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A Concept of Virtual-Flux Direct Power Control of Three-Phase AC-DC Converter

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ABSTRACT

This paper presents a proposed technique of virtual-flux direct power control (VF-DPC) as the improvement in control method from the basic of conventional direct power control (DPC) for front-end three-phase pulse width modulated (PWM) in ac-dc converter. Three sensors in order to measure the three phase input voltage have been eliminated in the proposed method of virtual flux (VF) regarding from the estimation technique. Theoritical principles of VF-DPC are discussed in this paper. The steady-state performance of VF-DPC and conventional DPC are evaluated and presented in this work to estinguish for the excellent performance. It is shown that the VF-DPC exhibits the several advantages, particularly in providing low total harmonic distortion with almost sinusoudal of input current and unity power factor (pf) operation under balanced three phase voltage supply. The simulation results from both methods through Matlab simulation have demonstrated the outstanding performance of the new proposed control technique from VF-DPC.

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1. INTRODUCTION

Research interest in three-phase pulse width modulation (PWM) rectifiers or known as PWM ac-dc converters in this paper has grown rapidly over the past few years due to several important advantages offered by the converters, such as bidirectional power flow and regulation of dc-bus voltage capabilities, low harmonic distortion of input currents and almost unity high power factors operation. Consequently, various control startegies have been proposed with the same main goal which is to generate almost sinusoidal input current waveform with higher power factor. Therefore, field-oriented control (FOC), voltage-oriented control (VOC), and Direct Torque Control (DTC) with different principles are introduced in several motoring applications. Regarding in [1] the implementation of FOC for the brushless doubly fed reluctance machines serve as a basic for future research on the emerging machine topology for wind turbines or pump-alike installations, where the cost advantages of its high reliability can be fully exploited. Then, the voltage oriented control (VOC) provides for robust and keep the system stable with fast response time to pertubations which guarantees for high performance via voltage and current control loops [2]. Subsequently, this paper is mainly focussing on the direct power control strategy (DPC) which is based on the instantaneous of active and reactive power control loops. In a conceptual of DPC, there is no internal current control loops and PWM modulator block. This is because the converter switching states are appropriately selected by a switching look-up table based on the instantaneous error between the commanded and estimated values of active and reactive power. Therefore, according to [3], fundamental for the DPC implementation is through a correct and fast estimation of the active and reactive line power. In addition, a common design of the DPC strategy consists of a total seven number of sensors which is six sensors at the input side in order to measure the three-phase current (three current sensors) and voltage (three voltage sensors). In addition, a dc voltage sensor is used to measure for the dc-link ouput voltage. According to [4] [5] and [6], by using all of these sensors will cause the system to be bulky and expensive. Instead, the sensing signal is usually subject to high frequency noise and interference. Any incidental misreading of a signal caused by a failed sensor may decrease the system reability and performance. Therefore, it is desirable to reduce the number of sensors to the minimum possibles. For that reason, compared from the conventional of DPC, a control strategy of VF-DPC are capable to reduce the amount of sensor used by eliminating the employment of ac input voltage sensors. This can be done by estimating the three-phase grid voltage through the computation of the time derivative of measured currents. The implementation of virtual-flux toward DPC brings the procedures of estimation is more reliable, since no differential operations are involved. Sebsequently, a lower sampling frequency can be used during real-time implementation. However, the effectiveness of the estimation procedure and the selection of the switching states of control strategy in virtual flux will have significant impact to the control performance of VF-DPC. Hence, this paper will bring the readers to understand the basic operation on conventional of DPC and how this control strategy can be enhanced by a new method of voltage sensorless of power estimation of virtual-flux due to the advantages of VF-DPC compared to conventional DPC: lower sampling frequency, a simpler voltage and power estimation algorithm and easy implementation of the unbalanced and distorted-line voltage compensation to obtain sinusoidal line currents (low total harmonic distortion) and excellent dynamics.

2. RESEARCH METHOD

Increasingly, ac-dc converters are required to provide good input power factor, low line current distortion and regeration. The pulse width modulation ac-dc voltage source converter has these features. Several control strategies of this kind of converter has been proposed [7]-[18] and one of them is a direct power control (DPC) with the new method basically from this control technique of virtual flux direct power control (VF-DPC) has been elaborated further in this paper.

