

# Direct Power Control Strategies for Multilevel Inverter Based Custom Power Devices

S. Venkateshwarlu, B. P. Muni, A. D. Rajkumar, and J. Praveen

**Abstract**—Custom power is a technology driven product and service solution which embraces a family devices such as Dynamic Voltage Restorer (DVR), Distributed Shunt Compensator (DSTATCOM), Solid State Breaker (SSB) etc which will provide power quality functions at distribution voltages. The rapid response of these devices enables them to operate in real time, providing continuous and dynamic control of the supply including voltage and reactive power regulation, harmonic reduction and elimination of voltage dips. This paper presents the benefits of multilevel inverters when they are used for DPC based custom power devices. Power flow control mechanism, salient features, advantages and disadvantages of direct power control (DPC) using lookup table, SVM, predictive voltage vector and hybrid DPC strategies are discussed in this paper. Simulation results of three level inverter based STATCOM, harmonic analysis of multi level inverters are presented at the end.

**Keywords**—DPC, DPC-SVM, Dynamic voltage restorer, DSTATCOM, Multilevel inverter, PWM Converter, PDPC, VF-DPC.

## I. INTRODUCTION

CUSTOM power devices like DSTATCOM and DVR are capable of providing a number of power quality functions which can be employed selectively or simultaneously. The devices appear as fully synchronous sources which are capable of absorbing and injecting reactive power on an electricity system at distribution voltages. PWM converters are widely used as front end converters in custom power devices. Direct power control strategies have gained importance in recent past due to faster response and superior control characteristics. This paper attempts to review and classify DPC strategies published in IEEE journals and conference records. DPC strategies have been applied to PWM converter based custom power devices [1-26]. DPC block for PWM converter essentially comprises of active and reactive power comparators, power estimators and switching pattern generators. The DPC application in PWM converter is analogous to direct torque control (DTC) in inverter fed three-

phase motor drives. Initially, DTC and DPC strategies had been implemented with lookup table based switching pattern generator. Improvement over random switching frequency of switching table based DPC can be achieved with integration space vector PWM strategy along with instantaneous active and reactive power comparators.

The basic DPC strategy is based on the instantaneous active and reactive power comparators. The active power command is provided from a dc-bus voltage control block, while the reactive power command is directly given from the outside of the controller. Errors between the commands and the estimated feedback power are input to the hysteresis comparators. Inner current control loops and PWM modulator are not required in DPC 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 powers [2].

Normally the PWM converter needs three kinds of sensors: dc-voltage sensor, ac-line current sensors and ac-line voltage sensors. 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. One of the most popular strategies is a conventional line Voltage Oriented Control (VOC) [1] - [3] in rotating coordinates with line voltage measurements. In recent times Direct Power Control (DPC) method [1] has gained much attention. This paper has been organized into five sections. First section gives basic DPC strategy, Second section gives custom power devices, third section gives various DPC strategies for pwm converters, fourth section gives operation of three level inverter, simulations of three level STATCOM and p-q estimator and the last section gives simulation results and conclusions.

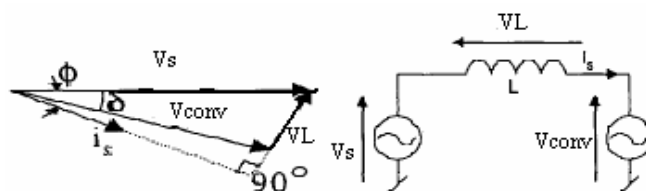


Fig. 1 General vector diagram for PWM converter

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## II. BASIC DPC STRATEGY

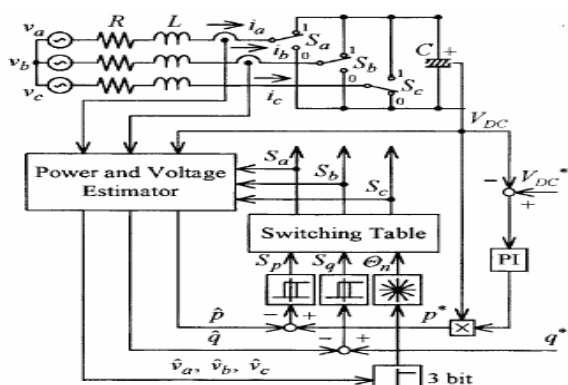


Fig. 2 Configuration of direct instantaneous active and reactive power controller

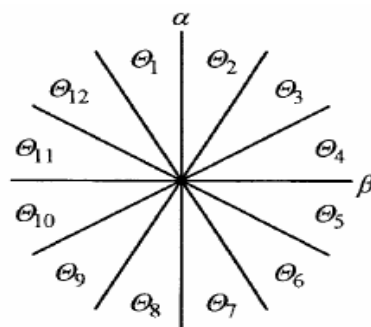


Fig. 3 Twelve sectors on stationary coordinates to specify voltage vector phase

In terms of the switching states of the converter, the three-phase line currents, the dc-bus voltage, and the inductance of the reactors, the estimated values of  $p$  and  $q$  and can be derived as:

$$\hat{p} = L \left( \frac{di_a}{dt} i_a + \frac{di_b}{dt} i_b + \frac{di_c}{dt} i_c \right) + V_{DC} (s_a i_a + s_b i_b + s_c i_c) \quad (2)$$

