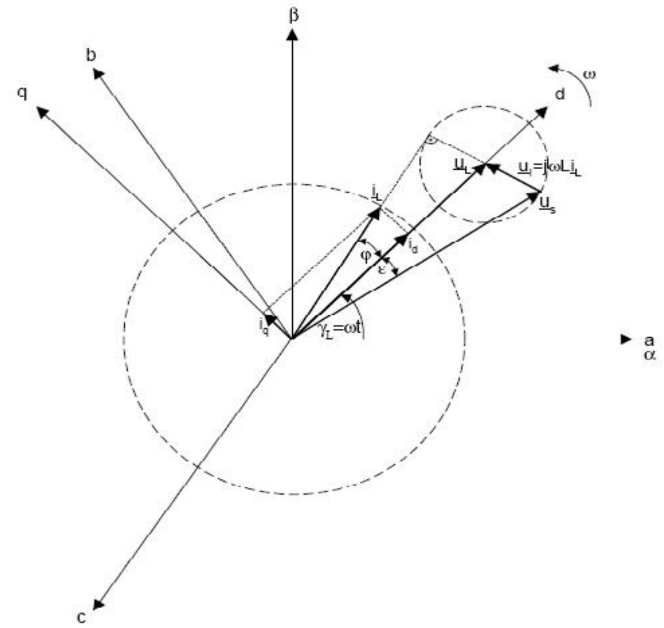

Fig. 2.9 Relationship between vectors in PWM Rectifier

Three phase line voltages and the fundamental line currents can be represented as

$$u_a=E_m \cos\omega t \qquad (2.4a)$$

$$u_b=E_m\cos\left(\omega t+\frac{2\pi}{3}\right) \qquad (2.4b)$$

$$u_c=E_m\cos\left(\omega t-\frac{2\pi}{3}\right) \qquad (2.4c)$$

$$i_a=I_m\cos(\omega t+\varphi) \qquad (2.5a)$$

$$i_b=I_m\cos\left(\omega t+\frac{2\pi}{3}+\varphi\right) \qquad (2.5b)$$

$$i_c=I_m\cos\left(\omega t-\frac{2\pi}{3}+\varphi\right) \qquad (2.5c)$$

where E_m (I_m) and ω are the amplitude of the phase voltage (current) and angular frequency respectively, with assumption that

$$i_a+i_b+i_c=0 \qquad (2.6)$$

The voltage equations 2.4(a), 2.4(b), 2.4(c) can be transformed into α-β stationary frame are expressed by:

$$u_{L\alpha}=\sqrt{\frac{3}{2}}\,E_m.\cos\omega t \qquad (2.7)$$

$$u_{L\beta}=\sqrt{\frac{3}{2}}\,E_{m.}\cos\omega t \qquad (2.8)$$

and the input voltages in the synchronous d-q coordinates (Fig. 2.9) are expressed by:

$$\begin{bmatrix} uLd \\ uLq \end{bmatrix}=\begin{bmatrix} \sqrt{\frac{3}{2}} \\ 0 \end{bmatrix}=\begin{bmatrix} \sqrt{u^2L_\alpha+u^2L_\beta} \\ 0 \end{bmatrix} \qquad (2.9)$$

Description of input voltage in PWM Rectifier

Line to line input voltages of PWM rectifier can be described with the help of Fig. 2.8 as:

$u_{Sab}=(S_a-S_b).u_{dc}$ (2.10a)

$u_{Sbc}=(S_b-S_c).u_{dc}$ (2.10b)

$u_{Sca}=(S_c-S_a).u_{dc}$ (2.10c)

and phase voltages are equal:

$u_{Sa}=f_a.u_{dc}$ (2.11a)

$u_{Sb}=f_b.u_{dc}$ (2.11b)

$u_{Sc}=f_c.u_{dc}$ (2.11c)

where:

$$fa= 2Sa-\frac{(Sb+Sc)}{3} \quad (2.12a)$$

$$fb= 2Sb-\frac{(Sa+Sc)}{3} \quad (2.12b)$$

$$fc= 2Sc-\frac{(Sa+Sb)}{3} \quad (2.12c)$$

The fa, fb, fc are assume 0, ±1/3 and ±2/3.