2.1. Modelling of three-phase ac-dc converter

The structure of topology for three-phase bidirectional of an ac-dc voltage source converter is shown in Figure 1. The converter is connected by three-phase ac supply and for each phase the series branch of inductor *L* and internal resistance *R* has been connected after the source in order to represents the internal impedance. Traditionally, in conventional of three-phase diode rectifier is regularly used because it is simple, inexpensive and robust. Conversely, this research insulated gate bipolar transistor (IGBT) is used as the converter bidirectional switches in this circuit via its simple and able to operate in high switching frequency [9]. Instead, this power switch can be the alternative to draw a continuous sinusoidal current from ac power supply with lower Total Harmonic Distortion (THD) and higher power factor (near unity). Later, the six IGBTs which are parallel with free-wheeling diodes are involved in rectifying the input voltages. Finally, the capacitor is connected in parallel to smoothen the output of DC voltage.

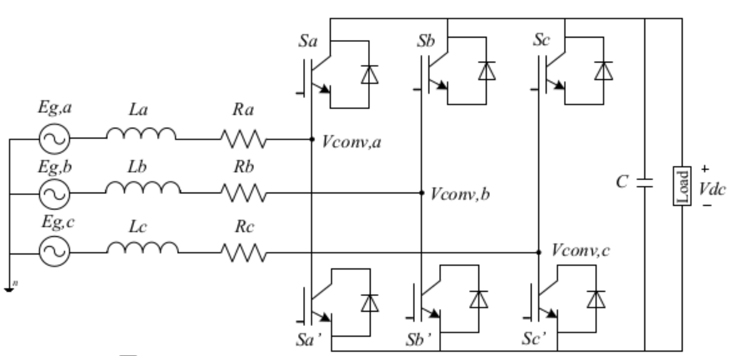

Figure 1. Three-phase PWM Rectifier System for Bidirectional Power Flow

2.2 Development for conventional of direct power control (DPC)

The three-phase AC to DC converter by direct power control block diagram is illustrated in Figure 2. A total of four voltage sensors are used to measure the three-phase AC input voltage and DC output voltage while three current sensors have measured the three-phase input currents. Then, the currents and voltages are fed into two "abc-αβ" blocks which utilise the Clarke Transformation. The subsystem 1 and subsystem 2 from the figure have represented the Clarke transformation for both three-phase input voltage and current. The block diagrams are constructed based on the formula of Clarke Transformation: Where the three-phase input components are represented by x_a, x_b and x_c while x_α and x_β are indicated for two-phase components. The equations can be rewritten as shown in equation (1) in order to obtain V_α and V_β. Next, the output after the transformation which in α-β frame is then fed into another block to obtain the estimated instantaneous active power, P, and reactive power, Q as indicate in equation (2) and (3). Then, P and Q are fed into the hysteresis comparator to obtain active and reactive power errors which is given by d_P and d_Q respectively. Following, the angle of input voltage in α-β frame, θ_n, is determined by the voltage vector angle converter block. The inputs to the switching table are θ_n, d_P and d_Q. At that point, the suitable switching states of the converter will be generated by the switching table and the output voltage is kept close to the reference DC voltage by tuning the PI controller appropriately.

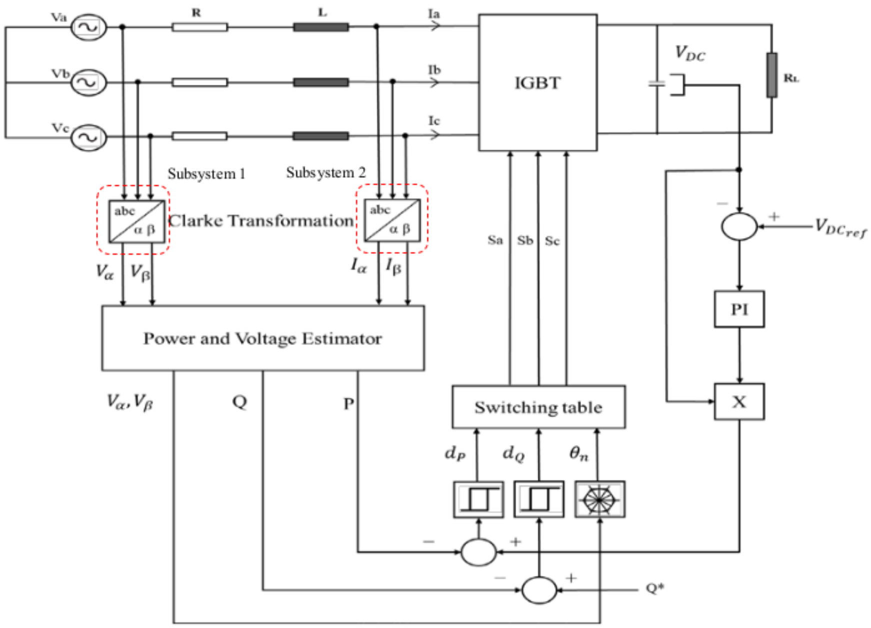

Figure 2. Control Structure of Direct Power Control

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3/2} & -\sqrt{3/2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{1}$$