TABLE I  
SWITCHING TABLE FOR DIRECT INSTANTANEOUS POWER CONTROL

Sp	Sq	$\theta_1$	$\theta_2$	$\theta_3$	$\theta_4$	$\theta_5$	$\theta_6$	$\theta_7$	$\theta_8$	$\theta_9$	$\theta_{10}$	$\theta_{11}$	$\theta_{12}$
1	0	101	111	100	000	110	111	010	000	011	111	001	000
	1	111	111	000	000	111	111	000	000	111	111	000	000
0	0	101	100	100	110	110	010	010	011	011	001	001	101
	1	100	110	110	010	010	011	011	001	001	101	101	100

In this configuration, the dc-bus voltage is regulated by controlling the active power, and the unity power factor operation is achieved by controlling the reactive power to be zero [1]. As shown in Fig. 2, the active power command is provided from a dc-bus voltage control block, while the reactive power command is directly given from the outside of the controller. Errors between the commands and the estimated feedback power are input to the hysteresis comparators and digitized to the signals  $S_p$  and  $S_q$ . Also, the phase of the power-source voltage vector is converted to the digitized signal  $\theta_n$ . For this purpose, the stationary coordinates are divided into 12 sectors, as shown in Fig. 3, and the sectors can be numerically expressed as:

$$(n-2)\frac{\pi}{6} \leq \theta_n < (n-1)\frac{\pi}{6} \text{ where } n=1,2,3,\dots,12 \quad (1)$$

By using several comparators, it is possible to specify the sector where the voltage vector exists.

The digitized error signals and digitized voltage phase are input to the switching table in which every switching state  $s_p$  and  $s_q$  of the converter is stored, as shown in Table I.

By using this switching table, the optimum switching state of the converter can be selected uniquely in every specific moment according to the combination of the digitized input signals. The selection of the optimum switching state is performed so that the power errors can be restricted within the hysteresis bands.

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

Supposing practical data processing of the above equations by using microprocessors or digital signal processors (DSP's), differential operations of the currents are performed on the basis of calculus of finite differences. Therefore, it is necessary to suppress steep current ripples due to the converter switching by employing a relatively large inductance and to calculate the finite differences of the currents as accurately as possible. Since the proposed estimation method has been derived throughout by using instantaneous variables, it is possible to estimate harmonic components of the power-source voltages, as well as the fundamental components. This implies that improvement of the total power factor and efficiency taking the harmonics into account can be expected by this method [4]. DPC has following advantages: Simpler voltage and power estimation algorithm, Easy implementation of the unbalanced and distorted line voltage compensation to obtain sinusoidal currents (low THD), excellent dynamics and no coordinate transformation is required.

## III. CUSTOM POWER DEVICES

All custom power devices are capable of providing a number of power quality functions which can be employed selectively or simultaneously. Two of the devices

DSTATCOM and the DVR share a similar architecture. Both are based on the voltage source converter. DVR is connected in series with the line where as DSTATCOM is in shunt with the line across the load.

Using a converter, the devices appear as fully synchronous sources which are capable of absorbing and injecting reactive power on an electricity system at distribution voltages.

### A. DSTATCOM

The basic voltage source converter scheme for reactive power generation is shown schematically, in the form of a single line diagram, in Fig. 4. From a DC input voltage source, provided by the charged capacitor  $C_s$ , the converter produces a set of controllable three-phase output voltages of the same frequency as that of the AC power system. Each output voltage can be controlled both in magnitude and phase angle, which is coupled to the corresponding AC system voltage through a relatively small (0.1 - 0.15 p. u.) tie reactance (which in practice may be provided by per-phase leakage inductance of the coupling transformer). Direct power control technique applied to DSTATCOM is shown in Fig. 5.

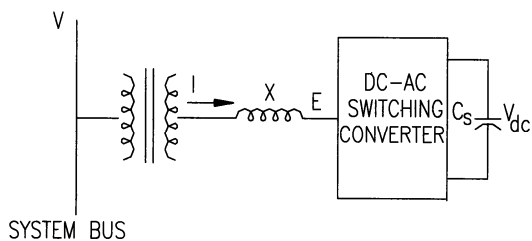


Fig. 4 Schematic of STATCOM

From Fig. 4, the active and reactive power exchanged between the system and converter is given by:

$$P = \frac{VE}{X} \sin \delta \quad (4)$$

$$Q = V \left( \frac{E}{X} \cos \delta - \frac{E}{X} \right) \quad (5)$$

Where  $\delta$  = Phase angle between  $V$  and  $E$ .

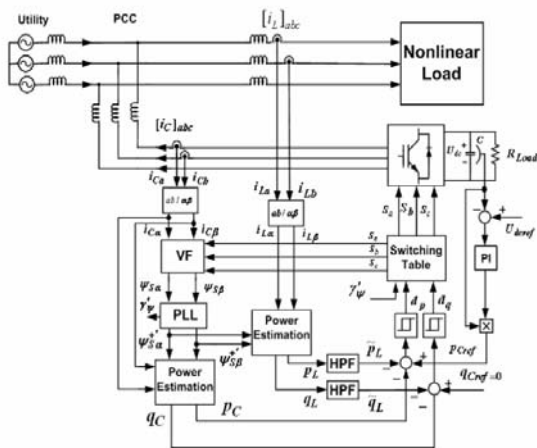


Fig. 5 DPC for DSTATCOM

### B. Dynamic Voltage Restorer

Rapidly growing power electronics technology is providing different power quality solutions. Modern technology is providing logistic solutions for huge electrical systems with the help of digital electronics systems. Dynamic Voltage restorer is a Flexible AC Transmission System (FACTS) device which mitigates the voltage sags and swells. The DVR designed for series connection into a power supply line. It controls voltage applied to load by injecting a voltage of component setting amplitude and phase angle into the line. Whenever voltage disturbance occurs, control voltage signals to PWM voltage source inverter generates the required compensation voltage to meet the requirement.

