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

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4. Virtual Flux based Direct Power Control

4.1 Introduction

DPC is based on the instantaneous active and reactive power control loops. In DPC there are no internal current control loops and no PWM modulator block, because the converter switching states are 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 of the DPC implementation is a correct and fast estimation of the active and reactive line power.

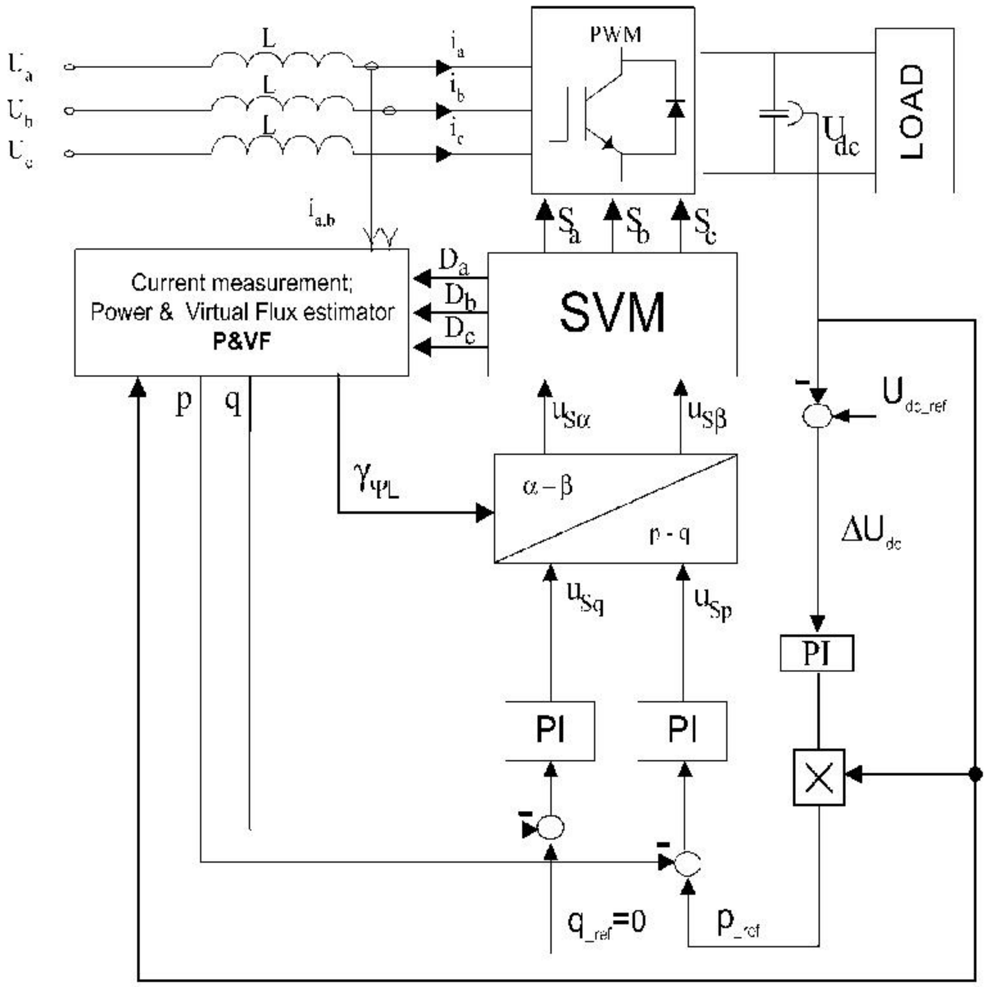

Fig. 4.1 Block scheme of Direct Power Control

4.2 Direct Power Control (DPC)

4.2.1 Virtual Flux Estimator

It is possible to replace the ac-line voltage sensors with a virtual flux estimator, which gives technical and economical advantages to the system such as simplification, isolation between the power circuit and control system, reliability, and cost effectiveness. The voltages imposed by the line power in combination with the ac-side inductors are assumed to be quantities related to a virtual ac motor as shown in Fig. 4.2(a). Thus, R and L represent the stator resistance and the stator leakage inductance of the virtual motor and line-to-line voltage: Uab, Ubc, Uca would be induced by a virtual air-gap flux. In other words the integration of the voltages leads to a virtual flux (VF) vector, ψL in stationary α- β coordinates [Fig. 4.2(b)].

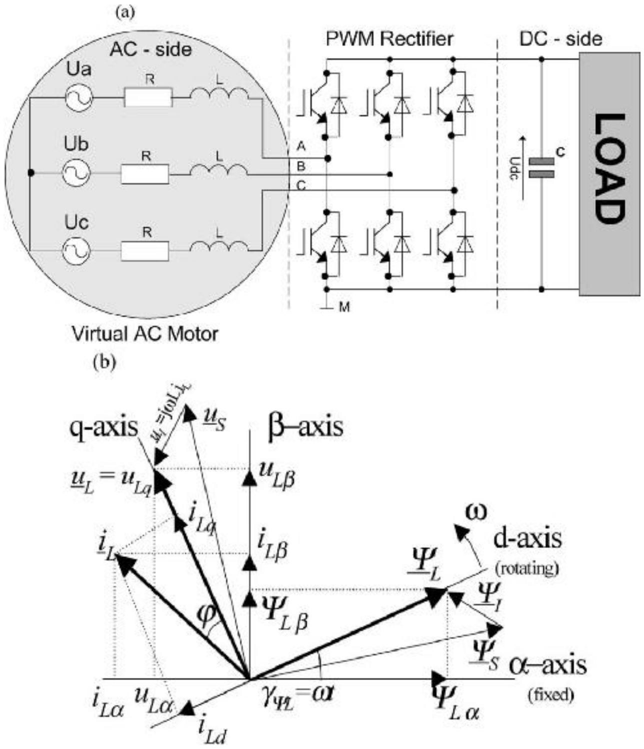

Fig. 4.2. (a) Three-phase PWM rectifier system with ac side presented as virtual ac motor.

(b) Reference coordinates and vectors: ψ_L - virtual flux vector of line; ψs- virtual flux vector of converter; ψ_l - virtual flux vector of inductor; u_s - converter voltage vector; u_L - line voltage vector; u_l - inductance voltage vector; i_L - line current vector.

$$\underline{\psi_L}=\begin{bmatrix}\psi L\alpha\\ \psi L\beta\end{bmatrix}=\begin{bmatrix}\int uL\alpha dt\\ \int uL\beta dt\end{bmatrix} \quad (4.1)$$

where

$$uL=\begin{bmatrix}uL\alpha\\ uL\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 1/2\\ 0 & \sqrt{3}/2\end{bmatrix}\begin{bmatrix}uab\\ ubc\end{bmatrix} \quad (4.2)$$

When we establish that

$$u_L=u_S+u_I \quad (4.3)$$

then, similarly to (4.3) a VF equation can be presented as

$$\underline{\psi_L}=\underline{\psi_S}+\underline{\psi_I} \quad (4.4)$$

Based on the measured dc-link voltage U_{dc} and the duty cycles of modulator D_a,D_b,D_c the virtual flux ψ_L components are calculated in stationary (α –β) coordinates system in the block (P&VF) as follows:

$$\psi_{L\alpha}=\int(\sqrt{\frac{2}{3}}U_{dc}(D_a-\frac{1}{2}(D_b+D_c)))dt+Li_{L\alpha} \quad (4.5a)$$

$$\psi_{L\beta}=\int(\sqrt{\frac{1}{2}}U_{dc}(D_b-D_c))dt+Li_{L\beta} \quad (4.5b)$$

4.3 Instantaneous Power Estimation Based on Voltage

The instantaneous values of active (p) and reactive power (q) are estimated by (4.6a) and (4.6b).It is known that the active power is scalar product of the current and the voltage, whereas the reactive power q is calculated as a vector product of them. The first part of both equations represents power in the inductance and the second part is the power of rectifier.

$$p=L(\frac{di_a}{dt}i_a+\frac{di_b}{dt}i_b+\frac{di_c}{dt}i_c)+U_{dc}(S_Ai_a+S_Bi_b+S_Ci_c) \quad (4.6a)$$

$$q=3L\frac{1}{\sqrt{3}}(\frac{di_a}{dt}i_c-\frac{di_c}{dt}i_a)-Udc[S_A(i_b-i_c)+S_B(i_c-i_b)+S_C(i_a-i_b)]) \quad (4.6b)$$

where:

S_A, S_B & S_C are the switching states of the PWM rectifier
ia, ib, ic are measured line currents
L is the inductance between the grid and the PWM rectifier.

