A Review on Direct Power Control for Applications to Grid Connected PWM Converters

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***Abstract*—The Direct Power Control strategy has become popular as an alternative to the conventional vector oriented control strategy for grid connected PWM converters. In this paper, Direct Power Control as applied to various applications of grid connected converters is reviewed. The Direct Power Control for PWM rectifiers, Grid Connected DC/AC inverters applications such as renewable energy sources interface, Active Power Filters, Doubly Fed Induction Generators and AC-DC-AC converters are discussed. Control strategies such as Look-Up table based control, predictive control, Virtual Flux DPC, Model based DPC and DPC-Space Vector Modulation are critically reviewed. The effects of various key parameters such as selection of switching vector, sampling time, hysteresis band and grid interfacing on performance of direct power controlled converters are presented.**

Keywords-Direct Power Control; Power Conversion; Pulse Width Modulation converters; Space Vector Pulse Width Modulation

I. INTRODUCTION

Power Electronics has emerged with strong merits of power processing and control of key parameters in the field of power system. Traditionally, grid connected converters are designed with either uncontrolled rectifiers or controlled converters followed or preceded by strong DC links due to robustness, cost-effectiveness and ease of implementation. Over the years, it has been observed that these systems are responsible for grid pollution. Strict regulations have been imposed on users of such systems especially when the grid is referred as 'weak' [1] which applies to all applications such as switch mode power supplies, UPS, adjustable speed drives, renewable energy sources interface and furnaces.

To meet the above requirements, PWM converters were introduced due to their advantages of nearly sinusoidal current, unity power factor and better DC link voltage regulation. It is worth noting that these objectives are more or less same in all the grid connected systems whereas slightly differs in certain applications e.g. in active power filters in terms of output current references [2]. Due to better dynamic response and close tracking to the reference, hysteresis current controlled PWM has been very popular though alternative techniques have also been suggested. In such cases, the control strategy used is based on grid voltage vector information and output currents are decomposed into currents responsible for active and reactive powers [3]. The major disadvantages of these schemes are: variable switching frequency, increased power losses, dependency on system parameters, and tuning of inner current control loops.

To obtain better dynamic response in the drive, a scalar control technique called Direct Torque Control abbreviated as DTC was proposed in [4] where Torque and Flux are treated as two variables of control and an appropriate switching vector is selected to obtain the desired operation [5]. Considering grid connected converters, Direct Power Control technique [6] was proposed by the same authors, which is still considered a benchmark work for grid connected converters applications. Direct Power Control (DPC) technique is based on p-q theory [2] where instantaneous power errors of active and reactive power components are kept within a fixed hysteresis band to provide reference values of powers. A lookup table is developed based on the effect of a particular space vector on the variation of power [6-13]. Alternatively, model based space vector selection [14-16] and predictive control [17-19] have also been suggested. The method has several advantages over conventional control techniques.

- No precise information of grid voltage is required. A binary word determines position of voltage vector.
- Appropriate switching states that results in minimal commutation of converters switches can be selected
- The method works equally well for sinusoidal as well as non-sinusoidal supply voltages.

Due to benefits mentioned above, direct power control has gained attention of many researchers. However, a clear approach of direct power control for specific applications still requires further investigation in order to improve performance.

In the present paper, an attempt has been made to review the applications of Direct Power Control for grid connected PWM converters. The paper is organized in five sections. In section II, the principle of DPC is explained in detail. Applications of DPC to various grid connected PWM Rectifier, DC-AC converters, Active Power Filter, AC-DC-AC converters are discussed in Section III. The control of doubly fed induction generator (DFIG) using DPC is also discussed. Section IV gives the classification of Direct Power Control technique and discusses the major improvements achieved. Section V highlights the key issues to be considered for the development of Direct Power Control. Conclusion and demerits are discussed in Section-VI.

