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Experimental validation of virtual flux concept in direct power control with dynamic performance

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ABSTRACT

The virtual-flux direct power control (VFDPC) technique is a sensorless control approach aimed at improving the performance of grid-connected power converters. The approach involves simulating the grid voltage and AC-side inductors similar to an AC motor drive system, a principle deriving from direct torque control (DTC). The basic idea of VFDPC is to indirectly estimate the voltage at the converter's input through the concept of virtual flux, enabling the real-time calculation of instantaneous active and reactive power without necessitating direct voltage measurements. An essential element of the VFDPC approach is the implementation of a lookup table, used as a decision-making tool that identifies the most suitable voltage vector (a particular output state of the converter) in accordance with real-time power conditions. This provides instantaneous and smooth control of power flow, leading to enhanced operational stability. This approach allows for continual optimization of the converter's output, enabling VFDPC to significantly decrease total harmonic distortion (THD) while preserving reliable steady-state and dynamic performance. Experimental validation demonstrates that incorporating real-time feedback into virtual flux estimates improves the precision of voltage prediction and the responsiveness of the power control system. Consequently, VFDPC exhibits enhanced adaptability for various grid and load situations, presenting an appropriate choice for current power systems that demand efficient, reliable, and sensorless operation.

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1. INTRODUCTION

The increasing integration of renewable energy sources and the advancement of smart grid infrastructure have raised the demand for power conversion systems that are both high-performing and energy-efficient, as well as flexible in response to fluctuating grid conditions [1], [2]. Grid-connected converters are essential in these systems, allowing bidirectional energy transfer, maintaining power quality, and assuring grid compatibility. To address these complex requirements, advanced control techniques have been developed, ensuring accurate management of power distribution and improved dynamic responsiveness. direct power control (DPC) techniques, derived from direct torque control (DTC) principles, gained significant attention due to their immediate response and less need for several sensors [3], [4].

Virtual flux direct power control (VFDPC) indicates an important improvement within the direct power control (DPC) framework. It functions by directly estimating grid voltage using virtual flux computation, hence allowing the real-time calculation of active and reactive power without employing voltage sensors [5], [6]. This not only reduces the development of hardware but also enhances system reliability. The integration of a voltage vector selection lookup table allows VFDPC to operate with low total harmonic distortion (THD) while providing a rapid and steady response during dynamic operating situations, such as abrupt load changes and grid disturbances [7]–[9].

Despite the advancements in the VFDPC control system, a significant issue continues to exist: the absence of robust real-time validation processes for virtual flux estimation. The accuracy and responsiveness of flux prediction are crucial for the effective operation of VFDPC, particularly in environments where the grid exhibits unpredictable behavior and load requirements fluctuate [10], [11]. Inadequate validation may lead to errors in power calculations, reduce stability, and degrade control performance, particularly during sudden occurrences. This study addresses the gap by looking into practical real-time validation methods for virtual flux in direct power control systems. The suggested method makes VFDPC more stable and flexible in less-than-ideal settings by constantly checking flux estimation against changing grid parameters [12]–[14]. The approach intends to make it easier to quickly change control actions in real time, which will lower THD and improve the overall accuracy of control.

This main contribution is the development and evaluation of a real-time validation framework for VFDPC, specifically designed for high-performance grid-connected converters. The suggested solution is evaluated under various dynamic scenarios, such as voltage sags and sudden load changes, in order to determine its ability to maintain system stability and performance. This study enhances the existing knowledge by illustrating how real-time flux validation can markedly improve control precision, dependability, and robustness in contemporary power systems [15]–[17]. Moreover, it enables the potential implementation of sensorless control methodologies in next-generation grid systems [18], [19].

2. METHOD

This study examines the real-time validation of the virtual flux idea in direct power control (DPC), prioritizing the improvement of dynamic performance despite variable grid settings [20]–[22]. The suggested methodology encompasses numerous essential elements designed to address the issues associated with virtual flux estimation, real-time control, and dynamic system behavior. Figure 1 depicts the three-phase grid-connected converter topology employed in this paper, which provides the fundamental structure for the implementation of the VFDPC approach. The illustration depicts the interface between the grid and the converter via inductive-resistive branches (La, Lb, Lc), and (Ra, Rb, Rc) together with the switching network that generates the necessary converter voltage vectors (Vconv,a), (Vconv,b), and (Vconv,c). This hardware arrangement facilitates the real-time implementation of virtual flux estimation and control logic, as examined in the following sections.