$$P_{inst} = \frac{3}{2}\left[V_\alpha I_\alpha + V_\beta I_\beta\right] \tag{2}$$

$$Q_{inst} = \frac{3}{2}\left[V_\beta I_\alpha - V_\alpha I_\beta\right] \tag{3}$$

Afterward, switching table is plays as an important role in the direct power control system. The input to the switching table is the instantaneous error of the active power, reactive power and the voltage vector position. This kind of switching table are enabling for the ac-dc converter to select their switching states. Therefore, in Figure 3 has shown the location for each sector in direct power control method (DPC). The sector selection for DPC is in αβ-plane and has been divided into twelve sectors with the angle is in the range of 0° to 30° rotates in anticlockwise [3]. Then, the instantaneous power error (d_P and d_Q) and voltage vector position (θ_n) are the inputs to the newly developed look-up table as shown in Table 1 which determines the voltage vector of the converter (V_n).

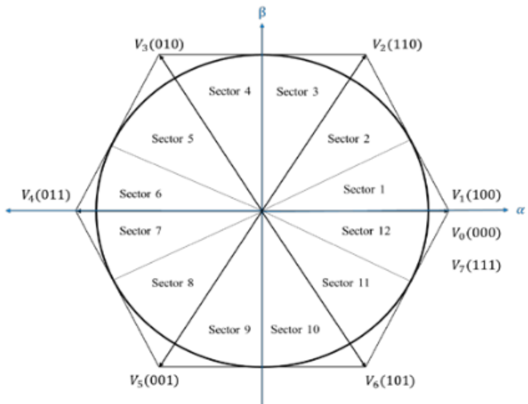

Figure 3. Sector Selection for Direct Power Control

Table 1. Switching Look-up Table for Direct Power Control

Power error status		Sector position (θ_n) and converter voltage vector (V_n)											
d_P	d_Q	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	0	V_1	V_1	V_2	V_2	V_3	V_3	[illegible]	V_4	V_5	V_5	V_6	V_6
0	1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
1	0	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
1	1	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2

2.2. Development for virtual flux direct power control (VF-DPC)

The virtual flux technique is used to estimate the input of instantaneous active and reactive powers as well as the three-phase grid voltage. The concept in VF-DPC is to combine the direct power control (DPC) scheme with the input voltage source estimation method in operating the three-phase ac-dc converter. An effective procedure to estimate the virtual flux components and the selection of converter voltage vectors is crucial in determining the success operation of VF-DPC. A simple low-pass filter is added into the system to compensate the errors in phase and magnitude produced during the virtual flux estimation procedure. At the mean time, VF-DPC is responsible to regulate the line currents and power factor including the dc-link output voltage by controlling the input of instantaneous active and reactive power. The control structure of VF-DPC is shown in Figure 4. Based on figure, the utility grid source voltage has been considered as a virtual ac machine. By assuming a balanced three-phase system, the voltage and current equation of the pulse-width modulation (PWM)-controlled rectifier can be described by equation (4) where $E_{g,abc}$ is the three-phase voltage supply, $I_{g,abc}$ is the three-phase line current, and $v_{conv,abc}$ is the three-phase converter pole voltage. Then, the phase voltages at the poles for each phase of the converter are equal as in equation (5) – (7) where, $S_{a,b,c}$ is the switching state of the converter, and v_{dc} is the link-output voltage. Any three-phase electrical quantities in *abc*-coordinates which are defined further be transformed into stationary αβ-coordinates by using the the transformation matrix as given in equation (1). According to figure, there is no line voltage sensor are required compared to conventional of DPC. There are several advantages regarding to this controller which is it contributes for the lower of Total Harmonic Distortion (THD) compared than DPC method [5]. Therefore, it allowing for the smooth control of the active and the reactive powers during each sector is selected. Instead, by minimize the number of sensor the size and cost can be reduced. However, in [6] has attempted some disadvantages for this control method due to the requirement for the fast microprocessor and analogue to digital converter. Faster in microprocessor are generating more heat and require aggressive cooling measures. Without properly dissipate the heat can cause for severe damage to the processor itself of to the other components particularly for insulted gate bipolar transistor (IGBT) devices.