II. THE BASIC RINCIPLE OF DIRECT POWER CONTROL

Conventionally, grid connected converters are controlled using hysteresis current controlled PWM [3, 7,8] where the current error space phasor is treated as a control variable. Whenever actual current deviates from the reference current, a switch of respective phase is turned ON/OFF depending on the instantaneous value of current error. For grid connected converters, KVL yields:

$$V_s = R_s i + L_s \frac{di}{dt} + V_c \quad (1)$$

where V_s is grid voltage vector, i is current vector and V_c is converters voltage vector. The grid voltage vector is denoted as

$$V_s = V_m e^{j\omega t} \quad (2)$$

where ω is the angular velocity of the grid voltage vector. In contrast, converters voltage occupies fixed states depending on switching combinations. For two level inverters, there are eight switching states. The hexagonal plane can be divided into either 6 or 12 sectors.

Hence, converters voltage vector is given by,

$$V_c = \sqrt{\frac{2}{3}} V_{dc} \left(S_1 + S_2 e^{j\frac{2\pi}{3}} + S_3 e^{j\frac{4\pi}{3}} \right) \quad (3)$$

where S_1, S_2 and S_3 are switching states of upper switch of PWM converter (1 or 0) and V_{dc} is DC link voltage. The difference of voltage (V_s - V_c) results in current error [9] .

The actual current space phasor is given as

$$i = i^* \pm \Delta i \quad (4)$$

where Δi is current error space phasor and it must be controlled in appropriate hysteresis band to obtain reference current.

The control of current error space phasor has following limitations:

- To obtain desired active and reactive power for converters, accurate information of voltage magnitude as well as phase are required.
- The switching state of converters depends on instantaneous value of current error which often results in non-optimal voltage vector selection.
- Expensive current control algorithm has to be incorporated in order to limit switching frequency of converter and to generate appropriate current references.

To overcome the above limitations, a direct power control algorithm was first proposed in [6]. In this section, the DPC algorithm is elaborated in order to understand and optimize the performance of grid connected PWM converters. For grid connected converters with voltage v_s and current i, instantaneous complex power is given by,

$$s = v_s \hat{i} \quad (5)$$

where $\hat{i}$ = complex conjugate of line current vector.

Differentiating (5), we get

$$\frac{ds}{dt} = v_s \frac{d\hat{i}}{dt} + \hat{i}\frac{dv_s}{dt} \quad (6)$$

Differentiation of current is obtained from Eq.(1) whereas differentiation of grid voltage is given by

$$\frac{dv_s}{dt} = j\omega V_m e^{j\omega t} \quad (7)$$

From (5) and (6), variation in power is calculated from,

$$\frac{ds}{dt} = \frac{v_s(\widehat{v_s} - \widehat{v_c})}{L_s} + j\omega \hat{i} v_s \quad (8)$$

$$\frac{ds}{dt} = \frac{1}{L_s}\left\{ |v_s|^2 - v_s \widehat{v_c} \right\} + j\omega s \quad (9)$$

Since (9) is processed using digital computers/ DSPs, differentiation of apparent power results in power variation whereas time differentiation is replaced by fixed sample time T_s which may be generated using timers/external interrupts. The final equation for complex power variation is written as,

$$\Delta s = \frac{1}{L_s}\left\{ |v_s|^2 - v_s \widehat{v_c} \right\} T_s + j\omega s T_s \quad (10)$$

The active and reactive powers are calculated as,

$$\Delta p = \text{Re}(\Delta s)$$
$$\Delta q = \text{Im}(\Delta s) \tag{11}$$

Substituting the values of the grid voltage vector as well as the converter voltage vector into (10) and (11) yields the power variation rates for state vectors in respective sectors. From (8)-(10), the following observations are made for the successful implementation of Direct Power Control algorithm:

- If control is to be done based on one state vector for one sample time only then the sample time T_s must be small enough to calculate variation in power. Large values of T_s may result in deviation from the reference resulting in large power variations [11]. As a consequence, more harmonics/THDs are introduced into the system which is highly undesirable.
- Large value of inductance is essential to keep variation of power within acceptable limits.
- Application of state vector and its effect also depends upon instantaneous power requirement.