In spite of the simplicity of power estimation, this solution possesses several disadvantages such as:

- High values of the inductance and sampling frequency are needed (important point for the estimator, because smooth shape of current is needed).
- Power estimation depends on the switching state therefore calculation of the power and voltage should be avoided at the moment of switching, because this gives high errors of the estimated values

4.4 Instantaneous Power Estimation Based on Virtual Flux

The measured line currents ia, ib and the estimated virtual flux components $\psi_{L\alpha}$, $\psi_{L\beta}$ are used to the power estimation. Using (4.3) the voltage equation can be written as (in practice, R can be neglected)

$$u_L=\begin{bmatrix}uL\alpha\\ uL\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 1/2\\ 0 & \sqrt{3}/2\end{bmatrix}\begin{bmatrix}uab\\ ubc\end{bmatrix} \quad (4.7)$$

$$\underline{\psi_L}=\int \underline{uL}\,dt$$

$$\underline{\psi_L}=\begin{bmatrix}\psi L\alpha\\ \psi L\beta\end{bmatrix}=\begin{bmatrix}\int uL\alpha dt\\ \int uL\beta dt\end{bmatrix} \quad (4.8)$$

$$i_L=\begin{bmatrix}iL\alpha\\ iL\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}3/2 & 0\\ \sqrt{3}/2 & \sqrt{3}\end{bmatrix}\begin{bmatrix}ia\\ ib\end{bmatrix} \quad (4.9)$$

$$u_S=u_{conv}=\begin{bmatrix}uS\alpha\\ uS\beta\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\begin{bmatrix}uAM\\ uBM\\ uCM\end{bmatrix} \quad (4.10)$$

In practice R can be neglected, which gives

$$\underline{u_L}=L\frac{di_L}{dt}+\frac{d\psi_S}{dt}=L\frac{di_L}{dt}+\underline{u_S} \quad (4.11)$$

Using complex notation, the instantaneous power can be calculated as follows:

$$p=Re(\underline{u_L}, i_L^*) \quad (4.12a)$$

$q = \text{Im}(\underline{u}_L, \underline{i}_L^*)$ (4.12b)

where * denotes conjugate of the line current vector. The line voltage can be expressed by the VF as

$$u_L = \frac{d\psi_L}{dt} = \frac{d(\psi_L e^{j\omega t})}{dt} = \frac{d\psi_L e^{j\omega t}}{dt} + j\omega\psi_L e^{j\omega t} = \frac{d\psi_L e^{j\omega t}}{dt} + j\omega\underline{\psi_L} \quad (4.13)$$

where $\underline{\psi_L}$ denotes the space vector and ψ_L its amplitude. For VF-oriented quantities, in α –β coordinates [Fig.4.2 (b)] and using (4.11) and (4.12)

$$u_L = \frac{d\psi_L}{dt}|_\alpha + j\,\frac{d\psi_L}{dt}\,|_\beta + j\omega\,(\psi_{L\alpha} + j\,\psi_{L\beta})\,) \quad (4.14)$$

$$u_L i_L^* = \{\frac{d\psi_L}{dt}|_\alpha + j\,\frac{d\psi_L}{dt}\,|_\beta + j\omega\,(\psi_{L\alpha} + j\,\psi_{L\beta})\,\}(i_{L\alpha} - j\,i_{L\beta}) \quad (4.15)$$

which gives

$$p = \{\frac{d\psi_L}{dt}|_\alpha i_{L\alpha} + j\,\frac{d\psi_L}{dt}\,|_\beta i_{L\beta} + \omega\,(\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha})\,\} \quad (4.16a)$$

and

$$q = \{-\frac{d\psi_L}{dt}|_\alpha i_{L\beta} + j\,\frac{d\psi_L}{dt}\,|_\beta i_{L\alpha} + \omega\,(\psi_{L\alpha} i_{L\alpha} + \psi_{L\beta} i_{L\beta})\,\} \quad (4.16b)$$

For sinusoidal and balanced line voltage the derivatives of the flux amplitudes are zero. The instantaneous active and reactive powers can be computed as

$p = \omega.\ (\psi_{L\alpha}\, i_{L\beta} - \psi L\beta\, i_{L\alpha})$ (4.17a)

$q = \omega.\ (\psi_{L\alpha}\, i_{L\alpha} + \psi_{L\beta}\, i_{L\beta})$ (4.17b)

4.4.1 Block Scheme of DPC

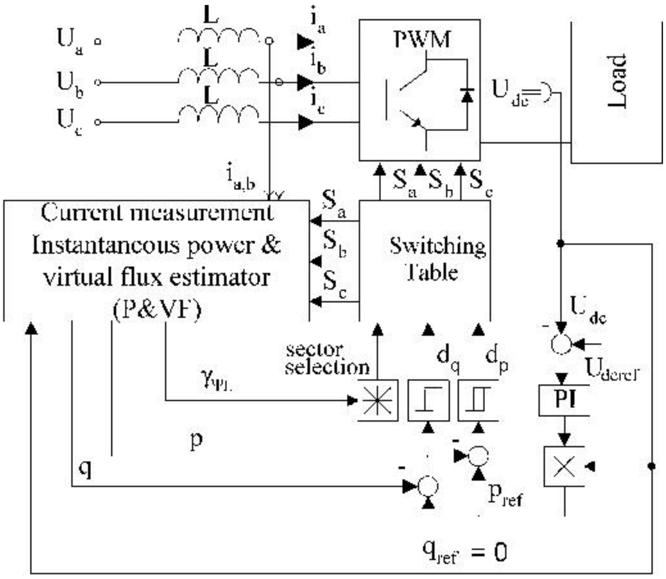

Fig.4.3.Block scheme of VF-DPC.

Fig. 4.3 shows the configuration of conventional DPC, where the commands of reactive power q_{ref} (set to zero for unity power factor) and active power p_{ref} (delivered from the outer proportional–integral (PI) dc voltage controller) are compared with the estimated and values [(4.17a) and (4.17b)], in reactive and active power hysteresis controllers, respectively. The digitized variables, dp, dq and the line voltage vector position $\gamma UL = arctg(uL\alpha / uL\beta)$ form a digital word, which by accessing the address of the lookup table selects the appropriate voltage vector according to the switching table

However, disturbances superimposed on the line voltage influence directly the line voltage vector position in the control system. Sometimes, this problem is overcome by phase-locked loops (PLLs) only, but the quality of the controlled system depends on how effectively the PLLs have been designed. Therefore, it is easier to replace angle of the line voltage vector γ_{UL} by angle of *VF* vector, $\gamma_{\psi L}$= arctg ($\psi_{L\alpha}/\ \psi_{L\beta}$) because $\gamma_{\psi L}$ is less sensitive than γ_{UL} to disturbances in the line voltage, thanks to the natural low-pass behavior of the integrators in the estimator [(4.5a) and (4.5b)} For this reason, it is not necessary to implement PLLs to achieve robustness in the flux-oriented scheme.

4.4.2 Block Scheme of DPC Using Space-Vector Modulation (DPC-SVM)

The concept of DPC and VF can also be applied to new control scheme. The DPC-SVM with constant switching frequency uses closed-loop power control, as shown in Fig.4.4.

The commanded reactive power (set to zero for unity power factor operation) and (delivered from the outer PI dc voltage controller) active power (power flow between the supply and the dc link) values are compared with the estimated and values (4.17(a) and 4.17(b)), respectively. The errors are delivered to PI controllers, where the variables are dc quantity, which eliminates steady-state error. The output signals from the PI controllers after transformation described as

$$\begin{bmatrix} uS\alpha \\ uS\beta \end{bmatrix} = \begin{bmatrix} -\sin\gamma\psi L - \cos\gamma\psi L \\ \cos\gamma\psi L - \sin\gamma\psi L \end{bmatrix} \begin{bmatrix} uSp \\ uSq \end{bmatrix} \quad (4.18)$$

Where

$$\sin\gamma_{\psi L} = \frac{\psi_{L\beta}}{\sqrt{\psi_{L\alpha}^{\ 2} + \psi_{L\beta}^{\ 2}}} \quad (4.19a)$$

$$\cos\gamma_{\psi L} = \frac{\psi_{L\alpha}}{\sqrt{\psi_{L\alpha}^{\ 2} + \psi_{L\beta}^{\ 2}}} \quad (4.19b)$$

are used for switching signals generation by the space-vector modulator (SVM).

4.4.3 Synthesis of Controllers

Direct power control with space vector modulation – DPC-SVM guarantees high dynamics and static performance via an internal power control loops. This method joins the concept of DPC and V-FOC. The active and reactive power is used as control variables instead of the line currents. The DPC-SVM with constant switching frequency uses closed active and reactive power control loops (Fig. 4.1.). The command active power *P c*are generated by outer DC-link voltage controller, whereas command reactive power *Q c* is set to zero for unity power factor operation. These values are compared with the estimated *P* and *Q* values respectively. Calculated errors P*e* and *Q e* are delivered to *PI* power controllers. Voltages generated by power controllers are *DC* quantities, what eliminates steady state error (PI controllers features), as well as in V-FOC. Then after transformation to stationary αβ coordinates, the voltages are used for switching signals generation by SVM block. The proper design of the power controller parameters is very important.