DVR injects a dynamically controlled voltage produced by PWM voltage source inverter in series to bus voltage by means of Transformer. The momentary amplitudes of three injected phase voltages are controlled to remove any detrimental effects of a bus fault to load voltage. As on voltage disturbance occurs on the power supply line let us say voltage sag, the exact difference of supply voltage to require load voltage is generated through the inverter to compensate the disturbance. The generated compensation voltage is in series added to the supply voltage to restore the disturbance. The functional diagram of a DVR is given in Fig. 6.

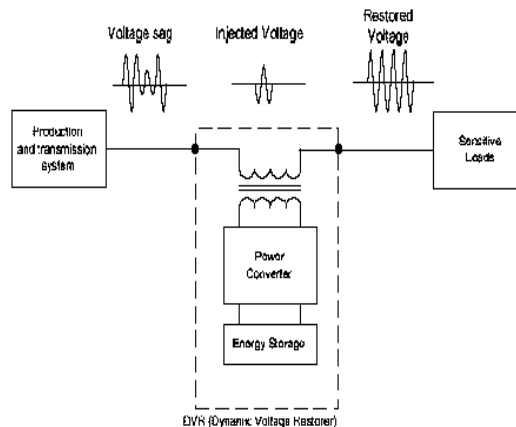


Fig. 6 Dynamic Voltage Restorer

The active power in which DVR is injecting to supply lines is taken from the DC link, where DC link can get power from either same supply line through a shunt converter or a separate energy source. The energy is required only during the sag interval [23].

### IV. DPC CONTROL STRATEGIES

DPC block for PWM converter essentially comprises of active and reactive power comparators, power estimators and switching pattern generators. DPC strategies can be classified based on switching pattern generation, estimation of active and reactive power calculation methodology or type of sensor usage. The key point to put DPC into practice is accurate and quick estimation of active and reactive powers. Fig. 7 shows the power control tree. Any Direct power control technique applied to three level inverters is natural extension of classical DPC applied to two level inverters, but in three level inverters

dc mid point between capacitors should be well balanced otherwise malfunctioning of inverter takes place. This is achieved by proper selection of internal (redundant) vectors which generate the same output voltage at different switching states. The inverter switching states are appropriately selected by a switching table according to the instantaneous error between references and estimated values of active and reactive power. However, to permit more flexibility in the vector selection in three level inverters, a single band hysteresis is replaced by a double band strategy and to achieve a proper mid-point balancing, a method to decide on the correct redundant vector is employed. As consequence of selecting more voltage space vectors in the three-level inverter DPC, the harmonic content in the output voltage and current can be reduced.

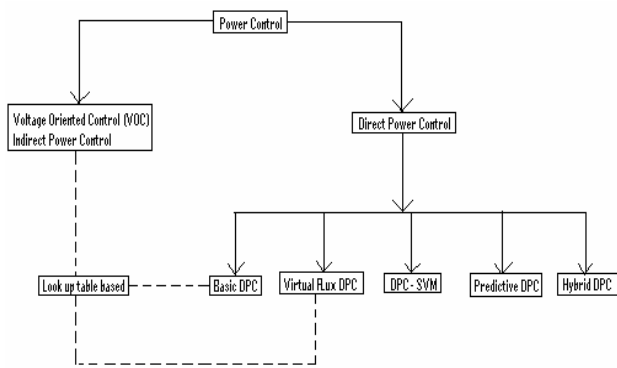


Fig. 7 Power Control Tree

A. Virtual Flux Direct Power Control

The VF-based approach has been proposed to improve the VOC [5], [6], [7]. 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. Thus, R and L represent the stator resistance and the stator leakage inductance of the virtual motor and line-to-line voltage:  $U_{ab}$ ,  $U_{bc}$ ,  $U_{ca}$ , would be induced by a virtual air-gap flux. In other words the integration of the voltages leads to a virtual flux (VF) vector  $\psi_L$ , in stationary  $\alpha - \beta$  coordinates. Based on the measured dc-link voltage  $U_{dc}$  and the duty cycles of modulator the virtual flux  $\psi_L$  components are calculated (Fig. 8).

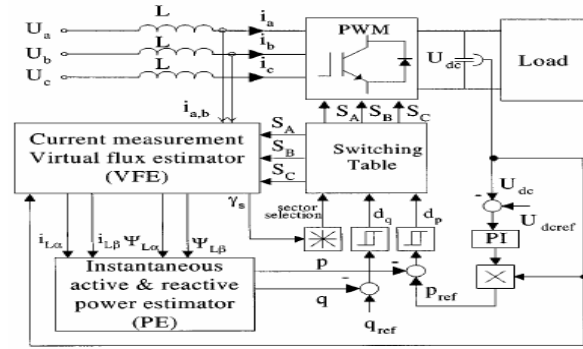


Fig. 8 Block scheme of Virtual Flux DPC

The main advantages of VF DPC are:

- No line voltage sensors are required.
- Simple and noise robust power estimation algorithm, easy to implement in DSP.
- Lower sampling frequency (like in conventional DPC).
- Sinusoidal line currents (low THD).
- No separate PWM voltage modulation block.
- Coordinate transformation is not required.
- No current regulation loops.
- High dynamics, decoupled active and reactive power control.