This paper is organized into four sections, starting with an introduction: i) Section 1 provides a detailed review of the existing research, offering an overview of DPC and the latest developments in VFDPC; ii) Section 2 covers the methodology, explaining key concepts behind VFDPC, such as how grid voltage and power are estimated, and introduces a newly developed switching lookup table; iii) Section 3 presents the results and analysis, focusing on system performance under balanced voltage conditions, its impact on total harmonic distortion (THD), and comparisons with traditional control methods; and iv) Section 4 concludes with a summary of the main findings, practical implications, and recommendations for future studies.

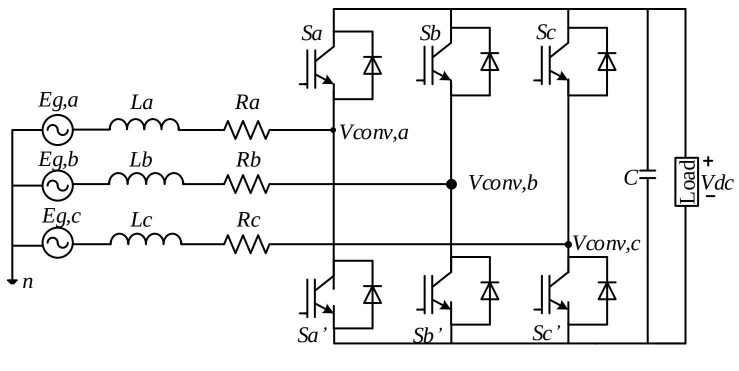

Figure 1. Three-phase grid-connected converter topology

2.1. Problem formulation

The VFDPC approach works by estimating two key things: the instantaneous active and reactive power inputs, and the virtual flux of the three-phase grid [23], [24]. Essentially, VFDPC combines a method for directly controlling power with a technique for estimating input voltage sources to manage an AC-DC converter efficiently. In VFDPC, accurately estimating the grid's virtual flux and choosing the right switching states for the converter are both essential for smooth operation. To improve accuracy, a low-pass filter is added to the system, which helps correct any phase or magnitude errors that may occur during virtual flux estimation. By carefully managing these power inputs, VFDPC can regulate both the line currents and the output voltage of the DC link. As shown in Figure 2, the control structure of VFDPC treats the utility grid's source voltage as though it were a virtual AC machine. This approach allows for precise and responsive power control in the converter system.

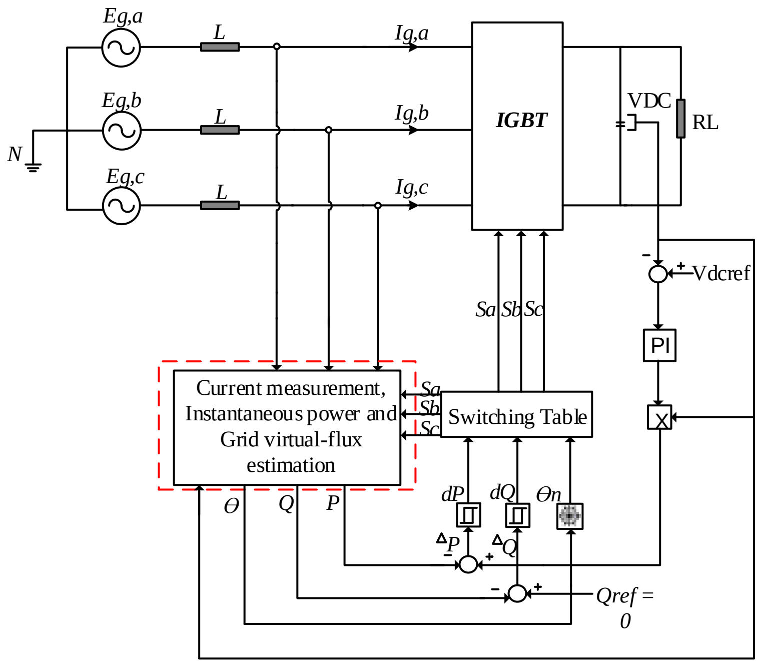

Figure 2. VFDPC control diagram

The (1) expresses the relationship between parameters that have been controlled in the rectifier by Pulse Width Modulation (PWM). From the equations, the grid voltage from the three-phase system is equal to the summation voltage from the internal resistance, inductance, and converter pole voltage. Following this, in (2)-(4) determines the phase voltage at the pole's converter. This parameter value is cooperating with the DC-link output voltage and the converter's switching states from each phase.