Model of Three-phase PWM Rectifier

The voltage equations for balanced three-phase system without the neutral connection can be written as (Fig. 2.7b):

$u_L = u_I + u_S$ (2.13)

$$u_L=Ri_L+L\frac{di_L}{dt}+u_S \quad (2.14)$$

$$\begin{bmatrix} ua \\ ub \\ uc \end{bmatrix} = R\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + L\frac{di}{dt}\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} usa \\ usb \\ usc \end{bmatrix} \quad (2.15)$$

and additionally for currents

$$C\frac{du_{dc}}{dt}=S_a i_a+S_b i_b+S_c i_c-i_{dc} \quad (2.16)$$

The combination of equations (2.11, 2.12, 2.15, and 2.16) can be represented as three-phase block diagram (Fig. 2.10).

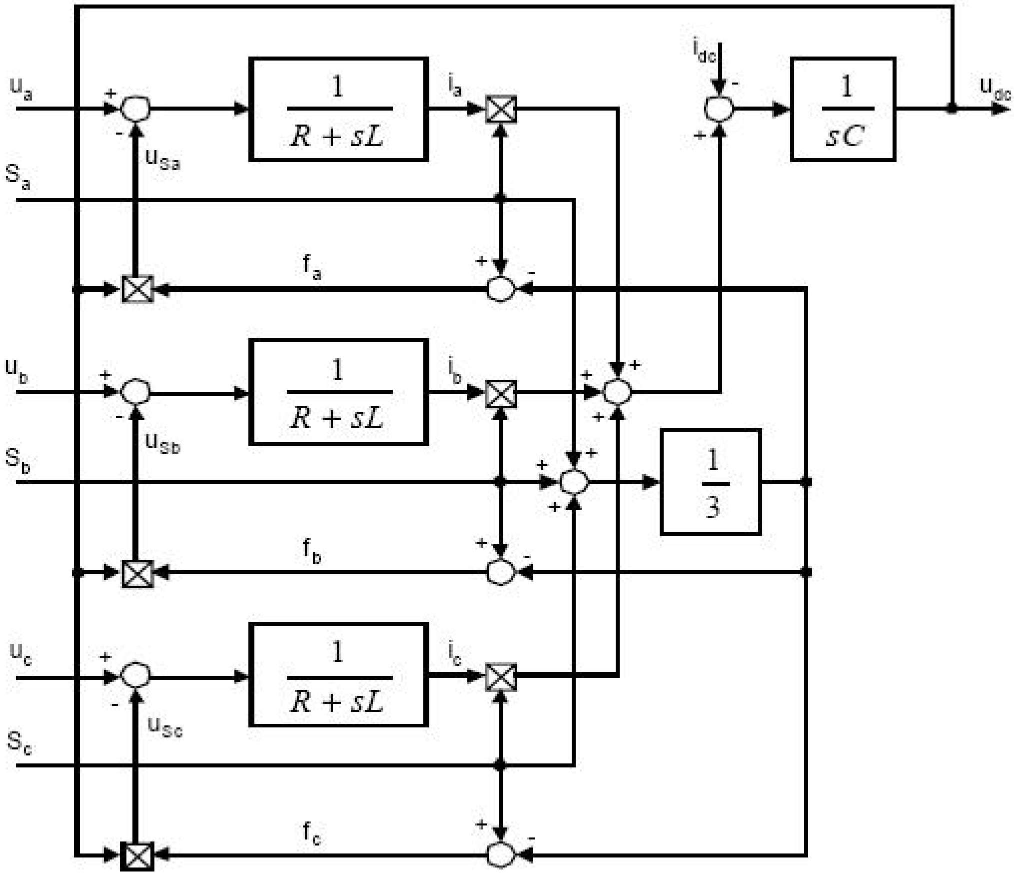

Fig. 2.10 Block diagram of voltage source PWM rectifier in natural three-phase coordinates

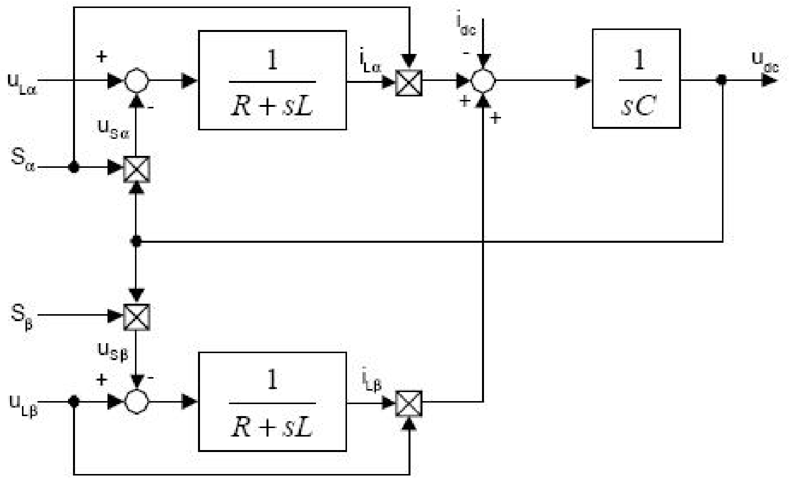

Fig. 2.11 Block diagram of voltage source PWM rectifier in stationary α-β coordinates