The typical disadvantages are:

- Variable switching frequency, Requires fast microprocessor and A/D converters.
- Violation of polarity consistency rules (to avoid  $\pm 1$  switching over dc link voltage).
- High sampling frequency is needed for digital implementation of hysteresis comparators.

B. Direct Power Control using Space Vector Modulation

All the draw backs in VF-DPC are eliminated in this DPC-SVM. Instead of the switching table; a PWM voltage modulator is applied. A new simple method of line voltage sensorless DPC with constant switching frequency using space-vector modulation (DPC-SVM) is presented. DPC is based on the instantaneous active and reactive power control loops [1], [8]. The DPC-SVM with constant switching frequency uses closed-loop power control, as shown in Fig. 8. The commanded reactive power  $q_{ref}$  (set to zero for unity power factor operation) and (delivered from the outer PI dc voltage controller) active power  $p_{ref}$  (power flow between the supply and the dc link) values are compared with the estimated q and p values (eq.6 and 7), respectively. The errors are delivered to PI controllers, where the variables are dc quantities, which eliminate steady-state error. The output signals from the PI controllers after transformation described as:

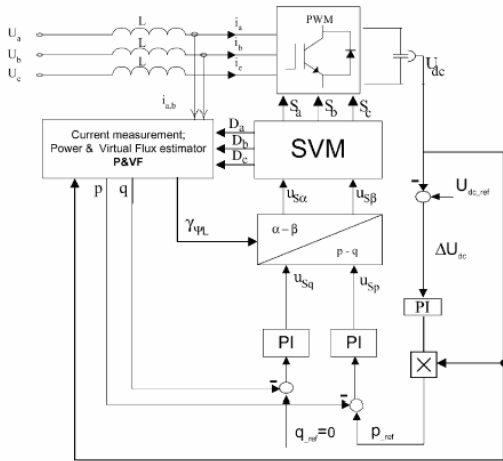


Fig. 9 Direct Power Control with Space Vector Modulation

$$p = \omega \cdot (\psi_{L\alpha} i_{L\beta} - \psi_{L\beta} i_{L\alpha}) \quad (6)$$

$$q = \omega \cdot (\psi_{L\alpha} i_{L\alpha} - \psi_{L\beta} i_{L\beta}) \quad (7)$$

$$\begin{bmatrix} u_{s\alpha} \\ u_{s\beta} \end{bmatrix} = \begin{bmatrix} -\sin \gamma\psi L & -\cos \gamma\psi L \\ \cos \gamma\psi L & -\sin \gamma\psi L \end{bmatrix} \begin{bmatrix} u_{sp} \\ u_{sq} \end{bmatrix} \quad (8)$$

where

$$\sin \gamma\psi L = \frac{\psi_{L\beta}}{\sqrt{(\psi_{L\alpha})^2 + (\psi_{L\beta})^2}} \quad (9)$$

$$\cos \gamma\psi L = \frac{\psi_{L\alpha}}{\sqrt{(\psi_{L\alpha})^2 + (\psi_{L\beta})^2}} \quad (10)$$

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

The simulation study has been performed with two main objectives in mind:

- Explaining and presenting the steady-state operation of the proposed DPC-SVM with a purely sinusoidal and distorted supply line voltage;
- Presenting the dynamic performance of DPC.

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 (than a conventional DPC [1]).
- Coordinate transformation and decoupling between active and reactive current is not required.
- No current regulation loops are required.
- It has good dynamics.
- It offers sinusoidal line currents (low THD), for ideal and distorted 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 [9].

### C. Predictive Direct Power Control

Predictive approaches have also been exploited in order to overcome the variable switching frequency problem of the DPC strategy. These solutions have been mainly employed in the control of AC machines [11-13]. Instead of selecting an instantaneous optimal voltage vector (DTC-case), predictive type approaches select an optimal set of concatenated voltage vectors, the so-called voltage vector's sequence. The control problem is solved computing the application times of the vectors of the sequence in such a way that the controlled variables converge towards the reference values along a fixed predefined switching period. This way constant switching frequency operation is obtained. The Predictive Direct Power Control (P-DPC) selects the best voltage-vector sequences and computes their application times in order to control the power flow through the VSI under a constant switching frequency operation. This strategy requires a predictive model of the instantaneous power evolution. Next, we show this predictive model and two possible control strategies [14].