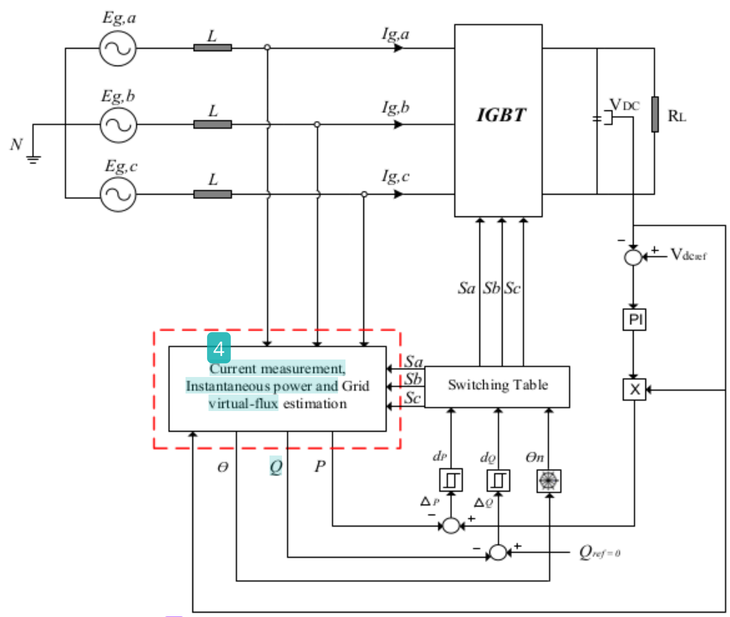

Figure 4. Control structure of virtual flux direct power control

$$\begin{bmatrix} E_{g,a} \\ E_{g,b} \\ E_{g,c} \end{bmatrix} = R \begin{bmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} I_{g,a} \\ I_{g,b} \\ I_{g,c} \end{bmatrix} + \begin{bmatrix} V_{conv,a} \\ V_{conv,b} \\ V_{conv,c} \end{bmatrix} \quad (4)$$

$$V_{conv,an} = (2S_a - (S_b + S_c))\frac{V_{dc}}{3} \quad (5)$$

$$V_{conv,bn} = (2S_b - (S_a + S_c))\frac{V_{dc}}{3} \quad (6)$$

$$V_{conv,an} = (2S_c - (S_a + S_b))\frac{V_{dc}}{3} \quad (7)$$

2.2.1 Conceptual design of a virtual flux

The grid virtual flux vector in a stationary frame $\overline{\psi}_{g,\alpha\beta}$ is defined as the integration of the grid voltage vector in a stationary reference frame $\overline{E}_{g,\alpha\beta}$ as shown in (8).

$$\psi'_{conv,\alpha\beta} = \int V_{conv,\alpha\beta} \quad (8)$$

By applying the equation of virtual flux in (8), the grid virtual flux vector can be estimated as shown in (9).

$$\psi_{g,\alpha\beta} = \int \left(\overline{V}_{conv,\alpha\beta} dt + RI_{g,\alpha\beta}\right) + LI_{g,\alpha\beta} \tag{9}$$

In practice, the value of internal line filter resistance R can be neglected since its value is much smaller than the value of the line inductance impedance Z_L. Therefore, from equation (9) can be rewritten in the stationary coordinates for acquiring the magnitude of grid virtual flux at both real and complex axes as shown in (10) and (11).

$$\psi_{g,\alpha} = \int V_{conv,\alpha} dt + LI_{g,\alpha} \tag{10}$$

$$\psi_{g,\beta} = \int V_{conv,\beta} dt + LI_{g,\beta} \tag{11}$$

Then, the ideal integration that is used to calculate the grid virtual flux as shown above might be saturate due to dc offset which is present in the sensed current or voltage. Thus, a low-pass filter is selected to replace the pure integrator. However, a simple low-pass filter are reduces the system performance because it produces errors in the phase and magnitude of the virtual flux components. In order to minimize these errors, equation in (10) and (11) is analyzed and adopted in the virtual flux estimation procedure which provides a low-pass filter characteristic at all frequencies. The α and β components of the actual convertervirtual flux $\psi_{conv,\alpha\beta}$ are calculated based on the operating frequency with a given notation of ω_e or ω, the low-pass filter cutoff frequency ω_c, and the estimate of the converter pole flux vector $\psi'_{conv,\alpha\beta}$. Therefore, (12) and (13) are used in the virtual grid estimation procedure as illustrated in Figure 5.