Such a study has already been carried out in [11-13] .

III. APPLICATIONS OF DPC ALGORITHM

A grid connected PWM converter can be considered as a dual of inverter fed induction motor (AC motor) Drive where the grid voltage vector is similar to the back EMF of the induction motor and the application of appropriate switching states lead to the control of the desired quantities. Hence, all the major advancements that have been reported in the control of induction motors can be implemented, with exact dual quantity, for PWM converters. Direct Power Control of PWM rectifiers was first proposed keeping such a view in mind.

A. PWM Rectifier

Three phase PWM rectifier as a front end converter is the most sought application in applied DPC literature. In PWM rectifiers, sinusoidal line current and unity power factor, which are the main objectives, can be directly obtained if reference active power P_{ref} is maintained equal to the power consumed in the load. This reference active power P_{ref} is a DC quantity and the reference reactive power Q_{ref} is set to 0. Any change in demand of power will be immediately reflected in reference power value P_{ref} to obtain an excellent dynamic response from the converter.

In [6], the requirement for voltage sensors has been eliminated using Direct Power Control so that power errors are maintained in prescribed limits. Switching states are selected from the look-up table and grid voltage is estimated. The scheme has severe drawbacks of very high sampling frequency requirements (111 kHz) as well as dependency on the inductance value to obtain instantaneous grid voltages. Despite of these limitations, this control strategy has shown an excellent dynamic behaviour and hence considered as a benchmark work for DPC. To eliminate the need of estimation of voltage based on instantaneous power values, a new technique which was based on estimation of voltage from Virtual-Flux concept was implemented [14]. As mentioned above, voltage imposed by the line in combination with the ac-side inductors can be assumed to be quantities related to induction motor (or AC motor) and hence the technique is named Virtual-Flux Direct Power Control. It is interesting to note that the equations of active and reactive powers of PWM converters in arbitrary reference frame are similar to the equations for power in the virtual AC motor.

In another approach [12], errors of active power and reactive power are considered as Output Regulation Subspaces (ORS) and the required voltage vector is calculated from the information of the grid voltage vector. The method still requires measurement of voltage, increasing the cost but it delivers unity power factor and lower THD under distorted or unbalanced supply. Also, wide variation in DC link voltage can be obtained with the method. It still requires however a look-up table for vector selection. Since the classical look-up table method does not guarantee superior performance with parameter variation, model based Direct Power Control for PWM Rectifier was investigated in [13]. This concept leads to accurate information of desired voltage vectors in given conditions because of an adaptive control law.

Even though solutions mentioned above can achieve good steady state and dynamic response with simplicity in terms of implementation, they suffer from the following disadvantages:

- Variable Switching Frequency [14]
- Requirement of fast and accurate microprocessor and A/D converters [6, 14]

Space Vector Modulation schemes have been applied to reduce variation in switching frequency and obtain constant switching frequency. A simple method based on virtual flux estimator concept and space vector modulation is implemented in [15] where active and reactive power errors are fed to PI controllers (which act as natural low pass filter) instead of hysteresis controller and reference voltage vector generated is realized using the Space Vector Modulation method to obtain the desired active and reactive power. Since virtual flux estimator itself acts as a low pass filter, the method works satisfactorily under sinusoidal as well as distorted supply voltages. Similar to this, constant switching frequency can be obtained using duty cycle control [16,17] where active vector is applied for a fraction of the duty period and null vector for the rest of the duration. Although implementation is based on modulation of the vector for a given duty cycle, different methods have been proposed to calculate applied vector and time duration [10,16-18]. Since the method is increasingly becoming popular, a task force was initiated by IEEE on Dynamic Average Modelling of DPC based PWM rectifiers [19]. The classification of control methods for PWM rectifiers is given in section IV.