Model of PWM Rectifier in stationary coordinates (α - β)

The voltage equation in the stationary α -β coordinates are obtained by applying by using transformations to (2.15) and (2.16) and are written as:

$$\begin{bmatrix} uL\alpha \\ uL\beta \end{bmatrix} = R\begin{bmatrix} iL\alpha \\ iL\beta \end{bmatrix} + L\frac{\mathrm{di}}{\mathrm{dt}}\begin{bmatrix} iL\alpha \\ iL\beta \end{bmatrix} + \begin{bmatrix} uS\alpha \\ uS\beta \end{bmatrix} \quad (2.17)$$

And

$$C\frac{\mathrm{du}_{dc}}{\mathrm{dt}} = (S_\alpha i_{L\alpha} + S_\beta i_{L\beta}) - i_{dc} \quad (2.18)$$

where:

$$S_\alpha = \frac{1}{\sqrt{6}}(2Sa\text{-}Sb\text{-}Sc)\;;\quad S_\beta = \frac{1}{\sqrt{2}}(Sb\text{-}Sc)$$

A block diagram of α-β model is presented in Fig. 2.11.

Model of PWM Rectifier in synchronous rotating coordinates (d-q)

The equations in the synchronous *d-q* coordinates are obtained as:

$$u_{Ld} = Ri_{Ld} + L\frac{\mathrm{di}_{Ld}}{\mathrm{dt}} - \omega Li_{Lq} + u_{Sd} \quad (2.19a)$$

$$u_{Lq} = Ri_{Lq} + L\frac{\mathrm{di}_{Lq}}{\mathrm{dt}} - \omega Li_{Ld} + u_{Sq} \quad (2.19b)$$

$$C\frac{\mathrm{du}_{dc}}{\mathrm{dt}} = (S_\alpha i_{L\alpha} + S_\beta i_{L\beta}) - i_{dc} \quad (2.20)$$

where:

$S_d = S_\alpha \cos\omega t + S_\beta \sin\omega t \qquad S_q = S_\beta \cos\omega t - S_\alpha \sin\omega t$

A block diagram of *d-q* model is presented in Fig. 2.12.

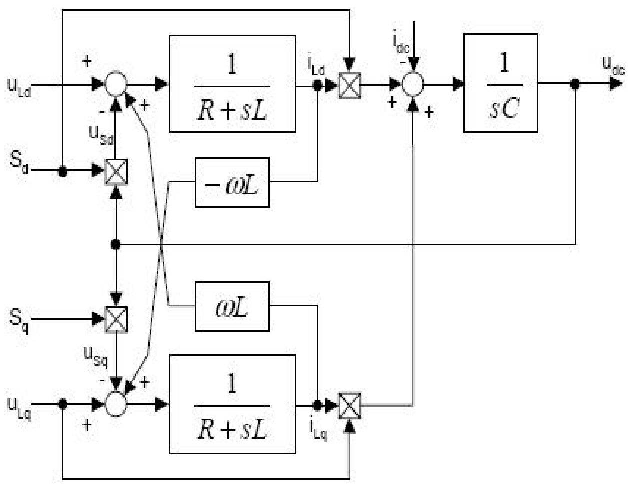

Fig. 2.12 Block diagram of voltage source PWM rectifier in synchronous d-q coordinates

R can be practically neglected because voltage drop on resistance is much lower than voltage drop on inductance, which equations (2.14), (2.15), (2.17), (2.19).can be modified as:

$$u_L = \frac{L\mathrm{di}_L}{\mathrm{dt}} + u_S \quad (2.21)$$

$$\begin{bmatrix} ua \\ ub \\ uc \end{bmatrix} = L\frac{\mathrm{di}}{\mathrm{dt}}\begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} + \begin{bmatrix} usa \\ usb \\ usc \end{bmatrix} \quad (2.22)$$

$$\begin{bmatrix} uL\alpha \\ uL\beta \end{bmatrix} = L\frac{\mathrm{di}}{\mathrm{dt}}\begin{bmatrix} iL\alpha \\ iL\beta \end{bmatrix} + \begin{bmatrix} uS\alpha \\ uS\beta \end{bmatrix} \quad (2.23)$$

$$u_{Ld} = L\frac{\mathrm{di}_{Ld}}{\mathrm{dt}} - \omega Li_{Lq} + u_{Sd} \quad (2.24a)$$

$$u_{Lq} = L\frac{\mathrm{di}_{Lq}}{\mathrm{dt}} - \omega Li_{Ld} + u_{Sq} \quad (2.24b)$$