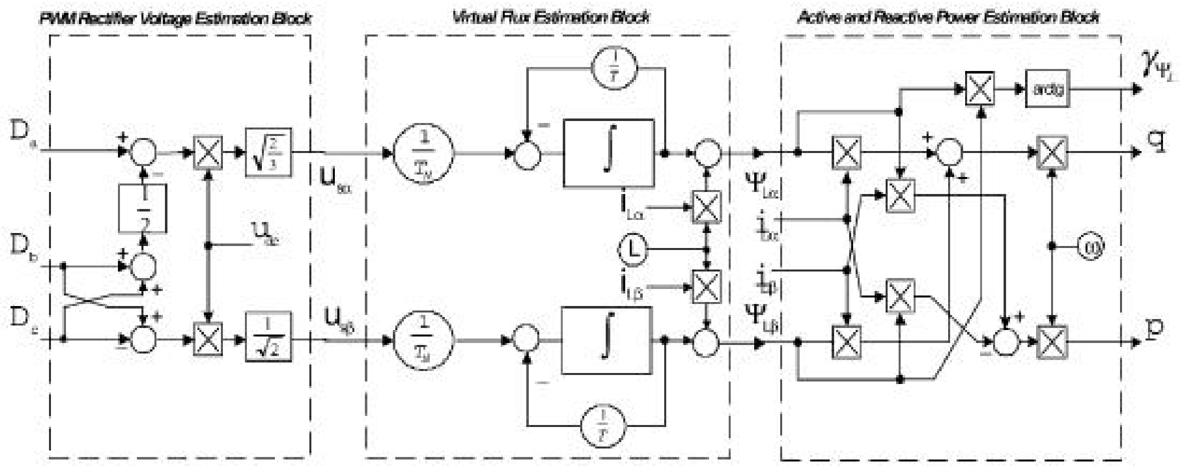

Fig. 4.4. (a) Block scheme of DPC-SVM. (b) Block scheme of DPC-SVM estimators (P&VF).

Power Controllers

A block diagram for a simplified power control loop in the synchronous *xy* Rotating coordinates (Fig. 4.5) is presented. Since, the same block diagram applies to both *P* and *Q* power controllers, description only for *P* active power control loop will be presented.

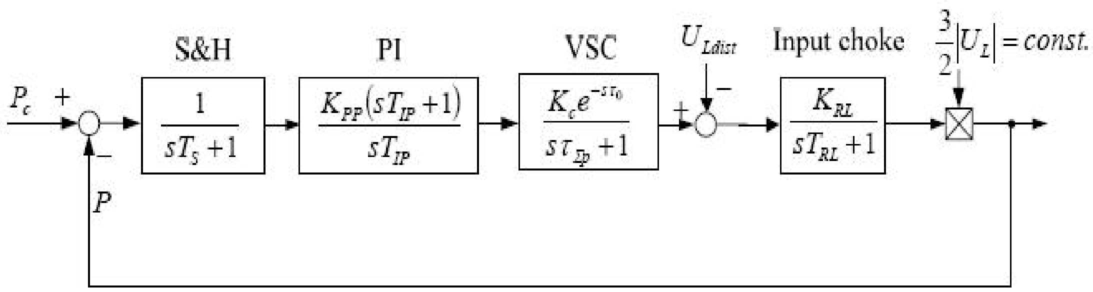

Fig. 4.5. Block diagram for a simplified active power control loop in the synchronous rotating reference frame

The model of Fig. 4.5 can be modified as shown in Fig. 4.6, where sum of the small time constants is defined by:

$$\tau \sum p = Ts + Tpwm \quad (4.20)$$

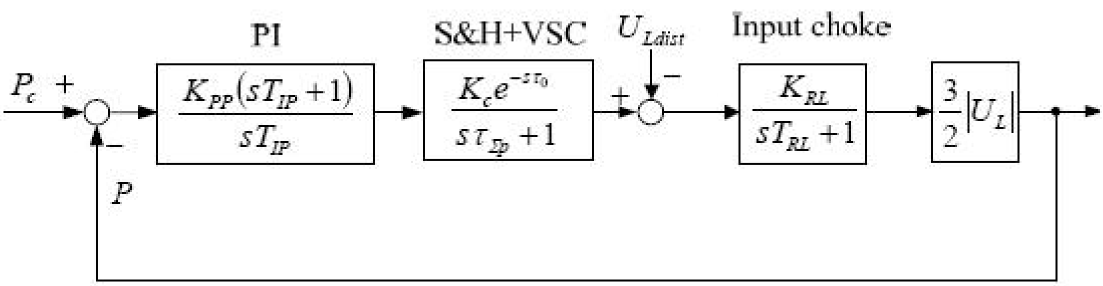

Fig. 4.6. Modified block diagram of Fig. 4.5

TΣp is a sum of small time constants, T_{RL}= R/L is a large time constant and K_{RL} =1/R is a gain of the input choke. From several methods of design, symmetry optimum - SO is chosen because its good response to a disturbance *U Ldist* step. For *U L= const,* the following open loop transfer function can be derived:

$$G_{op}(s) = \frac{K_{RL}\ K_{PP}\ (1+sT_{IP})}{sT_{IP}(s\tau\sum p+1)(sT_{RL}+1)} \times \frac{3}{2}|U_L| \quad (4.21)$$

With simplification (sT_{RL}+1) ≈sT_{RL} gives following closed loop transfer function for power control loop:

$$G_{zp}(s)=\frac{K_{RL}\ K_{PP}\ (1+sT_{IP})}{K_{RL}\ K_{PP}\ (1+sT_{IP})+s^2T_{IP}T_{RL}\ +s^3T_{IP}T_{RL}}\times\frac{3}{2}|U_L| \quad (4.22)$$

For this relation the proportional gain and integral time constant of the PI current controller can be calculated as:

$$K_{PP}\ =\ \frac{T_{RL}}{2\ K_{RL}}\times\frac{2}{3}|U_L| \quad (4.23)$$

$$T_{IP}\ = 4\tau\sum p \quad (4.24)$$

UL = line- line voltage

DC-link Voltage Controller

For DC-link voltage controller design, the inner current or power control loop can be modeled with the first order transfer function. The power control loop of voltage source rectifier – VSR can be approximated in further consideration by first order block with equivalent time constant T IT.

$$G_{pz}(s)=\frac{1}{1+s\ T_{\ IT}} \quad (4.25)$$

Where, $T_{\ IT} = 2\tau\sum p$ for power controllers designed by MO criterion or $T_{\ IT}\ =\ 4\tau\sum p$ for power controllers designed by SO criterion. Therefore, the DC-link voltage control loop can be modeled as in Fig. 4.7.

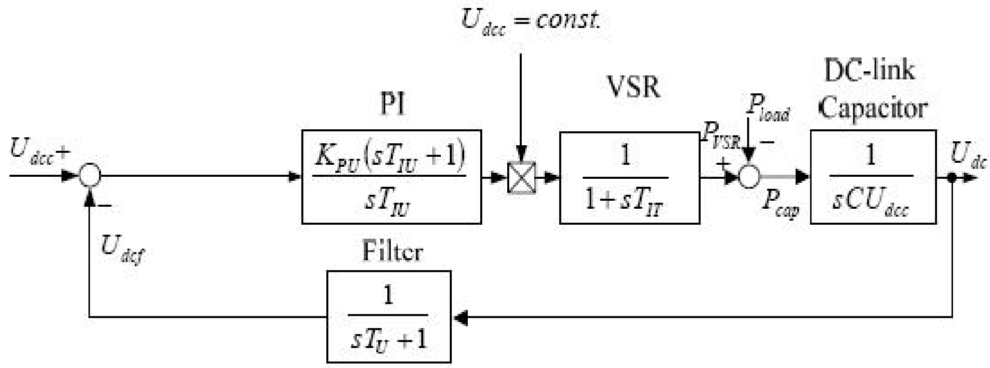

Fig. 4.7. Block diagram for a simplified DC-link voltage control loop

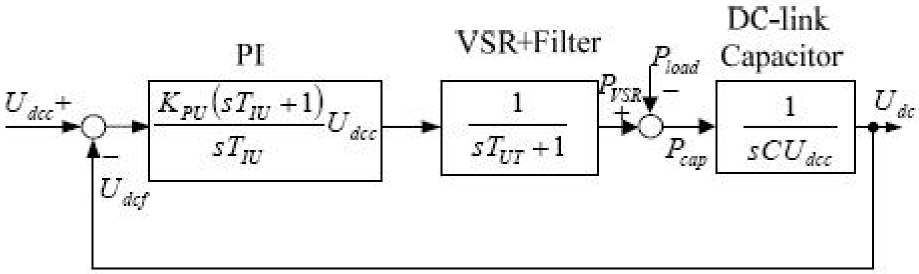

Fig. 4.8. Modified block diagram of Fig. 4.7

The block diagram of Fig. 4.7 can be modified as shown in Fig. 4.8.

For simplicity it can be assumed that

$$T_{UT} = T_U + T_{IT} \quad (4.26)$$

Where, *TU* is DC-link voltage filter time constant, *T UT* is a sum of small time constants and *CUdcc* is an equivalent of integration time constant. So, the open loop transfer function can be derived:

$$G_{Uo}(s)=\frac{K_{PU}(sT_{IU}\ +1)}{sT_{IU}(sT_{UT}\ +1)sCU_{dcc}} \quad (4.27)$$

This gives following closed loop transfer function:

$$G_{Uz}(s)=\frac{K_{PU}(sT_{IU}+1)}{K_{PU}(sT_{IU}+1)+s^2T_{IU}CU_{dcc}+s^3T_{IU}\ T_{UT}CU_{dcc}} \quad (4.28)$$

Hence, proportional gain *K PU* and integral time constant *T IU* of the DC-link voltage
controller can be calculated as follows:

$$K_{PU}=\frac{C}{2T_{UT}}\times U_{dcc} \quad (4.29)$$

$$T_{IU} = 4T_{UT} \quad (4.30)$$

U_{dcc} = output voltage

The goal of the control system is to maintain the DC-link voltage *U*dc, at the required level, while currents drawn from the power system should be sinusoidal like and in phase with line voltage to satisfy the *unity power factor* – UPF condition. The UPF condition is fulfill when the line current vector, $I_L = I_{Lx} + jI_{Ly}$, is aligned with the phase voltage vector, $U_L = U_{Lx} + jU_{Ly}$, of the line.