B. Renewable Energy Sources

Most of the renewable energy sources in grids employ PWM inverters since available power is in the form of DC e.g solar, Fuel Cell. This power is transferred to the grid by means of a three phase line. The key parameters of the control scheme of such interface are voltage and frequency control and islanding operation [11]. Direct Power Control can be effectively applied to the above control schemes. All the schemes of DPC of PWM converters are equally applicable to DC/AC inverter with the implications of output power limits which must be defined properly. In [20], authors use DPC algorithm for grid connected DC/AC converters for medium power application which is the often case with Distributed Generation. Due to spread spectrum of the method, a new LCL filter [20] design approach is adopted to reduce large filtering inductance requirements. A predictive control strategy based on DPC of DC/AC inverter is implemented [21, 22] to reduce commutations and to achieve desired power level with space vector modulation.

C. Active Power Filters

An active power filter is a special case of grid connected DC/AC inverter in which reference powers and reactive powers differ from all other applications. The common techniques available in literature are based on current control [2,7] and hence suffer from the same disadvantages mentioned for PWM converters. An optimal table is proposed in [23] for active filtering applications. The method is based on variation of hysteresis band to obtain regulation in switching frequency. Also, the method is applicable to ideal source voltages only. For unbalanced and distorted conditions, the method is implemented in [24] through the concept of high selectivity filter (HSF). Using the idea of virtual flux, PWM rectifier having active filtering function is implemented using the concept of DPC [25]. In this paper, combination of uncontrolled and PWM converter are used to control multi-drive systems. Using DPC, PWM converter provides compensating current for other uncontrolled converters resulting in reduction of overall THD in the system. Similarly, DPC is also applied to multilevel inverter based active power filters [26, 27]. In addition, techniques mentioned in [10, 20, 21, 22] are equally effective for such applications. A careful investigation of Direct Power Control to Active Power Filter applications can further improve the performance.

D. Doubly Fed Induction Generator (DFIG) for Grid Connected Applications

For wind turbine generating systems, DFIGs have become very popular because of their numerous advantages [28]. Vector control or Direct Torque Control techniques are applied to DFIG system to obtain the desired performance. However, the control of DFIGs is very complicated due to involvement of stator and rotor parameters, indirect control based on voltages and expensive current controllers. Any deviation of the parameter in control loop can further deteriorate the performance. Direct Power Control, can take advantage of its simplicity to control power fed to the grid. Active and Reactive Power calculations in DFIGs are done based on stator and rotor flux values. Virtual Stator Flux estimator is used [29] to select an optimal vector from the table. A DPC with constant switching frequency [30] gives satisfactory performance for large power (2 MW) DFIG independent of parameter variations. An algorithm called DPC+ is reported in [31] based on DPC under small variation in voltages. A discrete space vector modulation control is applied in [32] to reduce power ripples and current harmonics with constant operating switching frequency. The objectives of sinusoidal current with variation in steady state values of voltages and decoupled control of active power and reactive power with reduced ripples and good dynamic performance are yet to be investigated. Several attempts have been made towards this objective [28, 31, 33, 34].

E. AC-DC-AC (Back to Back) converters

In medium power drives, UPS and other application where DC-AC inverter is preceded by PWM AC-DC converter, the direct power control algorithm is applicable for both the inverter as well as the converters side. One such application of voltage source AC-DC-AC converter is mentioned in [35]. The reference power is calculated based on commanded current values, whereas current reference can be calculated based on any control technique of the drive. A unique approach of DPC of rectifier and DTC of inverter fed Induction Motor drive is employed in [36]. In all such applications, it is assumed that,

$$p^*_{rec} = p_{inv} \quad (11)$$

In addition, Direct Power Control is also applied to FACTS devices. A series converters control for multilevel inverter is discussed in [37, 38] which is further improved in [27] with sliding mode control. All the applications discussed so far applies two level or multilevel inverter topology based on VSI [38, 39]. For application involving AC-AC interaction, DPC has also been investigated for matrix converters based Unified Power Flow Controllers [40, 41].

