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A Design and Implementation of a New Control Based on Petri Nets for Three Phase PWM-Rectifier

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ABSTRACT

This article introduces a novel and effective diagram based on direct instantaneous power control (DPC) of a PWM-controlled rectifier connected to the grid without a switching table. An optimum control vector of the PWM rectifier's input voltage, which depends on the switching states determined by a Petri nets controller, is adopted. This approach limits the instantaneous detection errors of reactive and active powers, maintains the DC bus voltage at a reference level, and ensures current close to a sinusoidal wave, guaranteeing operation at a unit power factor. The instantaneous tracking errors of active and reactive powers and the angular position of the voltage are used as input variables for the proposed controller, which then selects the best control vector for the converter based on the transition of a Petri net. The significant advantages of DPC based on Petri nets compared to traditional switching tables are that hysteresis comparators are not required, and the classical regulation of active and reactive powers is achieved in all sectors. Simulation and testing findings demonstrated excellent performance, supporting the viability of the suggested control approach using Petri nets.

KEYWORDS

DPC, DSPACE, Optocoupler, Petri Nets, PWM Rectifier, THD, UPF

1. INTRODUCTION AND RELATED WORK

Static converter usage increased as a result of the expansion of power electronics applications. These static converters are becoming increasingly connected to power grids. The static converters mainly intended for the conversion and treatment of electrical energy between a source (electrical network, synchronous or asynchronous generators, battery, renewable sources ...) and a load (passive load,

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alternative machines, on-board network, etc.). The natural switching of power electronics converters is the reason why their behavior with respect to the energy source is non-linear. Unidirectional power flow, a low power factor, and a high amount of harmonic input currents are the main drawbacks of conventional rectifiers, which present substantial issues for electrical networks. They are one of the primary harmonic sources in distribution networks. These harmonics pollution can deteriorate the quality of the current and the voltage by propagating it into the network. Under some operational circumstances, static converters can produce a very high harmonic distortion rate (THDi). Due to this, appropriate international standards like IEEE standard 519 and IEC 61000 place restrictions on the current and voltage THDs in the supply network.

Numerous harmonic reduction techniques, such as those based on PWM rectifiers, are suggested in order to reduce the harmonic disturbance rate brought on by non-linear loads or power electronics linked to the grid (Lounnas et al., 2023; Dehnavi et al 2023; Hamida et al., 2023, 2022a,b,c; Alazrag et al., 2023; Othman et al 2023; Ardjal et al., 2023; Abdelmalek et al., 2021, 2018a,b). These PWM rectifiers provide a bi-directional power transfer, consume a current close to a sinusoid and can operate under a unit power factor. Several strategies for controlling PWM rectifiers are proposed in recent work (Djabali et al., 2021; Hadji et al., 2021) and classified into strategies are classified in two categories. The first approach relies on the current loop, whereas the second one relies on the power loop. The research (Alhasheem et al., 2020; Dragičević et al., 2020; Hornik & Zhong, 2010; Yin et al., 2008) demonstrates how internal loop currents, a form of indirect power regulation known as VOC (voltage-oriented control), ensure optimal dynamic and static performance. Another technique which is of interest, in the last few years presented initially by (Noguchi et al., 1996), where no internal loop of the current is used. It is based on the instantaneous power loops and consists in selecting a control vector according to a switching table (Yan & Hui, 2021). The latter is based on the angular position of the estimated voltage and the digitized error of the instantaneous active and reactive power. To identify the operating sector, the plane is divided into twelve sectors. The fact that this method's switching frequency is flexible is by far its biggest drawback. The Direct Power Control with Space Vector Modulation (DPC-SVM), which differs slightly from the DPC with switching table, is another structure that has been suggested in numerous research studies (Yan et al., 2021) to address the change of the switching frequency. In place of the hysteresis comparators, two proportional integral correctors (PI) are added, and the outputs of these two regulators are placed in a vector modulation block following a coordinate translation. Since the modulator already sets a limit on the current dynamics, these improvements enable operation at a constant switching frequency. Bouafia et al. (2009) presented a method for choosing the best control vector based on a fuzzy controller, which replaces the traditional switching table with a fuzzy logic-based controller. Predictive control model theories have recently increased in popularity (Kwak et al., 2014) and have been applied to direct power control to improve system performance (Song et al 2015). Another sort of direct power controller, dubbed predictive control of direct power control, has been presented based on the model's predictive control theory (Tang et al., 2022). A series of voltage vectors must initially be chosen throughout the implementation procedure. The cost function, which is generated as a function of expected values and power references, is then minimized to estimate the associated application time for these vectors. When the predictive direct power control technique is used, great control performance is usually attained. However, the behavior of the system can deteriorate due to the incorrect selection of the vector sequences.