$$\psi_{conv,\alpha} = \psi'_{conv,\alpha} + \psi'_{conv,\beta}\left(\frac{\omega_c}{\omega_e}\right) \tag{12}$$

$$\psi_{conv,\alpha} = \psi'_{conv,\alpha} + \psi'_{conv,\beta}\left(\frac{\omega_c}{\omega_e}\right) \tag{13}$$

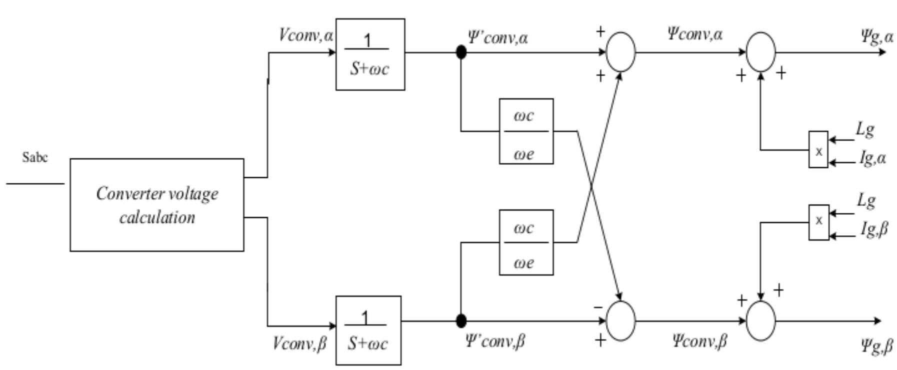

Figure 5. Control Blocks for Virtual Flux Estimation

Lastly, the estimation of the input active power P and reactive power Q in a stationary reference frame is given by (15) and (16), respectively

$$P = \left(\frac{3}{2}\right)\omega\left(\psi_{g,\alpha} I_{\beta} - \psi_{g,\beta} I_{\alpha}\right) \quad (14)$$

$$Q = \left(\frac{3}{2}\right)\omega\left(\psi_{g,\alpha} I_{\alpha} - \psi_{g,\beta} I_{\beta}\right) \quad (15)$$

The input reactive power Q is set to zero to make the input pf unity. In some applications, however, the front-end converter is required to operate in leading pf to compensate the motoring loads of lagging pf that are connected in a nearby utility grid. T hen, in Figure 5 has shown the sector selection for virtual flux vector. Similar as conventional DPC voltage sector which it represent an angle range between 0° to 30° for each sector. However, in VFDPC the sector one is located in an angle between -90° and -60° in the αβ plane as shown in the figure. The same step is applied for the other sectors and the switching lookup table applied for VFDPC is similar as in conventional of DPC method.

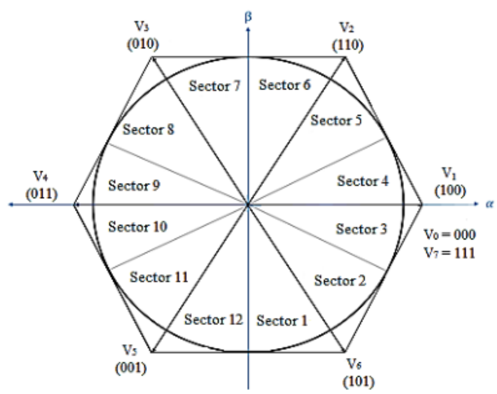

Figure 6. Sector Selection for Virtual Flux Direct Power Control

Table 2. Electrical Parameters of Power Circuit

Parameters	Value
Input phase voltage (peak), E_g	70.71 V
Source Voltage frequency, f	50 Hz
Dc-link volatage reference, $V_{dc,ref}$	150 V
Resistance of reactoes, R	0.2 Ω
Inductance of reactors, L	18 mH
Dc-link capacitor, C	10.8 mF
Load Resistance, R_L	140 Ω
Sampling time, f_s	20 µs