IV. CONTROL STRATEGIES

The performance of DPC to any application largely depends upon the selection of the control strategy. The different control strategies are investigated based on certain objectives.

A. Look-Up Table (LUT) approach

A basic approach in Direct Power Control Algorithm is to select appropriate inverter voltage vectors based on instantaneous power errors. Based on instantaneous power errors and hysteresis band limits, there are four possible combinations with each having its own physical significance. For example, when dp>0 and dq>0 (active and reactive power are more than reference values), converters/inverter should act in capacitive effect as sources of reactive power reducing instantaneous reactive power requirement and supplying instantaneous active power to the grid. Several alternative look up tables are proposed for optimal switching for respective applications such as grid connected inverter [42], Active Power Filter [23], PWM converters [10,16], and AC-DC-AC converters [35] which are basically based on the technique proposed in [6]. All the LUT based schemes suffer from disadvantages such as variable switching frequency resulting in wide current spectrum and introduction of lower order harmonics in line currents, high sampling frequency and steady state errors.

B. Model Based DPC

In a model based technique [13], output control vector applied to the converters is derived as a function of input control parameter using an adaptive control law. The method is an extension of the ORS concept [12] and applies few steps to decide reference vector for given active and reactive power errors.

- The reference vector for which active and reactive power errors ($\dot{p}$ and $\dot{q}$) are zero is treated as equilibrium point in α-β plane [12].
- Based on the equilibrium point, selection area is defined using binary word.
- An output control vector that compensates for given active and reactive power is determined and applied using PWM or SVM.

Due to control over power errors, smoothening inductor value is decreased. Moreover, the method is based on adaptive control law and is immune to parameter variations.

C. Virtual Flux DPC

To eliminate the requirement of line voltage sensors, estimation of voltage can be performed [6] leading to a technique called Virtual Flux Direct Power Control [14, 43] (VF-DPC) where it is assumed that Virtual Flux (of Virtual AC motor) is responsible for line voltage being induced. From line current measurement and current switching state, a virtual flux vector is calculated from,

$$V_s = V_c + L\frac{di_s}{dt} \qquad (13)$$

$$\psi_s = \int \left(V_c + L\frac{di_s}{dt} \right) dt \qquad (14)$$

Using torque equations of AC motor, the instantaneous powers are computed as

$$\begin{aligned} p &= \omega(\psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}) \\ q &= \omega(\psi_{s\alpha} i_{s\alpha} - \psi_{s\beta} i_{s\beta}) \end{aligned} \qquad (15)$$

. The method still uses look-up table for selection and application of voltage vector and hence results in variable switching frequency. Due to natural low pass filter characteristics, the method works satisfactorily under distorted line voltages whereas sampling frequency is lower than classical DPC approach.

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E. Predictive Algorithm

The principle of predictive algorithm of DPC uses information regarding the grid voltage vector and the variations in power due to the application of converters voltage for the given sample time. The equation below shows the basic principle on which predictive algorithm is applied.

$$\begin{aligned} P(k+1) &= P(k) + \sum_{i=1}^{n} \frac{dP_n}{dt} t_n \\ Q(k+1) &= Q(k) + \sum_{i=1}^{n} \frac{dQ_n}{dt} t_n \end{aligned} \qquad (16)$$

where $\frac{dP_n}{dt}$ and $\frac{dQ_n}{dt}$ are active and reactive power variations, respectively, due to respective voltage vector and t_n is fraction of sample time T_S for which the voltage vector is applied. Using the least square optimization technique, the time duration for kth control period are calculated such that

$$[\Delta P(k+1)]^2 + [\Delta Q(k+1)]^2 = \Delta \qquad (17)$$

is minimum. Depending upon the number of voltage vector applied in (15), the scheme is referred as two voltage vector sequence [22] or three voltage vector sequence [21]. A predictive DPC based on SVM is proposed in [17]. DPC combined with SVM leading to robust control of grid connected inverter for Distributed Generation has proven to have high speed and accuracy having low steady state errors [44]. Compared to other methods, predictive algorithm has less sampling frequency [10], constant switching frequency [17, 21, 22, 45] and minimum switching losses [21,46].