$$\begin{bmatrix} E_{grid,a} \\ E_{grid,b} \\ E_{grid,c} \end{bmatrix} = R \begin{bmatrix} I_{grid,a} \\ I_{grid,b} \\ I_{grid,c} \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} I_{grid,a} \\ I_{grid,b} \\ I_{grid,c} \end{bmatrix} + \begin{bmatrix} V_{converter,a} \\ V_{converter,b} \\ V_{converter,c} \end{bmatrix} \quad (1)$$

$$V_{converter,an} = \frac{V_{DC}}{3}\left(2S'_a - (S'_b + S'_c)\right) \quad (2)$$

$$V_{converter,bn} = \frac{V_{DC}}{3}\left(2S'_b - (S'_a + S'_c)\right) \quad (3)$$

$$V_{converter,cn} = \frac{V_{DC}}{3}\left(2S'_c - (S'_a + S'_b)\right) \quad (4)$$

Next, as in direct power control strategy, the voltage must be converted from abc-coordinates into alpha and beta coordinates, or known as the stationary reference frame. Matrix formulation has been implemented to do this transformation, as shown in (5).

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \quad (5)$$

Grid virtual flux can be obtained by integrating the vector of grid voltage, as shown in (6), and the final equations can be seen in (7).

$$\overline{\psi}_{g,\alpha\beta} = \int \left(\overline{E}_{g,\alpha\beta}(dt)\right) \quad (6)$$

$$= \int \left(\overline{V}_{conv,\alpha\beta} + R\overline{I}_{g,\alpha\beta} + \frac{L\overline{I}_{g,\alpha\beta}}{dt}\right) dt \quad (7)$$

Practically, the value of resistance can be neglected due to its small value compared to the value of line inductance. Therefore, the final equations without considering the value of resistance can be seen as shown in (8) and (9) for real and imaginary axes.

$$\psi_{g,\alpha} = \int V_{conv,\alpha} dt + LI_{g,\alpha} = \psi_{conv,\alpha} + LI_{g,\alpha} \quad (8)$$

$$\psi_{g,\beta} = \int V_{conv,\beta} dt + LI_{g,\beta} = \psi_{conv,\beta} + LI_{g,\beta} \quad (9)$$

In (10) and (11) are added to the estimation method to compensate for these errors. These equations are intended to take into account how the LPF behaves differently at different frequencies. This makes it possible to accurately reconstruct the flux at all frequencies except the fundamental grid frequency, which is kept constant. Then, the rectified flux components are recalculated using important factors such as the grid angular frequency, the filter cut-off frequency, and the characteristics of the converter's switching.

Figure 3 shows that this modification approach is built into the flux estimation loop. The picture shows the whole virtual flux estimate block, which uses transfer functions that represent the LPF behavior to process the converter voltage inputs. To get the virtual flux components right, more compensation terms are used. This better estimation method makes the system more resistant to measurement errors and keeps control consistency in real-world situations.

$$\psi_{conv,\alpha} = \psi'_{conv,\alpha} + \psi'_{conv,\beta}\left(\frac{\omega_c}{\omega_e}\right) \quad (10)$$

$$\psi_{conv,\beta} = \psi'_{conv,\beta} = \psi'_{conv,\alpha} - \psi'_{conv,\beta}\left(\frac{\omega_c}{\omega_e}\right) \quad (11)$$

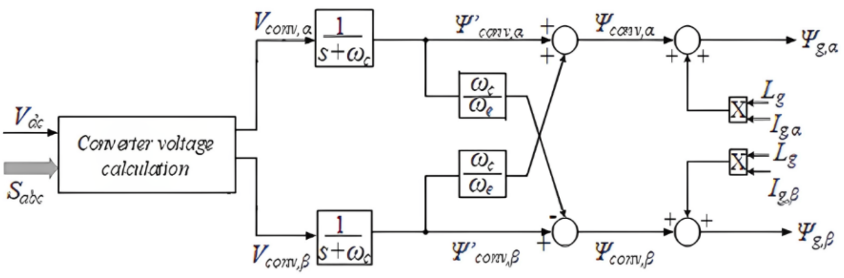

Figure 3. The diagram of a low-pass filter in virtual flux for the filtering process

2.2. Lookup table

The (12) and (13) provide the estimates for input active power and reactive power in a stationary reference frame.

$$P = \left(\frac{3}{2}\right)\omega\left(\psi_{g,\alpha}I_{g,\beta} - \psi_{g,\beta}I_{g,\alpha}\right) \quad (12)$$

$$Q = \left(\frac{3}{2}\right)\omega\left(\psi_{g,\alpha}I_{g,\alpha} + \psi_{g,\beta}I_{g,\beta}\right) \quad (13)$$