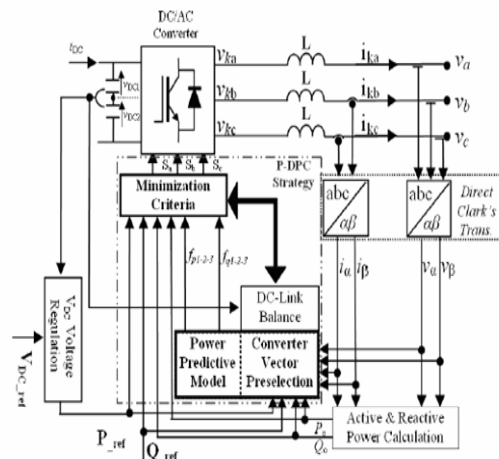


Fig. 10 Block diagram of Predictive DPC

### P-DPC based on a Three Voltage Vectors Sequence

This control approach employs the symmetrical 3+3 switching pattern, in such a way that the voltage vectors' sequence is divided in two sub-sequences of three voltage-vectors each, shown in Fig. 11. This control strategy is an extended version of the P-DPC based on a 2+2 voltage-vector' sequence. The second subsequence is symmetrical to the first one (it employs the same voltage-vectors and application times but reverses the application order), allowing the switching-frequency minimization. The control must select three of the applicable voltage vectors followed by the application times in the beginning of each control period. Fig. 11 shows an example of power trajectories under steady-state and transient operations.

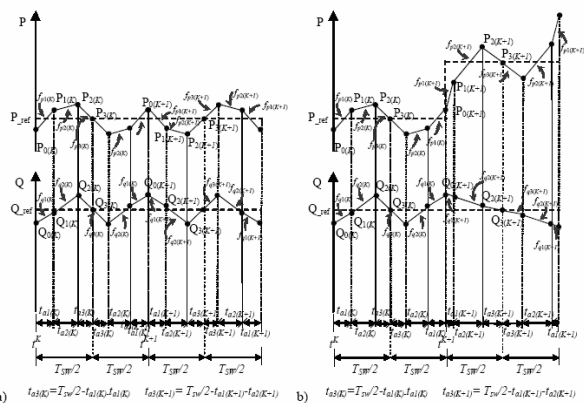


Fig. 11 Example of the steady state and transient behavior of P-DPC based on three vectors sequence

#### D. A Hybrid Direct Power Control Method

There are a large number of works reported to improve DTC using SVM, but in the case of DPC there is only one paper [17] presented to use a SVM algorithm to guarantee a constant switching frequency. In [17] a method in dq rotating coordinate is presented in which the real power and reactive power errors are directly sent through proportional-integral (PI) regulators to generate a dq voltage reference, and a space vector scheme is then used to control the rectifier. This work is very similar to [18] which is in DTC. Reference [19] had pointed out that the transient response of such control method is limited by the PI regulators in both the real power and reactive power loops. This work was motivated by [19] and [20] where DTC, SVM and predictive control are combined together to further improve the performance of DTC. In this paper, a novel control strategy that combines DPC, Space Vector Modulation (SVM) and predictive control is proposed.

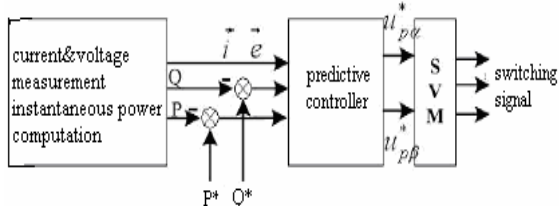


Fig. 12 A hybrid DPC

In digital implementation of the active power and reactive power control we strive to reduce the errors in a finite settling time.

In the present case, the control is designed to achieve zero active power and zero reactive power in one switching period. It is to say, the controller is designed to control active power and reactive power in a deadbeat fashion. Therefore, we can say:

$$\begin{bmatrix} p(k+1) \\ q(k+1) \end{bmatrix} = \begin{bmatrix} p(k) \\ q(k) \end{bmatrix} + \begin{bmatrix} \Delta p(k) \\ \Delta q(k) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} p^*(k) \\ q^*(k) \end{bmatrix} = \begin{bmatrix} p(k+1) \\ q(k+1) \end{bmatrix} \quad (12)$$

where  $k$  is the sampling time instant,  $\begin{bmatrix} p^*(k) \\ q^*(k) \end{bmatrix}$  is the reference vector of active and reactive power, and  $\begin{bmatrix} \Delta p(k) \\ \Delta q(k) \end{bmatrix}$  is the error vector of active and reactive power. The control ensures that in the  $(k+1)$ th period

$$\begin{bmatrix} \Delta p(k) \\ \Delta q(k) \end{bmatrix} = 0 \quad (13)$$

The instantaneous input active power ( $p$ ) and reactive power ( $q$ ) of the three phase voltage type active rectifier can be calculated by

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{3}{2} \begin{bmatrix} e_\alpha & e_\beta \\ e_\beta & -e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (14)$$

and the change in source inductance current over a constant switching period  $T_s$  is given by

$$\begin{bmatrix} \Delta i_\alpha \\ \Delta i_\beta \end{bmatrix} = \frac{T_s}{L} \begin{bmatrix} e_\alpha & -u_{p\alpha} \\ e_\beta & -u_{p\beta} \end{bmatrix} \quad (15)$$

In discrete form, (14) can be written as

$$\begin{bmatrix} p(k) \\ q(k) \end{bmatrix} = \frac{3}{2} \begin{bmatrix} e_\alpha(k) & e_\beta(k) \\ e_\beta(k) & -e_\alpha(k) \end{bmatrix} \begin{bmatrix} i_\alpha(k) \\ i_\beta(k) \end{bmatrix} \quad (16)$$