The control system, on the other hand, may be constructed using a technique that expressly uses the hybrid character of power electronics converters, given their continuous and discontinuous nature. There are two formalizations for automated modeling of these systems in this regard. It was discovered that automata utilizing state machines, which decouple the discrete and continuous portions, among the traditional techniques. This structure, on the other hand, necessitates a complete and explicit listing of all system states. Petri nets (PN) appear to be a viable alternative to PLCs for temporary / timed discrete event systems models (Cassandras et al., 2008). A PN provides analytical methodologies for an effective resolution of the control problem without the necessity for a thorough enumeration of the state space. Different models have been created based on fundamental PNs, some of which are detailed in (Vignolles et al., 2022). PNs have been widely used as a tool for the investigation and modelling of hybrid systems. Among the works discussed, it should be noted that the continuous PN, a hybrid of ordinary and continuous PNs, differential PNs, batch PN, a colored version of the batch PNs, and high-level hybrid PNs are all extensions of the continuous PNs (Sayah & Chenafa, 2021). Applications for PN include modelling and analysis of power systems and industrial processes. However, no research has combined the strategy for controlling rectifiers to PWM based on PN (Li et al., 2022). It is not necessary to use the PN at intermediate values of two subsequent discrete states in our application due to the discrete definition of the voltage levels and the binary working of the switches in the rectifier. These properties encourage the usage of basic PNs by making the suggested control system easier to execute.

This paper proposes a Petri net-based simplified DPC of a three-phase PWM-rectifier for determining the switching state of the converter. The suggested control system has a major goal to keep the DC bus voltage at the desired level while also achieving a unit power factor for the PWM rectifier by directly adjusting its active and reactive powers. The DPC system that has been created has two components. The best switching state of the converter is identified using Petri nets at each sampling moment, reducing both active and reactive power faults, therefore there is no need to use a predetermined switching table. Second, estimations are used as Petri net input variables in the traditional DPC structure and hysteresis comparators are used to reduce inaccuracy between reference powers. Simulations have been used to test the suggested control approach, and the results are presented. The results of the simulation and experiment demonstrate how much better than the traditional ones the new DPC is. A unit power factor is attained in both the steady state and transient state, the line currents are very close to sinusoidal waveforms, the DC bus voltage is tightly under control.

The remainder of the is organized as follows: Section 2 gives a summary of the fault detection system. Section 3 displays the dataset that was used for real fault detection. The machine learning models for model verification and exploration are discussed in Section 4. The accuracy criteria used to evaluate the performance and accuracy of the suggested models are described in Section 5. Section 6 also compares and summarizes the findings. Section 7 concludes with the conclusion.