The active and reactive power supplied from the source is given by

$$p=\mathrm{Re}\,\{u.i^*\} = u_\alpha i_\alpha + u_\beta i_\beta = u_a i_a + u_b i_b + u_c i_c \qquad (2.25)$$

$$q=\mathrm{Im}\,\{u.i^*\} = u_\beta i_\alpha + u_\alpha i_\beta = \frac{1}{\sqrt{3}}(u_{bc} i_a + u_{ca} i_b + u_{ab} i_c) \qquad (2.26)$$

It gives in the synchronous *d-q* coordinates:

$$p = (u_{Lq} i_{Lq} + u_{Ld} i_{Ld}) = \frac{3}{2} E_m I_m \qquad (2.27)$$

$$q = (u_{Lq} i_{Ld} - u_{Ld} i_{Lq}) \qquad (2.28)$$

(if we make assumption of unity power factor, we will obtain following properties

$I_{Lq} = 0$, $uLq = 0$, $u_{Ld} = \sqrt{\frac{3}{2}}$ Em, $i_{Ld} = \sqrt{\frac{3}{2}}$ Im q=0 (see Fig. 2.13)

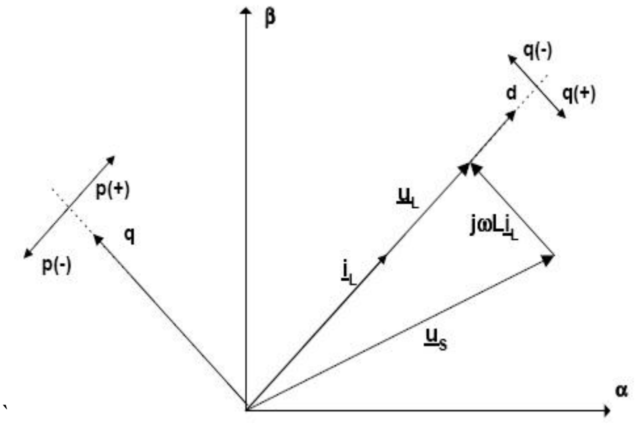

Fig. 2.13 Power flow in bi-directional AC/DC converter as dependency of *iL* direction.

2.4 Sensorless Control of PWM Rectifier

Normally, the PWM rectifier needs three kinds of sensors:

- DC-voltage sensor (1 sensor)
- AC-line current sensors (2 or 3 sensors)
- AC-line voltage sensors (2 or 3 sensors)

The sensorless methods provide technical and economical advantages such as simplification, isolation between the power circuit and control system, reliability and cost effectiveness. The possibilities to reduce the number of the expensive sensors have been studied especially in the field of motor drive application, but the rectifier applications differ from the inverter operation in the following reasons:

- Zero vector will shorted the line power,
- The line operates at constant frequency 50Hz and synchronization is necessary.

The most commonly used solution for reducing of sensors includes:

- AC voltage and current sensorless,
- AC current sensorless,
- AC voltage sensorless.

AC voltage and current sensorless

The two phase currents may be estimated based on information of DC link current and reference voltage vector in every PWM period. No fully protection is main practical problem in this system. Particularly for PWM rectifier the zero vectors (*U0*, *U7*) presents no current in DC-link and three line phases are short circuit simultaneously. New improved method is to sample DC-link current few times in one switching period. Basic principle of current reconstruction is shown in Fig. 2.14 together with a voltage vector's patterns determining the direction of current flow. One active voltage vector takes it to reconstruct one phase current and another voltage vector is used to reconstruct a second phase current using values measured from DC current sensor. A relationship between the applied active vectors and the phase currents measured from DC link sensor is shown in TABLE 2.2, which is based on eight voltage vectors composed of six active vectors and two zero vectors.