Control structure will operates in discontinuous environment therefore, it is necessary to take into account the sampling period *Ts*. It could be done by *sample & hold* – S&H block. Moreover, the statistical delay of the PWM generation $Ts\ pwm = 0.5Ts$ should be taken into account.

5. Direct Power Control with Active Filtering

5.1 Introduction

Harmonics-related problems in utility are due to the equipments connected, such as a diode or thyristor rectifiers, which takes non sinusoidal currents from the grid or any electronic equipments. To eliminate harmonic currents due to power electronic converters, active power filters and PWM rectifiers are used.. Both of them have basically the same circuit configuration and can operate based on the same control principle. Active filters are able to compensate not only current harmonics, but also a reactive power and unbalance of load. PWM Rectifiers as a non-polluting equipment with sinusoidal input currents are going to be more popular because of several advantages described as:-

- Precise regulation of output DC voltage,
- Low harmonic distortion of line currents,
- Near sinusoidal current waveforms,
- Regulation of input power factor to unity,
- Bi-directional power flow.

Active filtering function, which offers the advantages of active filters and PWM rectifiers. So, the PWM rectifiers supply its load and at the same time compensate AC line current (Fig.4.9) The Virtual Flux based Direct Power Control (DPC with Space Vector Modulator (SVM) is applied to control of a PWM rectifier.

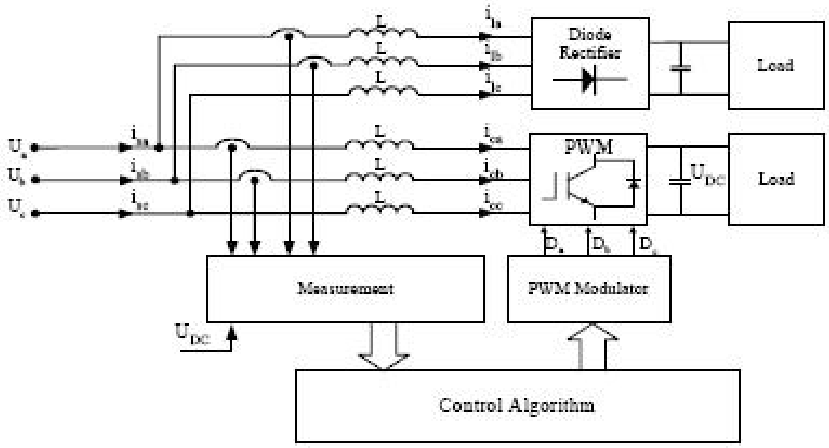

Fig 5.1.Block scheme of PWM Rectifier with active filtering function

5.2 Principles of Power Estimation

It is economically motivated to replace the AC-line voltage sensors with a virtual flux (VF) estimator. The principle of VF is based on assumption that the voltages imposed by the line power in combination with the AC side inductors can be quantities related to a virtual AC motor (see Fig.4.2 (a)). Where *R* and *L* represent the stator resistance and leakage inductance of the virtual motor. Phase-to-phase line voltages: *Uab*, *Ubc*, *Uca* can be considered as induced by a virtual flux. Hence the integration of the voltages leads to a virtual flux vector ΨL , in stationary α-β coordinates as follows:

$$\underline{\psi_L} = \begin{bmatrix} \psi L\alpha \\ \psi L\beta \end{bmatrix} = \begin{bmatrix} \int uL\alpha dt \\ \int uL\beta dt \end{bmatrix} \quad (5.1)$$

where

$$uL = \begin{bmatrix} uL\alpha \\ uL\beta \end{bmatrix} = \sqrt{(2/3)} \begin{bmatrix} 1 & 1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} uab \\ ubc \end{bmatrix} \quad (5.2)$$

When we establish that

$$u_L = u_S + u_I \quad (5.3)$$

then, similarly to (4.3) a VF equation can be presented as

$$\underline{\psi_L} = \underline{\psi_S} + \underline{\psi_I} \quad (5.4)$$

Based on the measured dc-link voltage U_{dc} and the duty cycles of modulator D_a, D_b, D_c the virtual flux ψ_L components are calculated in stationary (α –β) coordinates system in the block (P&VF) as follows:

$$\psi_{L\alpha} = \int (\sqrt{2/3}Udc(Da - 1/2(Db + Dc)))dt + LiL\alpha \quad (5.5a)$$

$$\psi_{L\beta} = \int (\sqrt{1/2}Udc(Db - Dc))dt + LiL\beta \quad (5.5b)$$

$$\underline{u_L} = Ri_L + di_L/dt + d\,\underline{\psi_S}/dt \quad (5.6)$$

In practice R can be neglected, which gives

$$\underline{u_L} = L\,di_L/dt + d\,\underline{\psi_S}/dt = Ldi_L/dt + \underline{u_S} \quad (5.7)$$

Using complex notation, the instantaneous power can be calculated as follows:

$$p = Re(\underline{u_L}, i_L^*) \quad (5.8a)$$

$$q = Im(\underline{u_L}, \underline{i_L}^*) \quad (5.8b)$$

where * denotes conjugate of the line current vector. The line voltage can be expressed by the VF as

$$u_L = d\,\underline{\psi_L}/dt = d(\psi_L e^{j\omega t})/dt = d(\psi_L e^{j\omega t})/dt + j\omega\,\psi_L e^{j\omega t} = d(\psi_L e^{j\omega t})/dt + j\omega\,\underline{\psi_L} \quad (5.9)$$

where denotes the space vector and its amplitude. For VF-oriented quantities, in – coordinates [Fig.4.2 (b)] and using (4.11) and (4.12)

$$u_L = d\underline{\psi_L}/dt|_\alpha + j\,d\,\underline{\psi_L}/dt|_\beta + j\omega(\psi_{L\alpha} + j\,\psi_{L\beta}) \quad (5.10)$$

$u_L i_L^* = \{d\underline{\psi_L}/dt\,|_\alpha + j\, d\, \underline{\psi_L}\,/dt\,|_\beta + j\omega\,(\psi_{L\alpha} + j\,\psi_{L\beta})\}(i_{L\alpha} - j\, i_{L\beta})$ (5.11)

which gives

$p=\{d\underline{\psi_L}/dt|_\alpha\, i_{L\alpha} + j\, d\, \underline{\psi_L}\,/dt\,|_\beta\, i_{L\beta}\,(\psi_{L\alpha}\, i_{L\beta} - j\,\psi_{L\beta}\, i_{L\alpha})\}$ (5.12a)

and

$q= \{-d\underline{\psi_L}/dt|_\alpha i_{L\beta} + j\, d\, \underline{\psi_L}\,/dt\,|_{\beta}\, i_{L\alpha}\,(\psi_{L\alpha}\, i_{L\alpha} + j\,\psi_{L\beta}\, i_{L\beta})\}$ (5.12b)

For sinusoidal and balanced line voltage the derivatives of the flux amplitudes are zero. The instantaneous active and reactive powers can be computed as

$p=\omega.\,(\psi_{L\alpha} i_{L\beta} - j\,\psi_{L\beta}\, i_{L\alpha})$ (5.13a)

$q=\omega.\,(\psi_{L\alpha} i_{L\alpha} + j\,\psi_{L\beta}\, i_{L\beta})$ (5.13b)

5.3 Control Algorithm of PWM Rectifier with Active Filtering Function

Control algorithm presented in Fig. 4.11. is divided into two parts: active rectifier and active filtering operation described bellow.

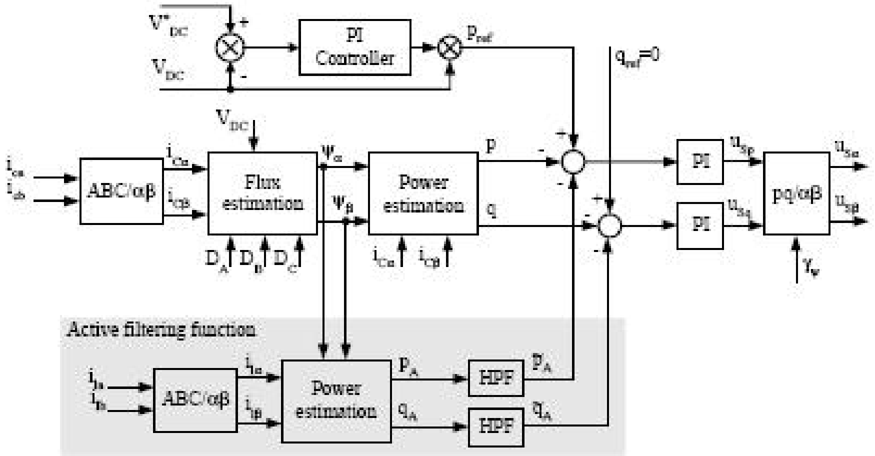

Fig.5.3. Block scheme of control strategy

5.3.1. PWM Rectifier operation

The commanded (delivered from the outer PI DC voltage controller) active power p_{ref} and reactive power q_{ref} (set to zero for unity power factor) values are compared with the estimated instantaneous p and q values, respectively. The errors are delivered to PI controllers, where the variables are DC quantities and steady state error were eliminated. The output signals from PI controllers after transformation described as:

$$\begin{bmatrix} uS\alpha \\ uS\beta \end{bmatrix} = \begin{bmatrix} -\sin\gamma\psi L - \cos\gamma\psi L \\ \cos\gamma\psi L - \sin\gamma\psi L \end{bmatrix} \begin{bmatrix} uSp \\ uSq \end{bmatrix} \quad (5.14)$$

where:

$$\sin\gamma_{\psi L} = \frac{\psi_{L\beta}}{\sqrt{(\psi_{L\alpha}{}^2 + \psi_{L\beta}{}^2}} \quad (5.15a)$$

$$\cos\gamma_{\psi L} = \frac{\psi_{L\beta}}{\sqrt{\psi_{L\alpha}{}^2 + \psi_{L\beta}{}^2}} \quad (5.15b)$$

are used as a reference signals for Space Vector Modulator.