Combining equations (11, 12, 13, 14 and 16), and through some mathematical process, we can get the desired AC side voltage of the converter

$$\begin{bmatrix} u^*_{p\alpha}(k) \\ u^*_{p\beta}(k) \end{bmatrix} = \begin{bmatrix} e_\alpha(k+1) \\ e_\beta(k+1) \end{bmatrix} - \begin{bmatrix} \Delta u^*_{p\alpha}(k) \\ \Delta u^*_{p\beta}(k) \end{bmatrix} \quad (17)$$

Where

$$\begin{bmatrix} \Delta u^*_{p\alpha}(k) \\ \Delta u^*_{p\beta}(k) \end{bmatrix} = \frac{L}{T_s E^2} \begin{bmatrix} e_\alpha(k+1) & e_\beta(k+1) \\ e_\beta(k+1) & -e_\alpha(k+1) \end{bmatrix} \begin{bmatrix} \frac{2}{3} \begin{bmatrix} \Delta p(k) \\ \Delta q(k) \end{bmatrix} - \begin{bmatrix} \Delta e_\alpha(k) & \Delta e_\beta(k) \\ \Delta e_\beta(k) & -\Delta e_\alpha(k) \end{bmatrix} \begin{bmatrix} i_\alpha(k) \\ i_\beta(k) \end{bmatrix} \end{bmatrix} \quad (18)$$

is the desired voltage change added to the source voltage, and  $E$  is the amplitude of the source voltage.  $e_\alpha(k+1)$ ,  $e_\beta(k+1)$

are predicted source voltages, which can be easily computed by adding a displacement  $\omega T_s$  to the angular position of the

phase voltage.  $\begin{bmatrix} u^*_{p\alpha}(k) \\ u^*_{p\beta}(k) \end{bmatrix}$  is the command signal of the SVM module[21].

#### V. MULTI LEVEL INVERTER OPERATION

Multilevel inverters can be of 3-level, 4-level, or more. The power circuit of a three-level inverter is shown in Fig.13. In three-level inverter the load terminal is connected to the positive bus by switching on devices  $S_{X1}$  and  $S_{X2}$ , to the DC neutral point by switching on  $S_{X2}$  and  $S_{X3}$ , and to the negative bus by switching on devices  $S_{X3}$  and  $S_{X4}$ . When outputting a level 0, one of the clamping diodes ( $D_{x1}$ ,  $D_{x2}$ ) conducts the phase current depending on the current polarity. The term level in the configuration can be referred to the number of nodes to which the inverter can be connected.



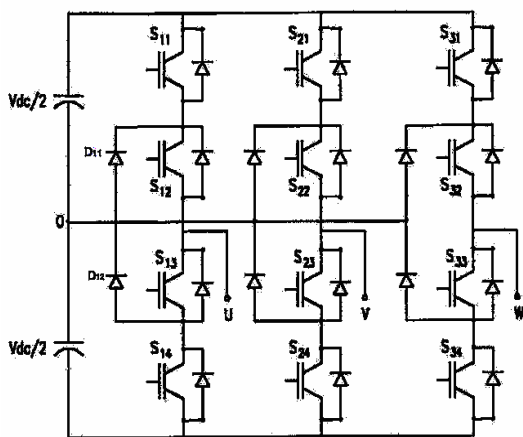


Fig. 13 The Schematic Diagram of Three-level Inverter

The switches ( $S_{11}, S_{14}$ ), ( $S_{21}, S_{24}$ ), ( $S_{31}, S_{34}$ ) are operating as main switches for PWM, and ( $S_{12}, S_{13}$ ), ( $S_{22}, S_{23}$ ) and ( $S_{32}, S_{33}$ ) are auxiliary switches to clamp the output terminal potentials to the neutral point potential, together with ( $D_{11} - D_{32}$ ). With such control, the output terminal potentials vary between  $(+V_{dc}/2$  to 0) or  $(-V_{dc}/2$  to 0), Whereas in conventional PWM inverters the output varies between  $+V_{dc}/2$  &  $-V_{dc}/2$ . As a result in three-level inverter the imposed voltages across the main switching devices are  $1/2 V_{dc}$  only.

In three-level inverter, the mid point (O) of the DC bus provides the third level in the output waveform with the conduction of neutral point diodes. During these periods, current is drawn from the neutral point. If this point is not connected directly to the supply neutral, then the current is drawn through DC link capacitors, causing one capacitor to charge whilst the other to discharge. Under normal operation, the mean current drawn from the neutral point potential remains constant.

However, during transient operation or if there is any imbalance in the output switching pattern a non-zero mean current will be drawn from (O), resulting in variation of the neutral point voltage.

### VI. THREE-LEVEL STATCOM

Fig. 14 shows the power circuit and control circuit of three-level converter based STATCOM. In this paper, a control scheme for three-level STATCOM, which is connected at the load end of a three-phase transmission and distribution network, is developed and modeled such that the net reactive power supplied from the source is zero. The control circuit monitors the reactive power consumed by the load and accordingly controls the output current of the PWM converter (directly controls the magnitude and phase angle of output voltage of the converter) to maintain the net reactive power drawn from the source as zero. Reactive power control circuit, as described here, is developed using instantaneous active and reactive power theory. As the instantaneous active and reactive power theory gives the basis for measuring the active and reactive power instantaneously, the better response to the VAR demand can be achieved with the voltage source PWM

converter, which can be operated at high switching frequency [22].