As a result, the differentiation of active and reactive power can be expressed as (14) and (15), respectively.

$$\frac{dP}{dt} = \frac{3}{2}\omega\left(\Psi_{g,\alpha}\frac{dI_{g,\beta}}{dt} + \frac{d\Psi_{g,\alpha}}{dt}I_{g,\beta} - \Psi_{g,\beta}\frac{dI_{g,\alpha}}{dt} - \frac{d\Psi_{g,\beta}}{dt}I_{g,\alpha}\right) \tag{14}$$

$$\frac{dQ}{dt} = \frac{3}{2}\omega\left(\Psi_{g,\alpha}\frac{dI_{g,\alpha}}{dt} + \frac{d\Psi_{g,\alpha}}{dt}I_{g,\alpha} + \Psi_{g,\beta}\frac{dI_{g,\beta}}{dt} + \frac{d\Psi_{g,\beta}}{dt}I_{g,\beta}\right) \tag{15}$$

The effectiveness of the voltage vector selection mechanism in VFDPC was determined by analyzing the system's behavior through simulations of instantaneous active and reactive power responses to designated converter voltage vectors. The results arise from the mathematical equations of power derivatives regarding voltage vector orientation. Figures 4 and 5 exhibit the derivatives of active and reactive power, respectively, in response to various converter voltage vectors. These waveforms illustrate how various vectors affect the rate of power change, consequently enhancing the decision-making process in choosing the ideal voltage vector to minimize power error.

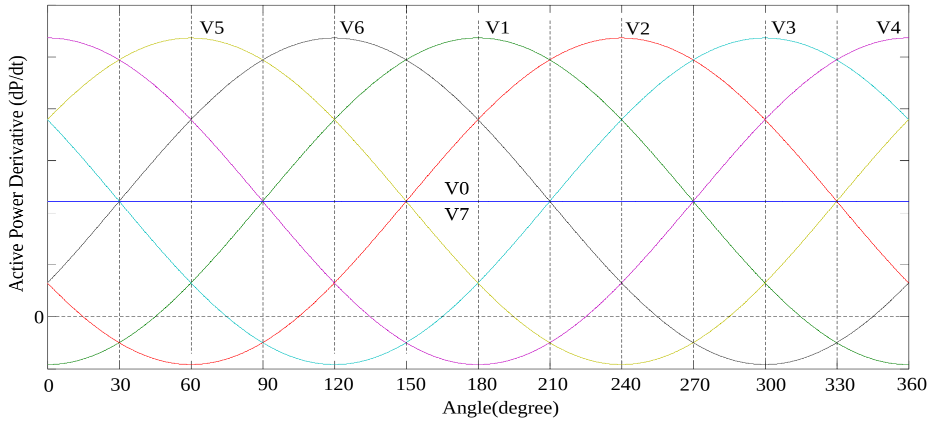

Figure 4. Active power derivative

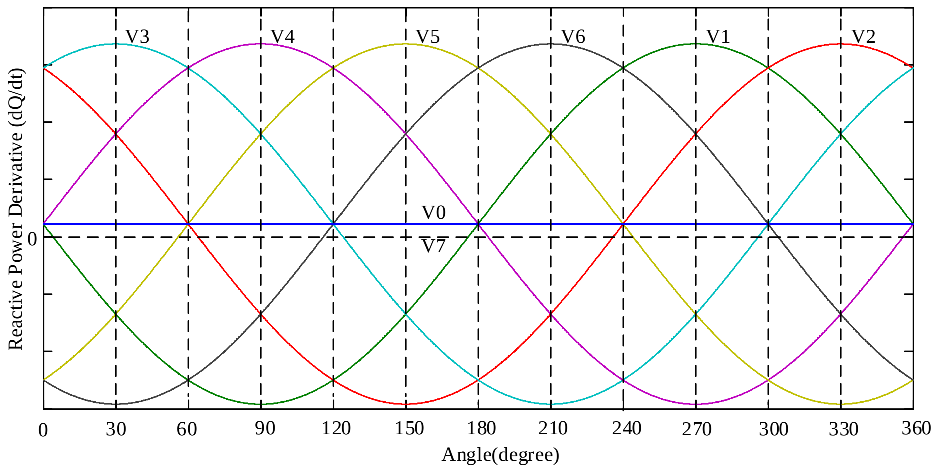

Figure 5. Reactive power derivative

The decision logic is integrated into a lookup table, illustrated in Table 1, which correlates the instantaneous power error states (dP, dQ) and the sector position with the appropriate voltage vector. The table classifies the 12 potential voltage vector sectors and designates control actions according to whether the active and reactive power errors are rising (1) or decreasing (0). For example, when both dP and dQ are minimal, the database promotes voltage vectors that maintain the current power level; conversely, when both errors are significant, the lookup table prioritizes vectors that rapidly rectify the differences.