5.3.2. Active Filtering operation

In 1983, Akagi has proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also known as instantaneous power theory , or p-q theory. It was used to calculate the reference compensation currents in the α -β coordinates .This presents modified algorithm based on virtual flux, which operates directly on instantaneous active and reactive power components. The instantaneous active and reactive powers are estimated using currents intended to compensate (diode rectifier input currents see Fig.(4.9.) and virtual flux according to Eqs (4.43a and 4.43b) as:

$p_A=\omega.\,(\psi_{L\alpha} i_{L\beta} - j\psi_{L\beta} i_{L\alpha})$ (5.16a)

$q_B=\omega.\,(\psi_{L\alpha} i_{L\alpha} + j\psi_{L\beta} i_{L\beta})$ (5.16b)

The calculated active power (pA) and reactive power (qA) are delivered to the high pass filter to obtain the variable value of the instantaneous active power (¯pA) and reactive power (¯qA) which finally are used as compensating components. Enclosure of active filtering function will cause suitable distortion of input PWM rectifier current. This will assure almost sinusoidal line current. It permits to use non polluting equipment what is PWM rectifier as a current harmonics eliminating device.

6. Modelling and Simulation of Control Strategies

6.1 Voltage Oriented Control

In Voltage Oriented Control (*VOC*) control system uses closed-loop current control in rotating reference frame. A characteristic feature for this current controller is processing of signals in two coordinate systems. The first is stationary α-β and the second is synchronously rotating *d-q* coordinate system. Three phase measured values are converted to equivalent two phase system α-β and then are transformed to rotating coordinate system in a block α-β*/d-q*.

By using equations 3.1 (a), 3.1(b), 3.2(a), 3.2(b), 3.13, 3.14, and 3.15, simulink block for control system was developed for Voltage Oriented Control which is shown in Fig.6.1

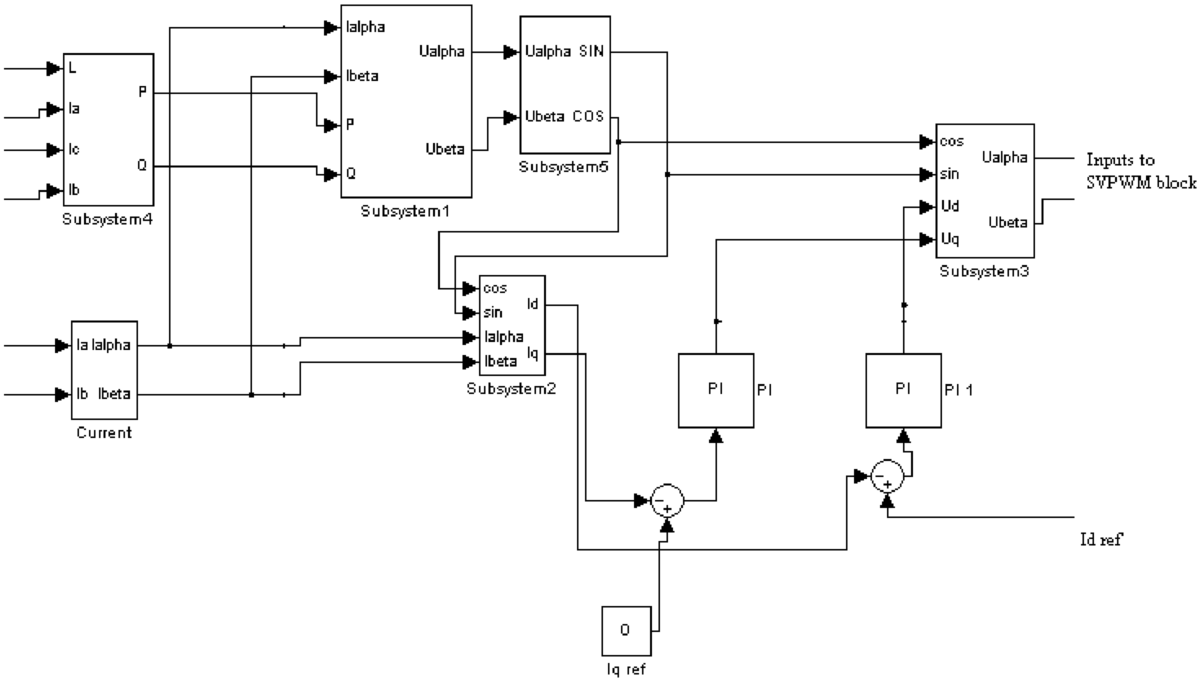

Fig 6.1.Simulink block for Voltage Oriented Control (*VOC*)

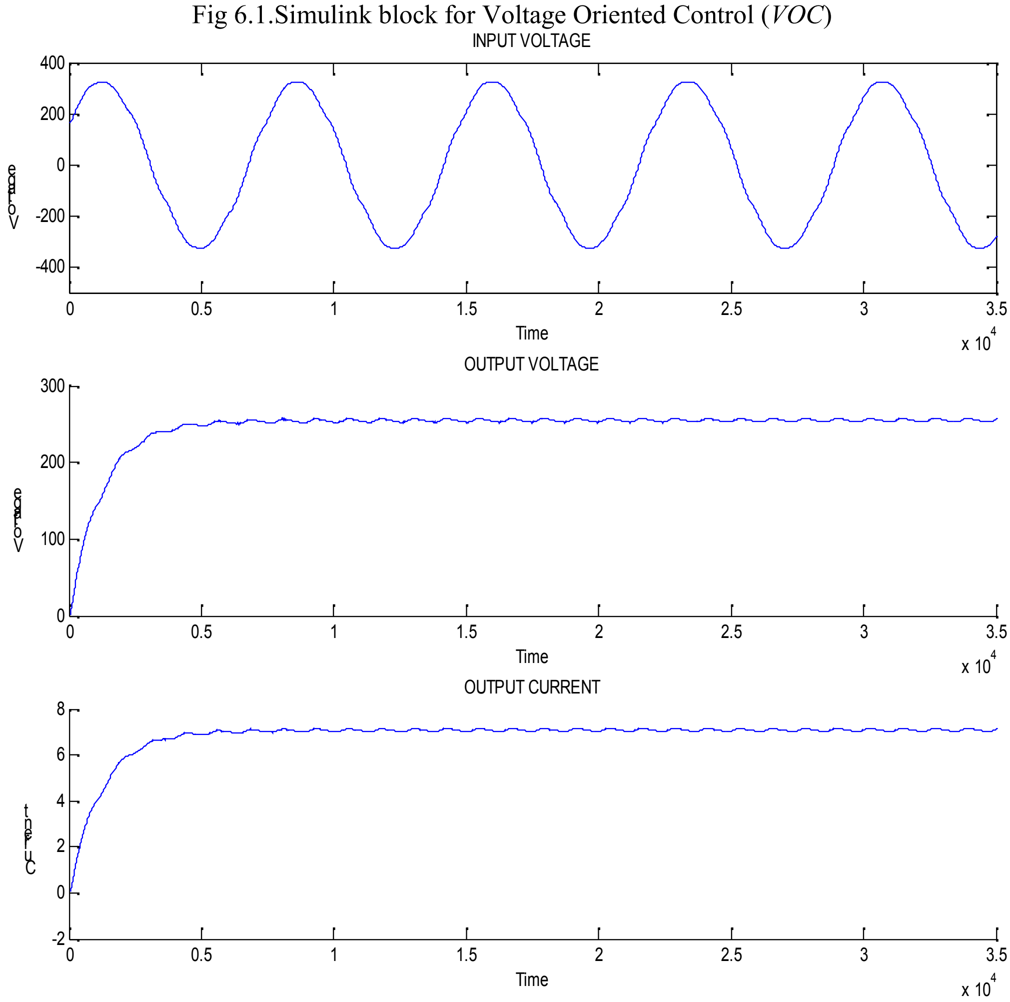

Fig 6.2 Waveforms of (a) Input Voltage (b) Output Voltage (c) Output Current

By simulating PWM rectifier using the control system shown in Fig. 6.1 gave the waveforms shown in Fig 6.2.