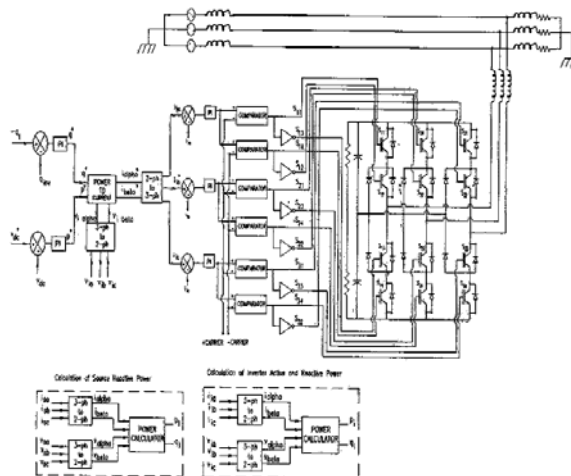


Fig. 14 Three level STATCOM in SABER

### VII. SIMULATION RESULTS

Simulation studies have been carried out on current controlled three-level converter based STATCOM to verify the control principle and the response of the STATCOM during connection to the three phase power network. Fig. 15 shows DC link voltage, source phase voltage, source phase current and load current. The STATCOM is connected to the power network at 40ms. It is observed from the Fig. 16 that the source current lags the source voltage before the STATCOM is brought into operation. The source current becomes in phase with the source voltage in 40 ms of STATCOM being connected to the network. Harmonic analysis also has been carried out on three-level inverter. It is observed that the three-level inverter has lower harmonic distortion both in load voltage and current compared to conventional two level inverters.

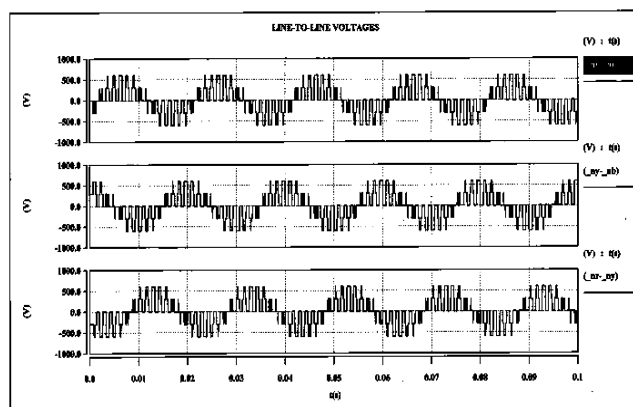


Fig. 15 Output line to line Voltages of Three-level Inverter

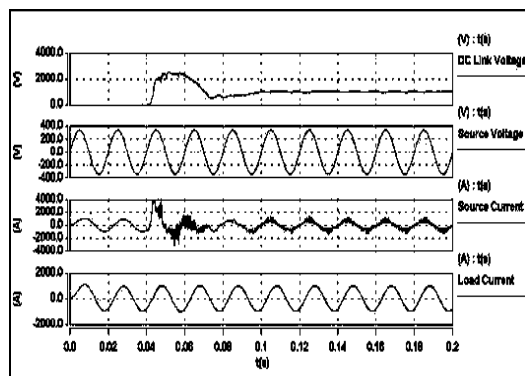


Fig. 16 Source Current and Source Voltage with STATCOM

### VIII. CONCLUSION

The various direct power control strategies for PWM converters are presented. Combining DPC, DPC-SVM and predictive approaches a hybrid method is evolved that is a hybrid DPC. Control equations of predictive and hybrid DPC are also presented. Multilevel inverters can be adopted in dpc strategies to enhance custom power devices capacity, flexibility of choosing voltage vectors as well as for minimizing harmonics. The simulation studies shows that the current controlled three-level converter with the developed control strategy can be used for reduction of harmonics and compensating reactive power in custom power devices. It is given in the following table II that as the number of levels in the inverter increases there is a considerable reduction in the harmonics [23]. Therefore Multilevel inverter based direct power control strategy for custom power devices is the most promising alternative for enhancement of the capacity and harmonic free output. Computation intensity of few dpc strategies are also presented in Fig. 17 at the end.

TABLE II

HARMONIC ANALYSIS OF MULTILEVEL INVERTERS

No of levels	THD in% (Line Vol-tage)	THD in % (Line Cur-rent)	Lower Order Harmo-nic	Output Vol-tage (p.u)	Output Power (p.u)	No.o f Clamp Swit-ches
2	30.22	35.55	5	1.00	1.00	6
3	16.44	12.31	7	1.90	1.90	12
5	10.89	6.16	11	3.71	3.71	24
7	5.90	2.48	13	5.52	5.52	36
9	4.80	1.45	17	6.59	6.59	48
11	5.18	1.68	19	7.98	7.98	60