Figures 4, 5, and Table 1 collectively present an in-depth explanation of the power error-based vector selection technique that supports the VFDPC algorithm. This integrated control logic facilitates precise and adaptive voltage vector application, ensuring perfect control of active and reactive power while improving the system's responsiveness to dynamic conditions.

Table 1. VFDPC lookup table

Power error status		Sector position (θ_n) and converter voltage vector (V_n)											
dP	*dQ*	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	V_4	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_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3

3. RESULTS AND DISCUSSION

Figure 6 presents the simulation results of the VFDPC control strategy. The results demonstrate that the voltage vector selection in the look-up table is appropriate, ensuring smooth input voltage and current, as shown in Figures 6(a) and 6(b). Additionally, this control strategy effectively converts the AC source to a DC output, following the reference value, as observed in Figure 6(c). Figure 6(d) illustrates the instantaneous active and reactive power, while Figure 6(e) confirms unity power factor operation, where phase voltages align with their corresponding currents. Finally, the total harmonic distortion (THD) measured in 6(f) is significantly reduced, meeting IEEE standard requirements.

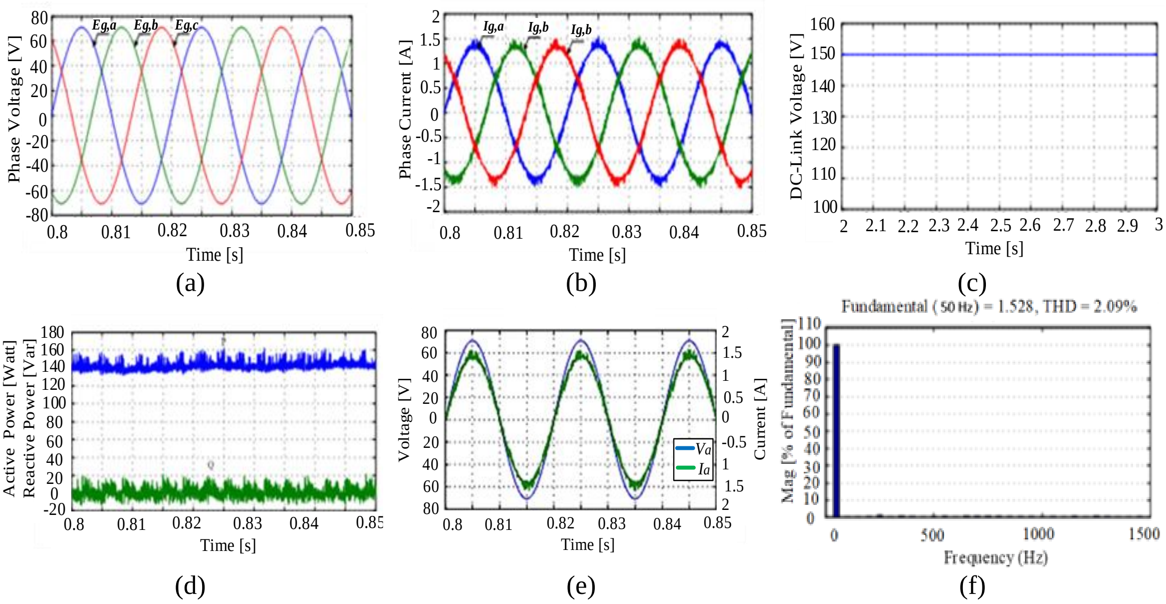

Figure 6. Simulation results from VFDPC control strategy: (a) phase voltage, (b) line current, (c) DC-link voltage, (d) active and reactive powers, (e) unity power factor, and (f) harmonic spectrum