6.2 Direct Power Control (DPC)

Direct Power Control (*DPC*) is based on the instantaneous active and reactive power control loops. In *DPC* there are no internal current control loops and no *PWM* modulator block, because the converter switching states are 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 of the *DPC* implementation is a correct and fast estimation of the active and reactive line power.

Simulink block for control system used in Direct Power Control (*DPC*) as shown in Fig. 6.3 is obtained from the eqs.4.5 (a), 4.5(b), 4.17(a), 4.17(b), 4.19(a).4.19(b).

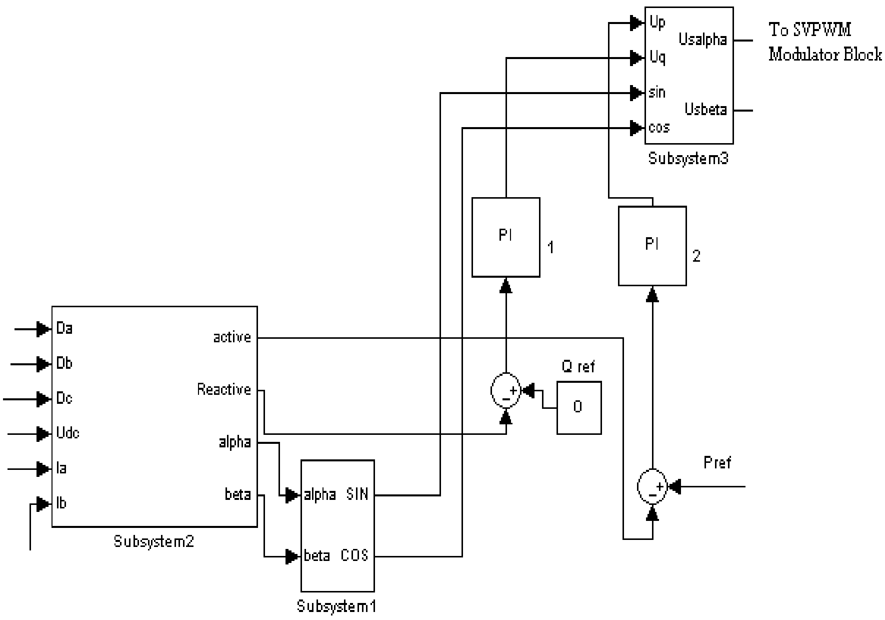

Fig 6.3.Simulink block for Direct Power Control (*DPC*)

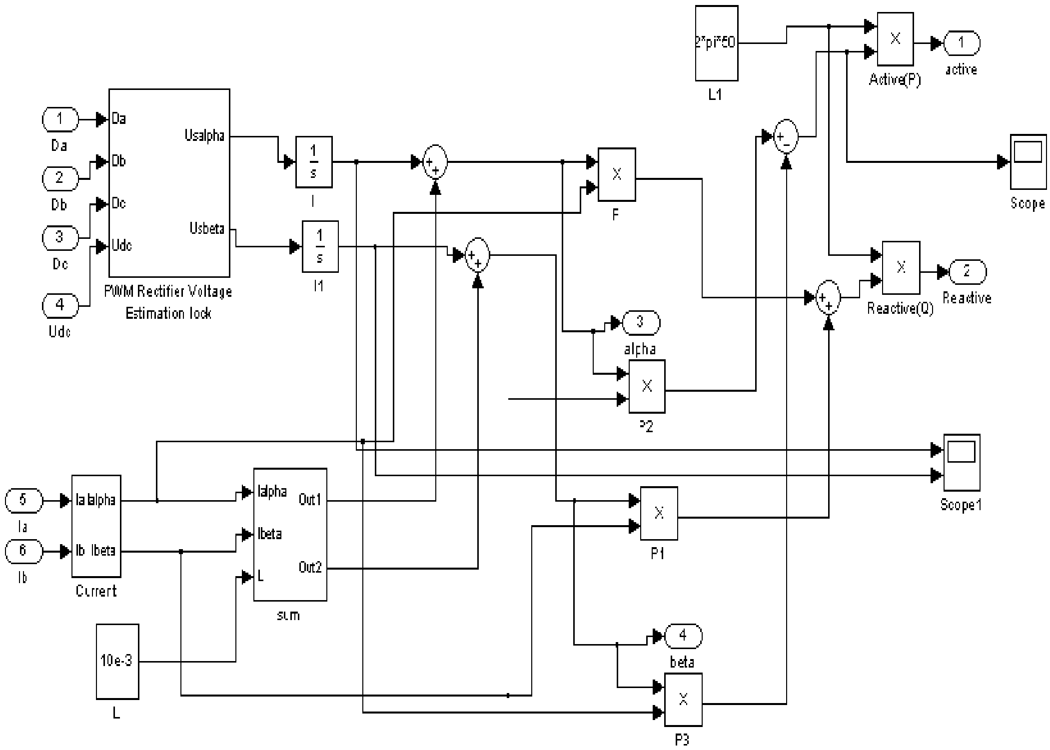

Fig 6.4.Simulink Inner block for active and reactive power estimation

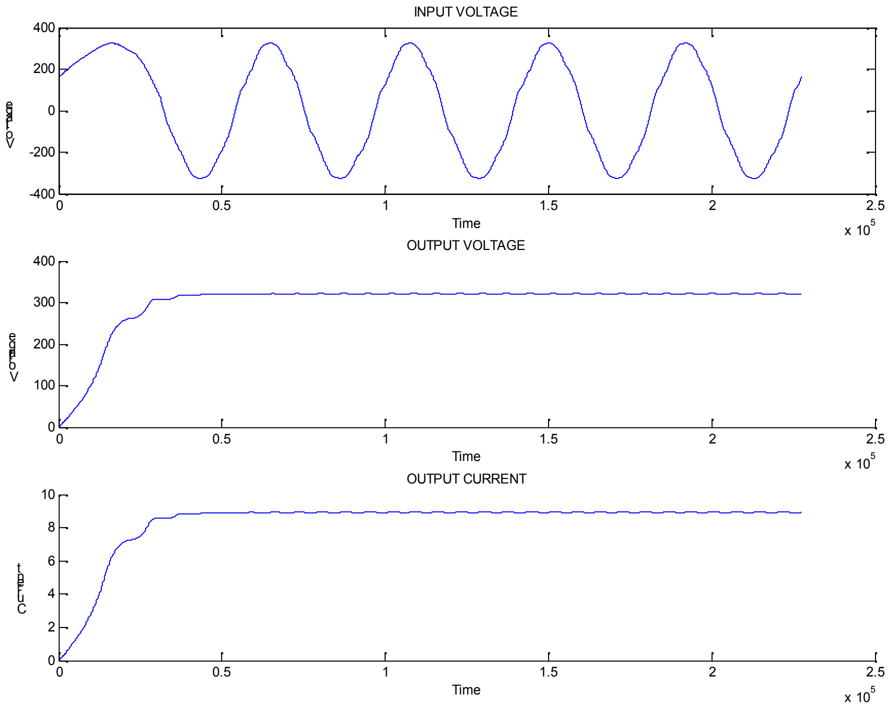

Fig. 6.5 (a) Waveforms of i) Input Voltage ii) Output Voltage iii) Output Current

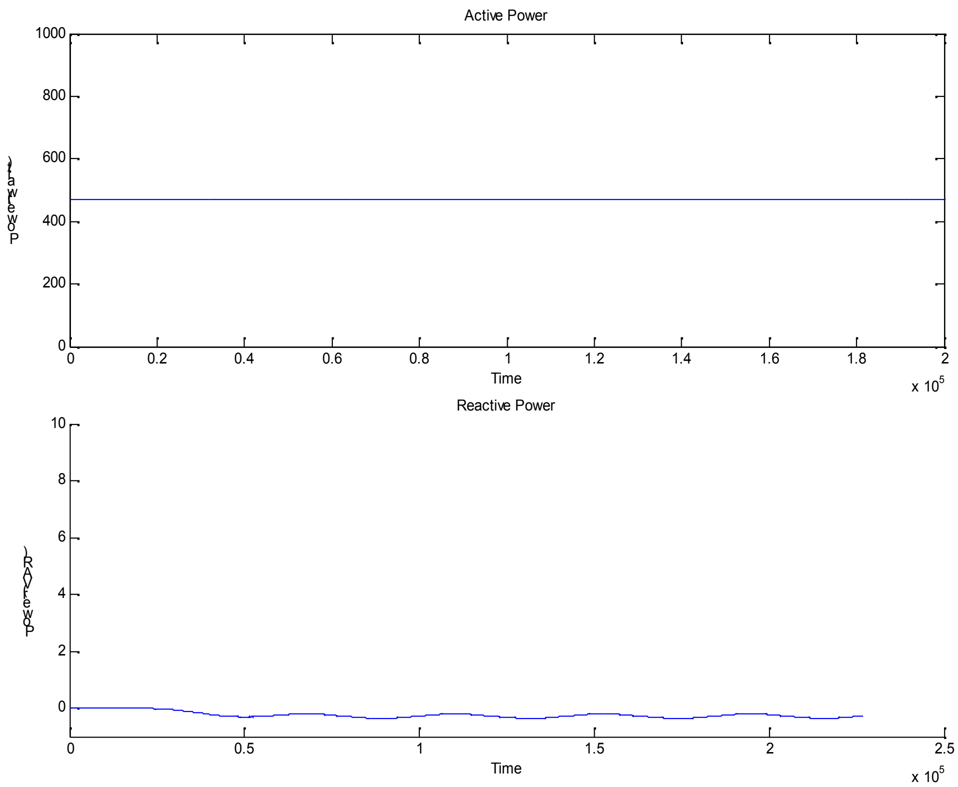

Fig.6.5 (b). Waveforms of i) Active Power ii) Reactive Power

6.3 Active Filtering

The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits, also known as instantaneous power theory, or p-q theory. It was used to calculate the reference compensation currents in the α -β coordinates .This presents modified algorithm based on virtual flux, which operates directly on instantaneous active and reactive power components. The instantaneous active and reactive powers are estimated using currents intended to compensate. The calculated active power (pA) and reactive power (qA) are delivered to the high pass filter to obtain the variable value of the instantaneous active power (¯pA) and reactive power (¯qA) which finally are used as compensating components. Enclosure of active filtering function will cause suitable distortion of input PWM rectifier current. This will assure almost sinusoidal line current.