2. MODELING OF THE SUGGESTED APPROACH

Dynamic systems modelling is used to explain and forecast the interactions of numerous components of phenomena that are considered as a system throughout time. It focuses on the process that governs how the components and system change over time. In the literature, there are many applications of dynamic modeling in machine learning, deep learning, computational intelligence, control systems, robotics, sensor network and cyber-security (Ben Smida et al., 2018; Lamamra et al., 2017; Grassi et al., 2017; Mohanty et al., 2021 ; Ghoudelbourk et al., 2022, 2021, 2016; Mekki et al., 2015; Dudekula et al., 2023 ; Hussain et al., 2023 ; El-Shorbagy et al., 2023 ; Ramadan et al., 2022 ; Ashfaq et al., 2022a,b; Waleed et al., 2022 ; Jothi et al., 2022, 2020, 2019, 2013 ; Lavanya et al., 2022 ; Inbarani et al., 2022, 2020, 2018, 2014, 2015 ; Boulmaiz et al., 2022 ; Fouad et al., 2021 ; Elfouly et al., 2021 ; Khan et al., 2021 ; Aslam et al., 2021 ; Nasser et al., 2021 ; Hussien et al., 2020 ; Kumar et al., 2019, 2015a,b ; Mjahed et al., 2020 ; Banu et al., 2017 ; Ben Abdallah et al., 2016, 2014; Emary et al., 2014a,b; Anter et al., 2015, 2013 ; Elshazly et al., 2013a,b ; Azar et al., 2013, 2012; Aziz et al., 2013). The general layout of the DPC applied to the three-phase PWM rectifier bridge using a switching table is depicted in Figure 1. The Direct Torque Control (DTC) principle is similar to that of induction machines (DTC). Instead of torque and stator flux, the regulated quantities are the active and reactive instantaneous powers. A control vector is chosen using the DPC based on a switching table. This method is based on the digitised error Sp, Sq of the estimated voltage's estimated angular position, as well as the instantaneous active and reactive power. Figure 3 illustrates how the plane ($\alpha\beta$)) is divided into twelve sectors to determine the working area. To manage the inaccuracy between the picked-up voltage and its reference, the output of the controller and the DC bus voltage are multiplied in both configurations to provide the reference of the active power. While the reference reactive power must be set directly to zero in order to get a unit power factor. This proposed research of direct power control based on Petri nets maintains the same operation as the conventional DPC shown in Figure 1, with the exception that the switching table block is swapped out for the controller depicted in Figure 2.

2.1 Study of Power Variations

The expression of the PWM-rectifier currents in the fixed reference frame (αβ) is given by:

$$\begin{cases} \dfrac{di_{\alpha}}{dt} = \dfrac{1}{L}\left(e_{\alpha} - U_{e\alpha} - Ri_{\alpha}\right) \\ \dfrac{di_{\beta}}{dt} = \dfrac{1}{L}\left(e_{\beta} - U_{e\beta} - Ri_{\beta}\right) \end{cases} \tag{1}$$

The evolution of the current vector $[i_{\alpha}\, i_{\beta}]^T$ can be controlled by choosing the vector of the voltages $[U_{e\alpha}, U_{e\beta}]^T$ at the input of the PWM-rectifier, as shown in equation 1. The variation of the vector of the currents mainly depends on the vector of the voltages of the network $e_{\alpha\beta}$ of the control vector $U_{e\alpha\beta}$ to be applied, the resistance R is neglected compared to the inductance L, and so first-order discrimination can be adopted over a switching period T. Equation 2 gives the variation of the vector components of the currents as follows:

Figure 1. Classical DPC scheme

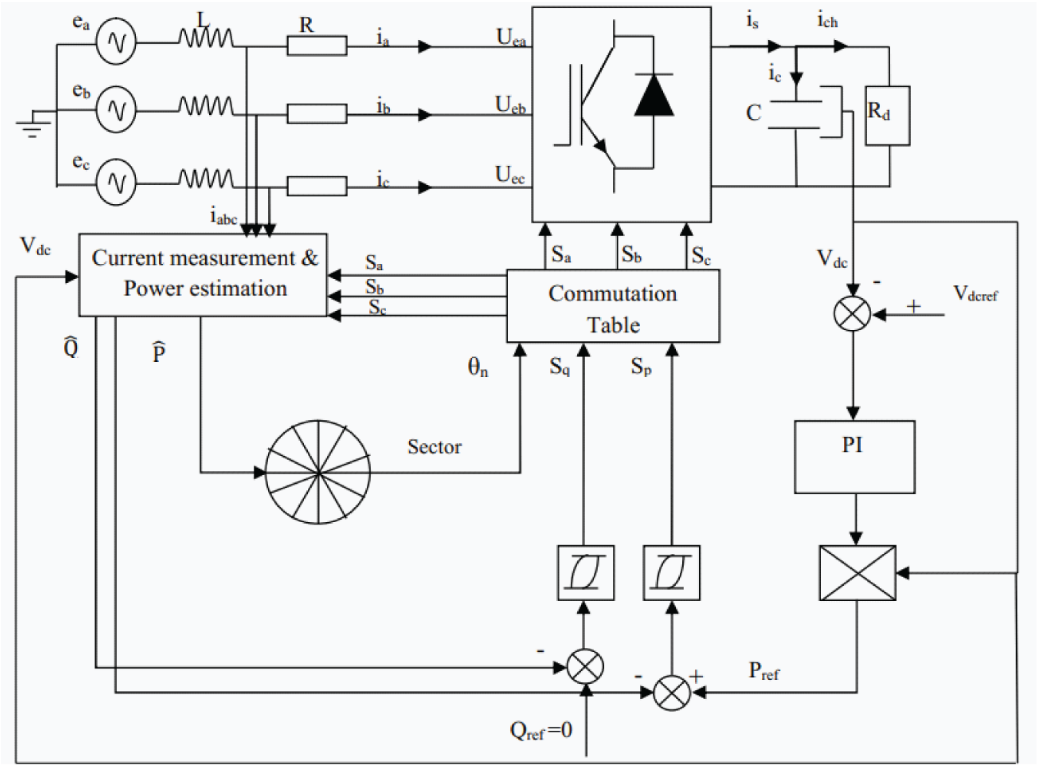
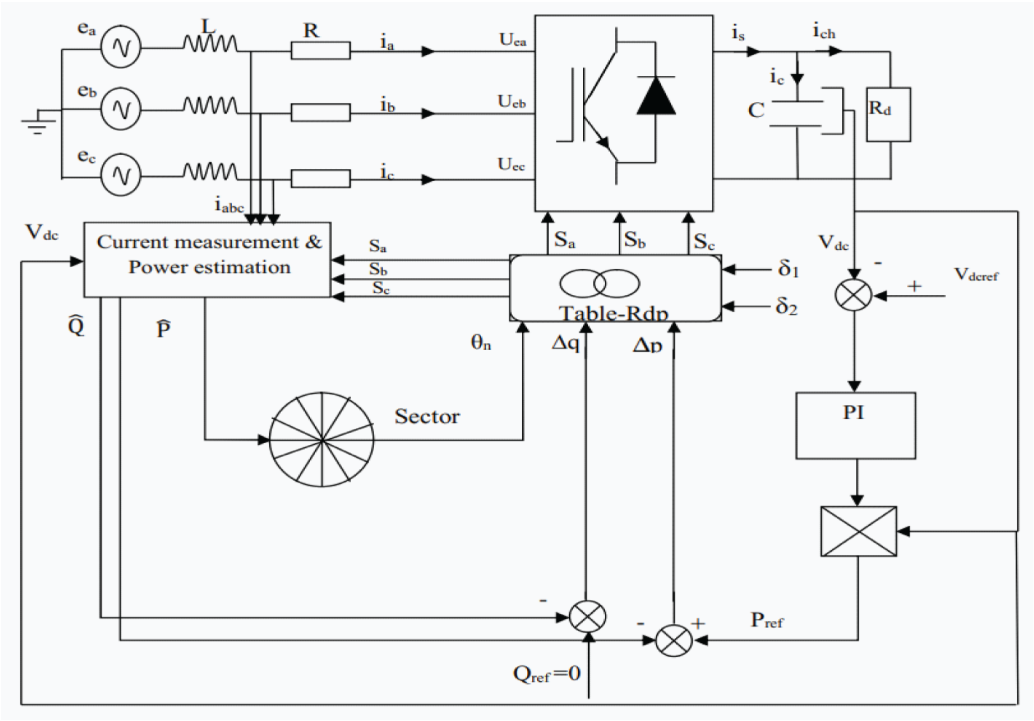


Figure 2. A new DPC scheme



$$\begin{cases} \Delta i_{\alpha} = i_{\alpha}\left(k+1\right) - i_{\alpha}\left(k\right) = \dfrac{T}{L}\left(e_{\alpha}\left(k\right) - U_{e\alpha}\left(k\right)\right) \\ \Delta i_{\beta} = i_{\beta}\left(k+1\right) - i_{\beta}\left(k\right) = \dfrac{T}{L}\left(e_{\beta}\left(k\right) - U_{e\beta}\left(k\right)\right) \end{cases} \tag{2}$$

The expression of the instantaneous powers in (αβ), can be written:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} e_{\alpha} & e_{\beta} \\ e_{\beta} & -e_{\alpha} \end{bmatrix} * \begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} \tag{3}$$