3.1. Experimental validation for VFDPC control strategy

The development of the control algorithm is performed using MATLAB/Simulink and real-time implementation with the dSPACE DS1104 Digital Signal Processing (DSP) board inserted in a desktop computer [25]. The experimental prototype of the AC-DC converter system has been developed in the Universiti Teknikal Malaysia Melaka (UTeM) laboratory to study and examine the proposed DPC scheme. The main hardware configuration for the experimental setup is shown in the block diagram of Figure 7. The setup consists of a three-phase grid supply, a three-phase transformer, line inductors, an AC-DC converter power circuit, gate drivers and isolation, DC-link capacitors, a variable resistive load, voltage, and current sensors, and a DSP controller board. The sampling time, Ts, for real implementation has been increased to 66.667 µs or 15 kHz sampling frequency because of the speed limit of the DSP board. A large capacitance of the DC-link capacitor at the output of the AC-DC converter acts as a short circuit across the three-phase supply if no proper start-up method is implemented during the initial operation of the front-end PWM rectifier system. A high current will flow continually through the capacitor until the capacitor builds up sufficient voltage. This condition will result in a large starting current which can disturb the supply AC voltage, blow the line fuses, or damage the switching devices such as IGBTs and bridge diodes. Therefore, a systematic approach to starting up the AC-DC converter system unit is necessary. In the proposed control method, the following way of charging up the unit is established. The capacitor is pre-charged to a certain DC voltage value Vdc, through the anti-parallel diode of the IGBT switches.

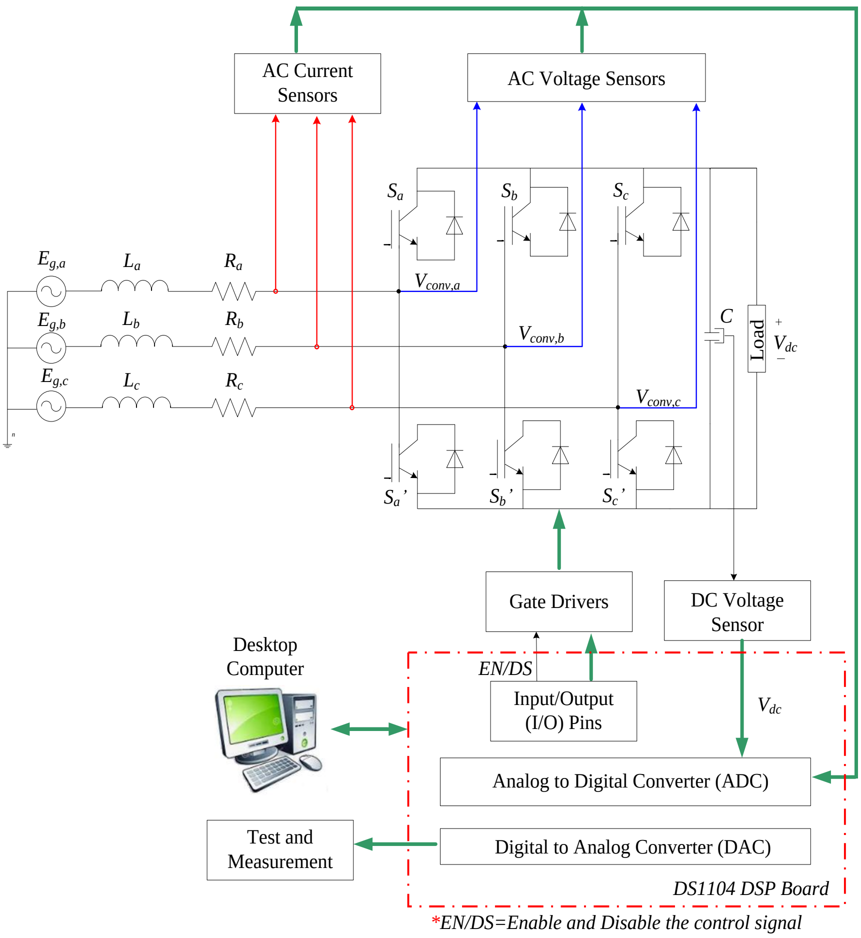

Figure 7. dSPACE DS1104 digital signal processing (DSP)

Figure 8 represents the balanced input three-phase grid side voltage waveforms once the VFDPC has been activated. In Figure 8(a), the balanced voltage waveforms of the three-phase grid are shown. Figure 8(b) then illustrates the VFDPC in action, using the new switching table to generate nearly sinusoidal line currents operating at a unity power factor, as illustrated in Figure 8(c). The reactive power reference Qref is set to 0 Var to obtain unity power factor operation so that the phase voltages are in phase with their associated currents. The most upper waveform in Figure 8(d) shows the DC output voltage, Vdc is well regulated at a reference voltage, Vdc, ref of 150 V, while maintaining the sinusoidal three-phase current. Owing to precise virtual flux estimation, both active and reactive power are accurately calculated, as depicted in Figure 8(e). Finally, the AC-DC converter utilizing VFDPC with a new switching table generates a current total harmonic distortion (THD) of 4.5% as shown in 8(f). This THD value complies with the IEEE standard, which requires THD to remain below 5%.