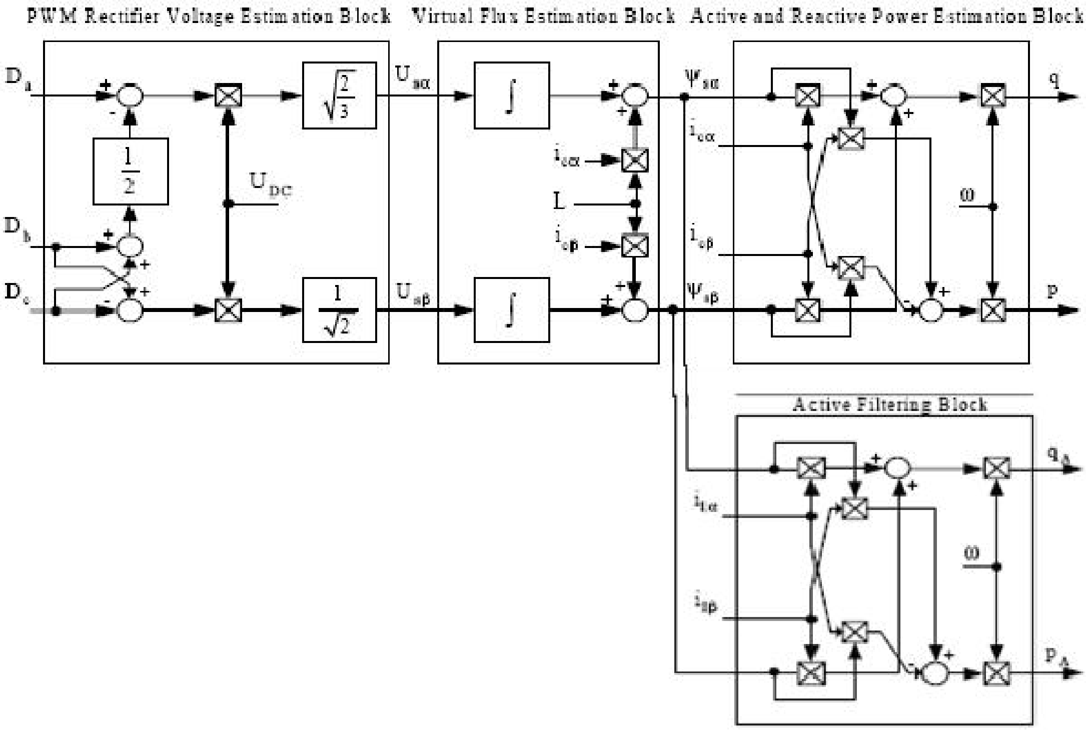

Fig. 6.6. Simulink block diagram for Power Estimators

By using eqs 5.5(a), 5.5(b), 5.13(a), 5.13(b), 5.15(a), 5.15(b), 5.16(a), 5.16(b) above simulink block is obtained. Simulation of Fig. 6.6 gave the following results.

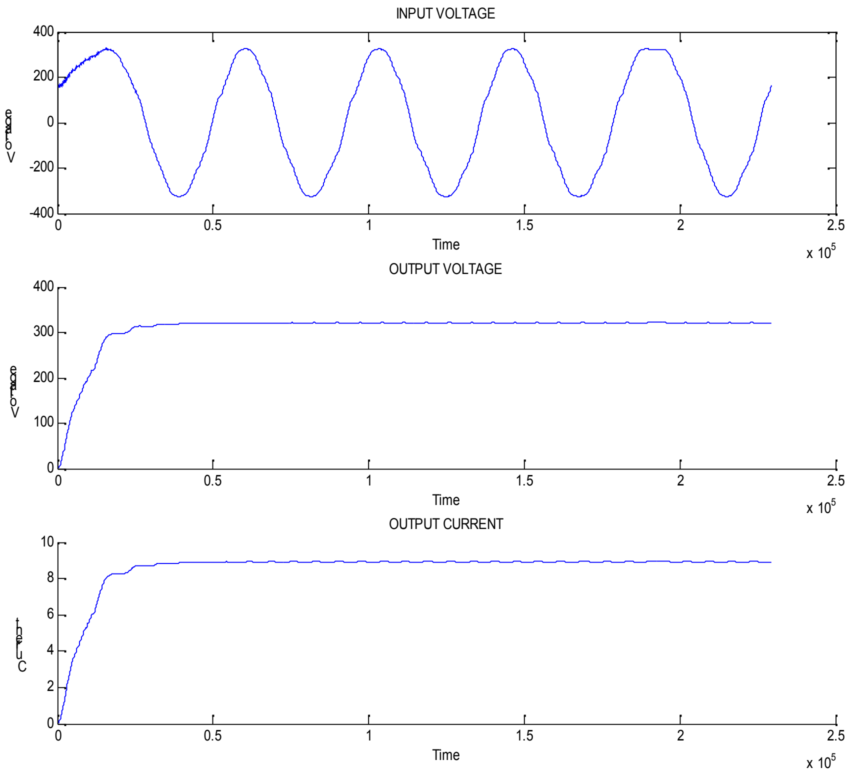

Fig 6.7(a). Waveforms of i) Input Voltage ii) Output Voltage iii) Output Current

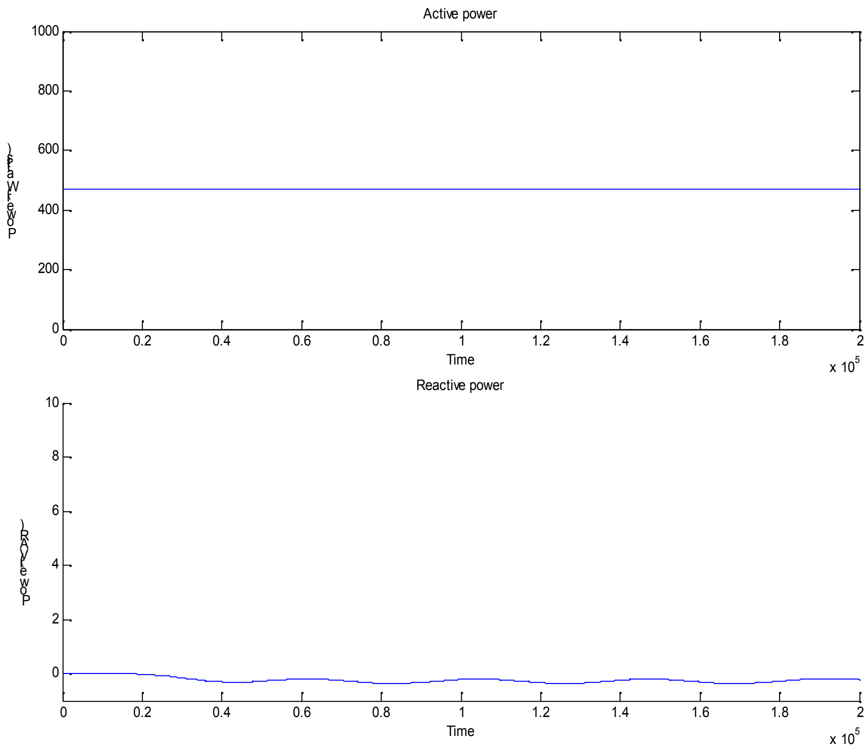

Fig 6.7(b).Waveforms of i) Active Power ii) Reactive Power

7. Performance Comparison

7.1 Introduction

In this chapter, the various control strategies for PWM rectifiers are compared to observe their performance with reference to circuit complexity, robustness, reliability, dynamic response, parameter sensitivity and total harmonic distortion.

7.2. Performance Comparison of PWM Rectifiers

From the simulations of the Control strategies for PWM Rectifier i.e the virtual flux based Direct Power Control (VF-DPC), active filtering function along with direct power control and conventional Voltage Oriented Control (VOC) in rotating coordinates with a novel line voltage estimator, Total Harmonic Distortion, Dynamic performance and Parameter sensitivity of these control strategies are compared.