F. Space Vector Modulation

To limit switching frequency variations and reduce the number of commutations in converters, desired voltage vector is synthesized using SVM. The method is mostly used in conjunction with the above methods or any other method. In Model based DPC, synthesis of calculated voltage vector is an example of SVM. The method is applied in [10, 17, 45] for predictive algorithm, whereas Virtual flux DPC based SVM is discussed in [15].

It should be noted that although the above methods are commonly found in literature, other techniques such as sliding mode control [34, 47], and fuzzy control [48] are also referred to provide comparable performance for given applications.

V. KEY ISSUES OF DIRECT POWER CONTROL

There are many key issues or factors which affect the performance of the Direct Power Control algorithm: selection of switching vector from the table/ on line calculation, effect of sample time, determination of hysteresis band and grid interfacing are of utmost importance and are further elaborated in this section.

A. Selection of Switching Vector

Direct power control uses bang-bang type of controller where appropriate switching vector is selected for the given sample time. The selection may be done using either look up table; model based control, predictive control. It is essential to understand the effect of state vector on the power variation. To simplify the understanding of phenomena, it is assumed that line voltage drop across the impedance is negligible and that the boundary of the hexagon is sufficient to accommodate infinite power throughout the operation. The tip of the voltage vector is assumed to be the equilibrium point of the state vectors *dp* and *dq* in the PQ plane and the variation of power due to application of voltage vector is obtained. The attempts to optimize the selection of switching state depending upon type of the application are widely reported in [6, 16, 23, 49].

The major observations can be summarized as follows:

- When the grid voltage vector is in sector-I, application of vector V_2 results in an increase of both active and reactive power. On the other hand, application of voltage vector V_1 results in an increase of active power and decrease of reactive power.
- Application of voltage vector other than V_1 and V_2 results in decrease of active power which needs to be analyzed very carefully. It has been found that application of null vectors $\mathbf{V_0}$ (000), $\mathbf{V_7}$ (111) results in medium reduction of active power [10] and reduction in number of commutation of switches.
- Reactive power variations are sinusoidal function of the angle between the voltage space vector and the grid voltage vector i.e. a positive angle results in an increase in reactive power and a negative angle results in a decrease in reactive power. Table I shows such a selection of voltage vector for respective error in k^{th} sector while referring to 6-sector approach.

TABLE I. SELECTION OF STATE VECTOR IN KTH SECTOR

dp>0, dq>0	V_{k+3}
dp>0, dq<0	V_{k-1}
dp<0, dq>0	V_{k+1}
dp<0, dq<0	V_k

B. Effect of Sample Time

The method being a digital control, works on fixed sample time. Sample time of the system plays a crucial role in implementation since too large sample times reduce the performance of the system whereas too small sample times increase the burden on the controller. Normally, a look up table based approach requires high sampling frequency of the order of 50-100 kHz [6, 14, 23, 49]. This necessitates microprocessor and A/D system with higher speeds. Since the technique is mainly applied to grid connected systems with medium and large power ratings, the cost of such high speed system is not considered as constraint.

The use of the model based technique or space vector modulation, further reduces sampling frequency requirement. In modulator based technique, where multiple converter voltage vectors are used to meet reference power requirement, sampling frequency is twice that of the switching frequency [21, 50]. When duty cycle control based techniques are used [16] , sampling frequency can be further reduced to 20 kHz.