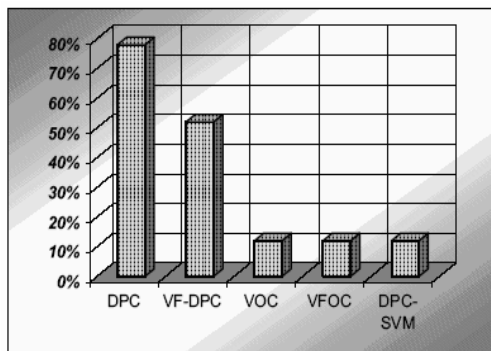


Fig. 17 Computation intensity of DPC strategies

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### REFERENCES

- [1] T. Noguchi, H. Tomiki, S. Kondo, I. Takahashi "Direct Power Control of PWM Converter Without Power-Source Voltage Sensors" IEEE Transaction on Industry Applications, Vol. 34, No. 3, May/June 1998, pp. 473-479.
- [2] V. Blasko "Adaptive Filtering for Selective Elimination of Higher Harmonics from Line Currents of a Voltage Source Converter" IEEE IAS Conference 1998, pp. 1222-1228.
- [3] F. Blaabjerg, J. K. Pedersen "An Integrated High Power Factor Three-Phase AC-DC-AC Converter for AC-machines Implemented in one Microcontroller" IEEE PESC Conference, 1993, pp. 285-292.
- [4] Steffan Hansen, Mariusz Malinowski, Frede Blaabjerg, Marian P.Kazmierkowski "Sensorless Control Strategies for PWM Rectifier" IEEE Transaction on Industry Applications 2000, pp. 832-838.
- [5] J.L. Duane, A Van Zwam, C. Wijnands and Vandenput A, "Reference frames fit for controlling PWM rectifiers", IEEE Trans.on Ind. Electronics, Vol. 46, No. 3, pp. 628-630, 1999.
- [6] P.J.M. Smidt and J.L. Duarte, "An Unity power factor converter without current measurement", EPE'95, Sevilla, pp.3.275-3.280, 1995.
- [7] M. Weinhold, "A new control scheme for optimal operation of three phase voltage dc link PWM converter," in *Proc. PCIM Conf.*, 1991, pp. 371-383.
- [8] T. Ohnishi, "Three-phase PWM converter/inverter by means of instantaneous active and reactive power control," in *Proc. IEEE IECON'91*, 1991, pp. 819-824.
- [9] M. Malinowski, "Adaptive modulator for three-phase PWM rectifier/inverter," in *Proc. EPE-PEMC Conf.*, 2000, pp. 1.35-1.41.
- [10] Mariusz Malinowski, Marek Jasinski and Marian P. Kazmierkowski, "Simple Direct Power Control of Three-Phase PWM Rectifier Using Space-Vector Modulation (DPC-SVM)" IEEE Transactions on Industrial Electronics, Vol. 51, No. 2, April 2004.
- [11] A.Linder and R.Kennel, "Direct Model Predictive Control—A new Direct Predictive Control Strategy for Electrical Drives", *Proceedings of EPE 2005*, Dresden, Germany.
- [12] A.BenAbdelghani, C.A.Martins, X.Roboam, and T.A.Meynard, "Use of Extra Degrees of Freedom in Multilevel Drives", *IEEE Trans. Industrial Electronics*, vol 49, Oct. 2002, pp.965-977.
- [13] M.Pacas and J. Weber, "Predictive Direct Torque for the PM Synchronous Machine", *IEEE Trans. Industrial Electronics*, vol 52, Oct. 2005, pp.1350-1356.
- [14] Sergio Aurtenechea, Miguel Angel Rodríguez, Estanis Oyarbide, José Ramón Torrealday, "Predictive Direct Power Control - A New Control Strategy for DC/AC Converters" IEEE Transactions on Industrial Electronics, 2006.
- [15] M. Malinowski, "Sensorless Control Strategies for Three - Phase PWM Rectifiers", *Thesis*, Faculty of Electrical Engineering Institute of Control and Industrial Electronics, 2001, Warsaw, Poland.
- [16] G.Escobar, A.M.Stankovic, J.M Carrasco, E.Galván, and R.Ortega, "Analysis and Design of Direct Power Control (DPC) for a Three Phase Synchronous Rectifier via Output Regulation Subspaces", *IEEE Trans. Power Electronics*, vol.18, May 2003, pp.823-830.
- [17] M. Malinowski and M. P. Kazmierkowski, "Direct power control of three phase PWM rectifier using space vector modulation—Simulation study," *IEEE-ISIE*, vol. 4, 2002, pp. 1114-1118.
- [18] X. Xue, X. Xu, T. G. Habetler, and D. M. Divan, "A low cost stator flux oriented voltage source variable speed drive," *IEEE-IAS*, pp. 410-415, 1990.
- [19] Thomas G. Habetler, Francesco Profumo, Michele Pastorelli, Leon M. Tolbert, "Direct Torque Control of Induction Machines Using Space Vector Modulation," *IEEE Trans. on Ind. Applications*, VOL. 28, NO. 5, Sept/Oct 1992.
- [20] A. M. Khambadkone, S. K. Panda, A. Tripathi, "Spacevector based, constant frequency, direct torque control and dead beat stator flux control of AC machines," *IEEE-IECON*, Vol. 2, pp. 1219-1224, 2001.
- [21] Tongzhen Wei "A Novel Direct Power Control Method of Three-Phase Active Rectifiers in Industrial Drive System" *Proceedings of the 2007*



IEEE International Conference on Mechatronics and Automation August  
5 - 8, 2007, Harbin, China.

- [22] B.P. Muni, S. Venkateshwarlu, A.D. Rajkumar, "Simulation studies of three level inverter based STATCOM", International Conference, CPU, New Delhi, 2002.
- [23] S. Venkateshwarlu, B.P. Muni, J. Praveen, A.D. Rajkumar, "Enhancement of custom power devices power quality using multilevel inverters" NPSC, IIT Madras, 2004.