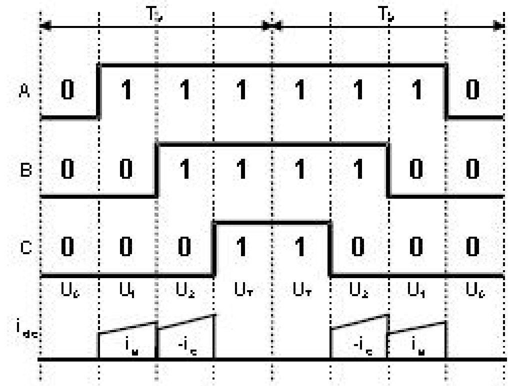

Fig. 2.14 PWM signals and DC link current in sector I

Table: 2.2 Relationship between voltage vectors, DC-link current and line currents.

Voltage Vector	DC link current i_{dc}
U_1(100)	$+i_a$
U_2(110)	$-i_c$
U_3(010)	$+i_b$
U_4(011)	$-i_a$
U_5(001)	$+i_c$
U_6(101)	$-i_b$
U_0(000)	0
U_7(111)	0

The main problem of AC current estimation based on minimum pulse-time is DC-link current sampling. It appears when either of two active vectors is not present, or is applied only for a short time. In such a case, it is impossible to reconstruct phase current. This occurs in the case of reference voltage vectors passing one of the six possible active vectors or a low modulation index (Fig. 2.15). The minimum short time to obtain a correct estimation depends on the rapidness of the system, delays, cable length and *dead-time*. The way to solve the problem is to adjust the PWM-pulses or to allow that no currents information is present in some time period. Therefore improved compensation consists of calculating the error, which are introduced by the PWM pulse adjustment and then compensate this error in the next switching period.

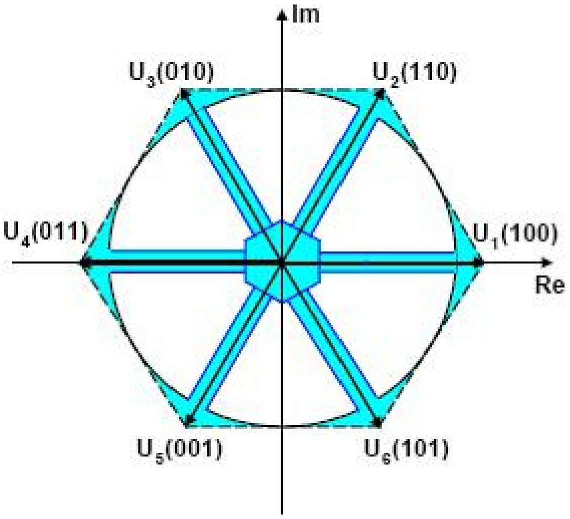

Fig. 2.15. Voltage vector area requiring the adjustment of PWM signals, when a reference voltage passes one of possible six active vectors and in case of low modulation index and over modulation

The AC voltage and current sensorless methods in spite of cost reduction posses several disadvantages: higher contents of current ripple, problems with discontinuous modulation and over modulation mode ,sampling is presented few times per switching state which is not technically convenient, unbalance and start up condition are not reported.

AC current sensorless

This method provides simple solution based on inductor voltage (*uL*) measurement in two lines. Supply voltage can be estimated with assumption that voltage on inductance is equal to line voltage when the zero-vector occurs in converter (Fig. 2.16)

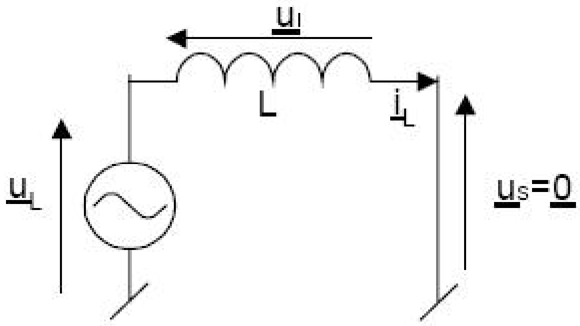

Fig. 2.16. PWM rectifier circuit when the zero voltage vector is applied.

On the basis of the inductor voltage described in equation (2.34)

$$u_{lR} = L\frac{di_{LR}}{dt} \qquad (2.34)$$

the line current can be calculated as:

$$i_{LR} = \frac{1}{L}\int u_{lR}\,dt \qquad (2.35)$$

Equation (2.35) represents current will not be affected by derivation noise, but it directly reduces the dynamic of the control. This gains problems with over-current protection.

AC voltage sensorless

Previous solutions present some over voltage and over current protection troubles. Therefore the *DC*-voltage and the *AC*-line current sensors are an important part of the over-voltage and over-current protection, while it is possible to replace the *AC*-line voltage sensors with a line voltage estimator or virtual flux estimator.

Different control strategies are discussed in Part-II.

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