7.2.1 Total Harmonic Distortion

From the spectrum analysis, total harmonic distortion for Direct Power Control (THD = 2.45 % **)** is improved when compared to conventional Voltage Oriented Control (THD = 16.06 %) also further it is known that by adding active power filtering function to the Direct Power Control, total harmonic distortion further improved(THD = 5.33%). The harmonic spectrums of all these three methods are shown in Fig.7.1 to Fig. 7.3.

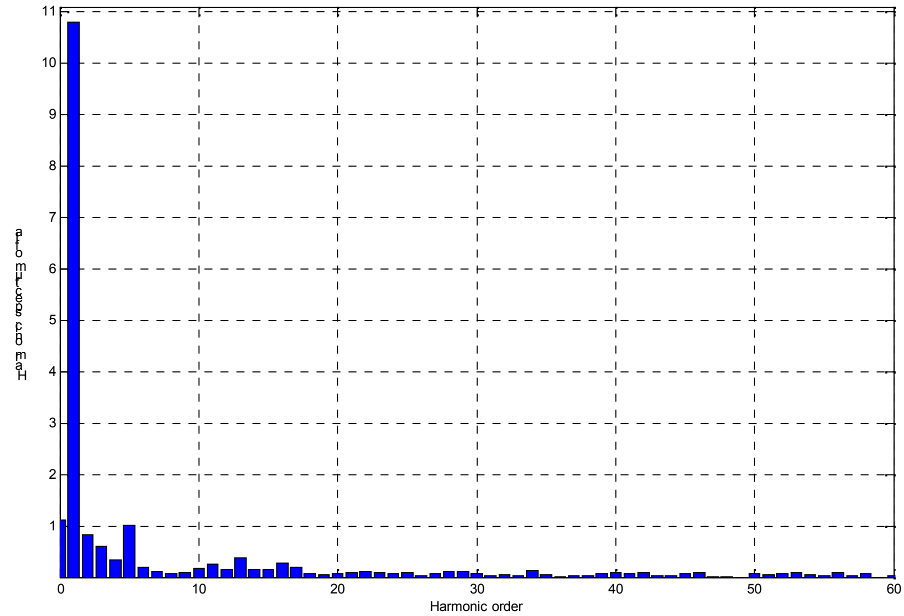

Fig.7.1. Total harmonic Distortion of Input Current of VOC

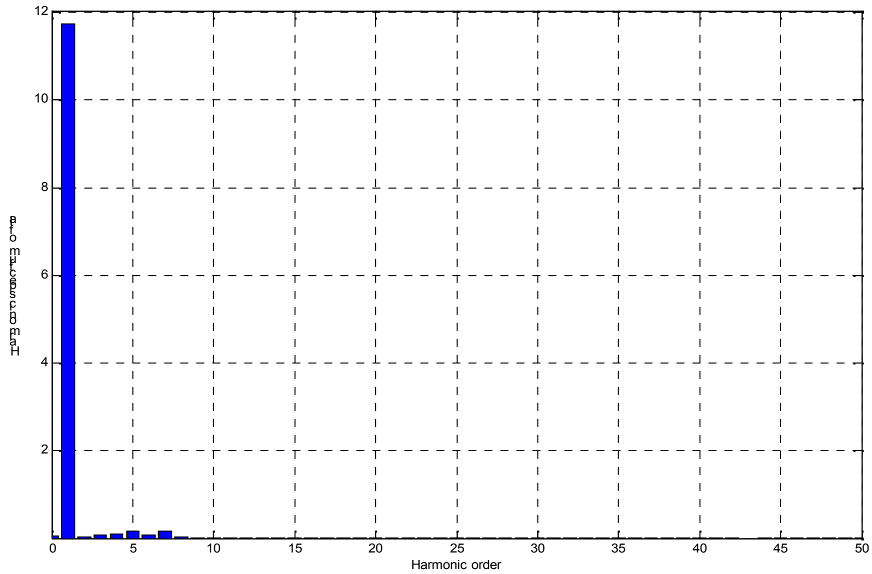

Fig.7.2. Total harmonic Distortion of Input Current of DPC

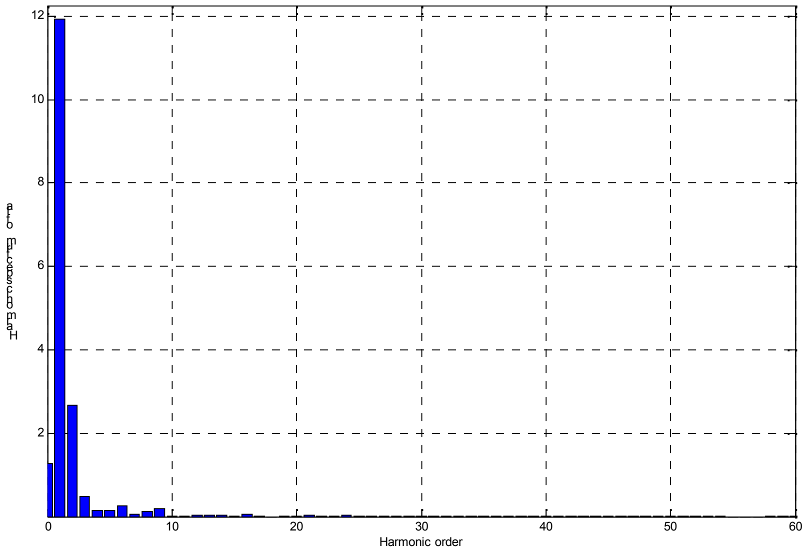

Fig.7.3. Total harmonic Distortion of Input Current of DPC with active filtering function

7.2.2. Parameter sensitivity

From the simulations it is understood that the value of the line inductance affect the value of *THD*. The *VOC* technique is insensitive to these variations, because the line inductance affects only the estimated angular position of the line voltage or virtual flux vectors. Therefore, it influences the input power factor but not the *THD* of the current. To the contrary, in the *DPC* schemes, the line inductance directly affects the estimated active and reactive power values, which in the closed control loop define switching instants and, as a result, the current *THD*.

7.2.3. Dynamic performance

In the virtual-flux based control systems to reduce the control error, the VF-DPC scheme selects directly an appropriate voltage vector, providing very fast power control. Contrastingly, the dynamic response of a VOC rectifier is determined by the performance of current controllers. With PI controllers, the rectifier's reaction is slower than that with hysteresis controllers. From the results there is no need for PWM modulation in the DPC because the switching states are determined by table based errors in the instantaneous active and reactive power. However in the conventional VOC the modulation strategy has a strong influence on the performance of the PWM rectifier.

8. Conclusions

8.1 Conclusions

The *VF* estimation is much less noisy than that of the line voltage. Moreover, a line voltage or virtual flux estimator can replace AC-line voltage sensors without deterioration in protection and performance of PWM rectifiers. Therefore, taking into account all operational features the Virtual Flux Based Direct Power Control (VF-DPC) technique seems to be the most advantageous of all. Both the strategies can be compared as follows:

VF-DPC versus VOC

- simpler algorithm,
- no current control loops,
- coordinate transformation and PI controllers are not required,
- no separate PWM voltage modulation block,
- decoupled active and reactive power controls,
- good dynamic performance,
- power estimation gives possibility of obtaining instantaneous variables with all harmonic components, which have an impact on improvement of the total power factor and efficiency.

A line voltage sensorless DPC with constant switching frequency (DPC-SVM) for a three-phase PWM boost type rectifier. The DPC-SVM system constitutes a viable alternative to the conventional control strategies and it has the following features and advantages.

- No line voltage sensors are required;
- The noise-resistant power estimation algorithm is easy to implement in a DSP.
- The control algorithm is simple, which gives the possibility of implementing it in an inexpensive microcontroller (e.g., TMS 2406).
- It has a lower sampling frequency.
- Coordinate transformation and decoupling between active and reactive current is not required.
- No current regulation loops are required.
- It has good dynamics.
- It offers low THD), for line voltage
- There is constant switching frequency (easy design of the EMI filter) by SVM application.
- Advanced SVM strategies for reduction of switching losses can be implemented.

The main features and advantages of the line voltage sensorless Virtual Flux based Direct Power Control Space Vector Modulated (DPC-SVM) for 3-phase PWM rectifier with active filtering function can be summarized as:

- No line voltage sensors are required,
- Simple control algorithm without several coordinate transformation,
- No current control loops, the system operates directly on instantaneous active and reactive powers,
- Good dynamics and no coupling between active and reactive power,
- Constant switching frequency thanks to SVM,
- Proposed system can operate as a PWM rectifier, Shunt Active Filter or it can take the role of PWM rectifier having active filtering function. This extends tasks of PWM rectifier on eliminating of higher harmonics in line current. In this case PWM rectifier supply its load and at the same time compensate for harmonics AC line current,
- Active filtering function it is possible to use non polluting equipment what is PWM rectifier as a current harmonics eliminating device, it is also possible to add this function to currently working PWM rectifiers.

8.2 Future Scope of Project

The above control strategies can be implemented to PWM rectifier using DSP. Hardware set up has power circuit, control and measurement systems. Power circuit consists of two inverters and diode rectifier (in case of active filtering function method) also we can use induction motor as active load or resistor as passive load. The control system can be obtained by using either dSpace or DSP.

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