3. RESULTS AND ANALYSIS

The entire AC to DC converter system is simulated in the Matlab/Simulink environment in order to study its performance under steady-state conditions. The main parameter used in the simulation is tabulated in Table 2 while in Figure 7 and 8 has represent simulated basic signal which from the top is line voltage, estimated line voltage and line current waveforms. Basically, it can be seen that the new concept of virtual flux is capable to employing towards for the conventional of direct power control regarding to the capability of this method to produce the similarity output of voltage waveform. Additionally, the new enhancement in this control system of virtual flux is able to produce a current waveform which is more sinusoidal compare by the conventional control method. In fact, the current waveform which is approach to be more sinusoid will have a lower frequency component in it thus contributing to the lowest value of harmonic distortion for the signal. Therefore, the comparison for the total harmonic distortion (THD) of the input line current from both control method is shown in Figure 9. It is apparent to see from the simulation result, the harmonic rate of virtual flux is 4.19% compare to the THD from direct power control which is 4.88% higher than VF-DPC control method.

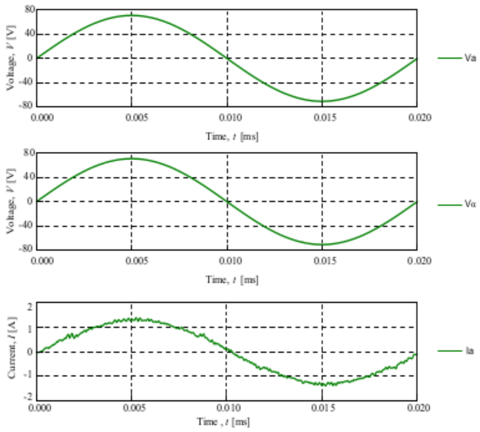

Figure 7. Conventional DPC

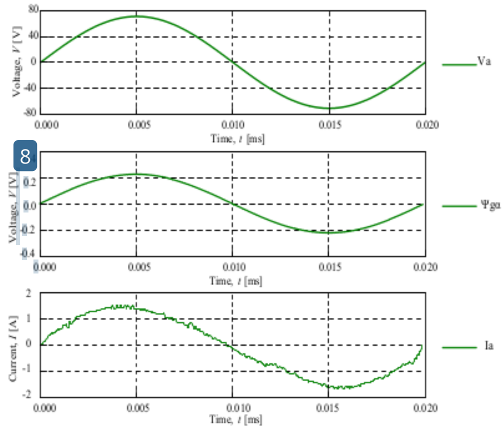

Figure 8. Proposed VF-DPC

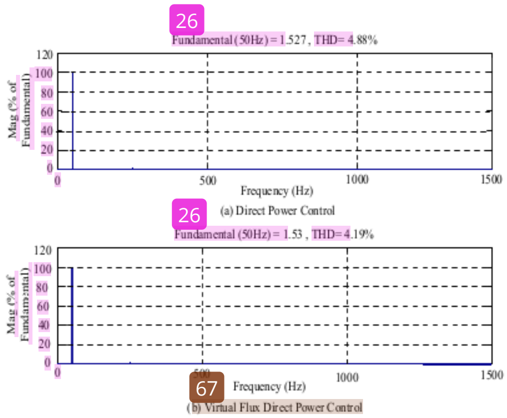

Figure 9. Three-phase PWM Rectifier System for Bidirectional Power Flow

4. CONCLUSION

The presented Direct Power Control (DPC) system constitutes a viable alternative to the pulse width modulated three-phase ac-dc voltage source converter. In the DPC the active and reactive powers has been used as the controlled output. The appropriate selecting for the switching states from a switching table based on the errors, which are limited by a hysteresis band are successfully simulated and presented in this paper. Then, based on duality with a PWM inverter-fed induction motor drives, a new control scheme as an extension from the DPC which is based on the estimation of grid voltage and the instantaneous of active and reactive power calculation known as Virtual Flux Direct Power Control (VF-DPC) has been proposed in this work. The VF-DPC is capable to minimize the employment of sensors by eliminating the used of three voltage sensors located at the input side of the ac-dc converter. Those three voltage sensors are essential in a conventional DPC in order to measure the three phase supply voltage. Hence, the size and cost of the ac-dc converter system can be reduced. Basically, both control methods are successfully simulated in the Matlab/Simulink block diagram. However, at the end of result, the new proposed system from virtual flux of direct power control has shown for the lower of total harmonic distortion for three phase input current compare with the conventional control method of direct power control (DPC). Hence it can be stated that this control method are capable to improve quality of input current.

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