C. Determination of Hysteresis Band

In look-up table approach, vector selection from the table depends upon the pre-determined hysteresis band. A fixed hysteresis band of ±4-5% is usually set [10] to obtain satisfactory performance. The set hysteresis band of active and reactive power also depends upon accuracy and resolution of ADCs as well as sample time of the system. Since these variations are different for selected converter voltage vectors, they must be treated separately and are discussed below.

- Active Power: For grid voltage vector in k^{th} sector, only the nearest two active vectors in the sector are responsible for the increase of active power whereas all other vectors (six vectors) are responsible for the decrease in active power. This variation is a function of angle between the grid voltage vector and the inverter state vector and hence becomes unequal in magnitude. This may lead to large switching frequency variation and poor control over reference power quantity. In such case, there are two approaches to reduce the variation of active power. One being the application of active vector for a fraction of time period and null vector in rest of the period using duty cycle control as in [15, 16, 50]. Another is to change the symmetry of hysteresis band in positive and negative direction such that frequency variation is limited to acceptable limits.
- Reactive Power: The reactive power limit follows the same criteria of the hysteresis band. But the reactive power variation is equally spaced in all sectors. For example, three active vectors produce position variations whereas the remaining three active vectors produce negative power variations. Also, reactive power control is always considered a secondary function (except in case of Active Power Filter or FACTS) and hence limits are simplified and are symmetrical.

Depending upon the magnitude of variation, the vectors are also divided among small, medium and large groups.

D. Grid Interfacing

There are two aspects of grid interfacing while applying any control strategy for grid connected converters (or inverter).

- Passive filter (L or LC) for interfacing
- Determination of grid voltage vector position.

To eliminate switching ripples of current and/or voltage as a consequence of operation of PWM converters, appropriate values of inductances and capacitances must be connected at the point of coupling. In DPC, high gain of controller necessitates the use of inductors with high value [13]. Thus, overall cost, size and weight of the system are increased. Additionally, due to the wide spectrum of frequency in current waveform, it becomes difficult to decide the optimum value of passive filters. The possible remedies are:

- Reduction of variation in switching frequency or adopt constant switching frequency technique discussed above
- Design a suitable LCL filter [20] for grid connected systems.

In contrast to, voltage oriented control method where the determination of absolute position of grid voltage vector is necessary, direct power control method requires position of the grid voltage vector in particular sector of α-β plane. Based on the sector number, voltage vector of converters is selected. The sector pertaining to the grid voltage vector can be decided from their magnitudes [6, 23, 35], using virtual flux vector [14, 15, 18, 25, 31] or using conventional Phase Locked Loops. It is obvious that magnitude based determination of sector cannot work satisfactorily when line voltages are unbalanced or distorted. Virtual flux based technique has shown satisfactory performance under all these conditions due to its ability to act as low pass filter.

The review of DPC techniques for various application related to grid connected PWM converters are tabulated in Table II for quick reference.

TABLE II. REVIEW OF DPC TECHNIQUES FOR VARIOUS APPLICATIONS

DPC technique	PWM Rectifier	Renewable energy Sources	Active Power Filter	Doubly Fed Induction Generator	AC-DC-AC converters
Look Up Table	√	√	√	√	√
Model Based	√			√	
Virtual Flux DPC	√	√	√	√	
Predictive Control	√	√		√	
Space Vector Modulation	√	√		√	

VI. CONCLUSION

Direct Power Control of the grid connected PWM applications such as PWM Rectifier, grid connection of Renewable Energy sources, Active Power Filter, UPFC, AC-DC-AC converters and Doubly Fed Induction Generators (DFIG), are reviewed in this paper. The method is reported to have excellent dynamic performance, higher efficiency and easy implementation. Due to the high gain of the controller, it poses several challenges in terms of variation in switching frequency, high sampling frequency, accurate estimation of voltage vector and reduced power ripples. Various methods have been proposed to meet the above challenges and are discussed in this paper. A section on key features incorporated in this paper has revealed the present challenges in implementation of DPC algorithm to the new reader.

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