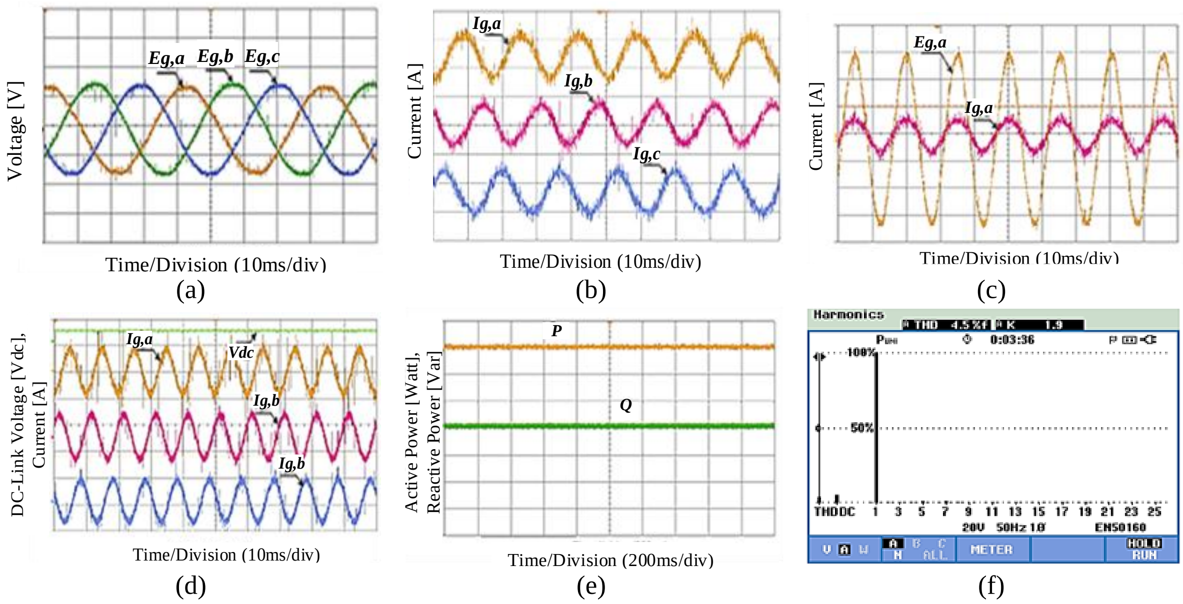

Figure 8. Simulation results from VFDPC control strategy: (a) phase voltage, (b) line current, (c) DC-link voltage, (d) active and reactive powers, (e) unity power factor, and (f) harmonic spectrum

3.2. Load variation

Experiment tests are also conducted to verify the dynamic performance of the VFDPC. Figure 9 shows transient responses for the rapid change of load power under unity power factor operation. The additional resistor is abruptly connected in parallel with the existing resistor at the output of the PWM rectifier to cause a sudden increase in the load power. As a result, the estimated input active power, P, and the phase currents increase simultaneously to fulfill the load power demand. The proposed control method can maintain the DC-link output voltage at the reference value of 150 V and the sinusoidal line currents with a unity power factor. The estimated reactive power, Q, is kept at 0 Var to maintain the unity power factor operation of the PWM rectifier.

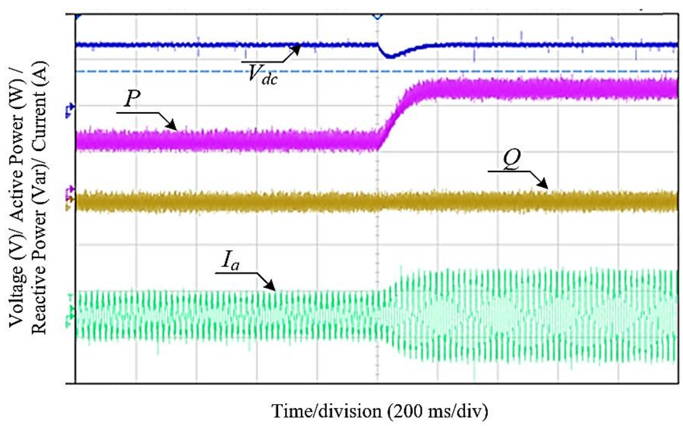

Figure 9. Transient response for load increasing in VFDPC from experimental results under balanced voltage supply conditions. From top: DC-link output voltage (107 V/div), estimated input active power (150 W/div), estimated input reactive power (75 Var/div), and phase *a*-current (2.5 A/div)

Evaluation of the dynamic response under the change of load power from high to low power demand is performed by instantly disconnecting the additional resistors in parallel with the existing load resistor of 140 Ω. Figure 10 shows the transient response during this condition. The input estimated active power, P, and the phase current are decreasing concurrently to meet the decreasing load demand. The DC output voltage level is kept almost constant at its reference value of 150 V while maintaining the sinusoidal line currents flowing through the AC-DC converter system.

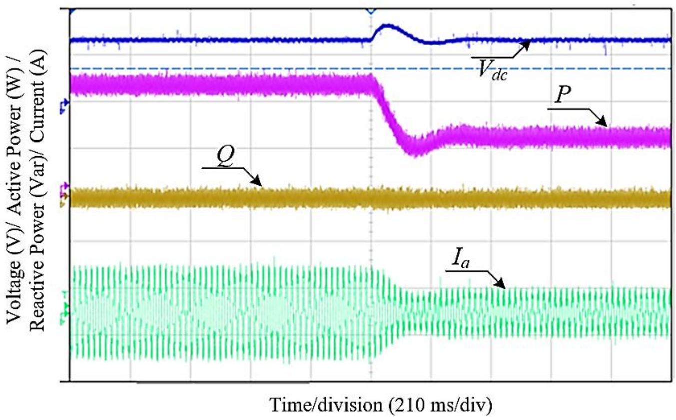

Figure 10. Transient response for load power decreasing in VFDPC from experimental results under balanced voltage supply conditions. From top: DC-link output voltage (107 V/div), estimated input active power (75 W/div), estimated input reactive power (75 Var/div), and phase *a*-current (2.5 A/div)

3.2. DC Voltage reference variation

The dynamic behavior of the front-end rectifier under a step change in output voltage reference is shown in Figure 11. In the figure, the DC output voltage increases according to a change of the DC voltage reference from 150 V to 235 V. The estimated active power, P, is also increased and decreased steadily to new values during the changes of output voltage while maintaining the estimated reactive power, Q at 0 Var. The proposed control method can generate almost sinusoidal phase currents with low THD and unity power factor before and after the changes of the DC output voltage reference.

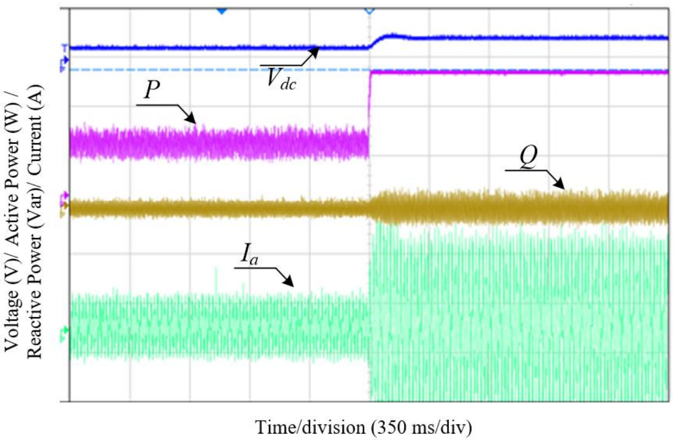

Figure 11. Dynamic response during a change in DC voltage reference in the proposed DPC from experimental results under balanced voltage supply conditions. From top: DC-link output voltage (107 V/div), estimated input active power (75 W/div), estimated input reactive power (75 Var/div), and phase *a*-current (2.5 A/div)

4. CONCLUSION

This study has shown that the virtual-flux direct power control (VFDPC) method provides a reliable, sensorless technique for controlling grid-connected converters via precise virtual flux estimation. By imitating the dynamic characteristics of AC machines, VFDPC facilitates accurate real-time calculations of active and reactive power, hence enhancing stable and efficient power flow management. The implementation of a voltage vector selection lookup table showed improvements in dynamic response and system stability, especially during transient impacts. Experimental results validated the method's efficacy in substantially decreasing total harmonic distortion (THD) while preserving excellent steady-state performance results that correspond with theoretical predictions and prior research findings. This study enhances current research by including real-time validation procedures, thus filling a significant gap in ensuring the dependability and adaptability of virtual-flux-based control. In contrast to conventional DPC approaches, this paper provides an optimized hardware design while maintaining control accuracy, facilitating wider implementation in advanced, renewable-dominant grid settings. The study not only confirms existing ideas on sensorless control and flux estimates but also extends the field by presenting a demonstrated, scalable approach for improved power converter performance under complex and dynamic operating configurations.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of the paper.

DATA AVAILABILITY

All data supporting the findings of this study in this paper, including the equations, data, and parameters used, have been made publicly available.

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