The switching period is much lower than the period of the mains voltage; it can be deduced that the variation of the voltage during a switching period can be neglected, therefore:

$$\begin{cases} e_{\alpha}\left(k+1\right) = e_{\alpha}\left(k\right) \\ e_{\beta}\left(k+1\right) = e_{\beta}\left(k\right) \end{cases} \tag{4}$$

From equation 4, the variations of the instantaneous active and reactive powers at the end of the switching period can be written as follows:

$$\begin{cases} \Delta P = e_{\alpha}\left(k\right) * \Delta i_{\alpha} + e_{\beta}\left(k\right) * \Delta i_{\beta} \\ \Delta Q = e_{\beta}\left(k\right) * \Delta i_{\alpha} + e_{\alpha}\left(k\right) * \Delta i_{\beta} \end{cases} \tag{5}$$

Equation 2 is replaced in 5 yields:

$$\begin{cases} \Delta P = \frac{T}{L}\left(e_{\alpha}\left(k\right)^{2} + e_{\beta}\left(k\right)^{2}\right) - \frac{T}{L}\left(e_{\alpha}\left(k\right)U_{e\alpha}\left(k\right) + e_{\beta}\left(k\right)U_{e\beta}\left(k\right)\right) \\ \Delta Q = \frac{T}{L}\left(e_{\alpha}\left(k\right)U_{e\alpha}\left(k\right) - e_{\beta}\left(k\right)U_{e\beta}\left(k\right)\right) \end{cases} \tag{6}$$

Equation 6 shows that the vector of grid voltages and the vector of the PWM-rectifier voltages used during the switching period are both important factors in the fluctuation of the instantaneous active and reactive powers. There are six non-zero voltage vectors to control the instantaneous active and reactive powers. The good choice of voltage vector offers a minimization of the variations of the powers compared to their references. Therefore, there are different ways to select the corresponding switching state which controls the evolution of active and reactive power. For i = 0 to 6, the variation of the active and reactive powers is given by:

$$\begin{cases} \Delta P_{i} = \frac{T}{L}\left(e_{\alpha}\left(k\right)^{2} + e_{\beta}\left(k\right)^{2}\right) - \frac{T}{L}\left(e_{\alpha}\left(k\right)U_{e\alpha i}\left(k\right) + e_{\beta}\left(k\right)U_{e\beta i}\left(k\right)\right) \\ \Delta Q_{i} = \frac{T}{L}\left(e_{\alpha}\left(k\right)U_{e\alpha i}\left(k\right) - e_{\beta}\left(k\right)U_{e\beta i}\left(k\right)\right) \end{cases} \tag{7}$$

The vectors of the rectifier voltages, corresponding to all the possible switching sequences, are represented vectorially in the reference frame (αβ) as shown in Figure3.

The values of these vectors in real quantities are given in Table 2.

Figure 3. Voltage vector position in fixed frame

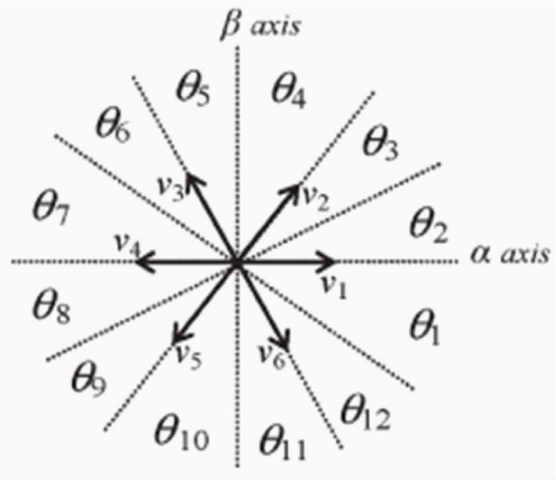


Table1. Switching table

S_P	S_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_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6
0	1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1
1	0	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5
1	1	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2	V_1

Note: V_1(100), V_2(110), V_3(010), V_4(011), V_5(001), V_6(101)

Table 2. Voltage input of PWM-rectifier

i	e_a	e_b	e_c	$U_{e\alpha i}$	$U_{e\beta i}$
0	0	0	0	0	0
1	$2/3V_{dc}$	$-1/3V_{dc}$	$-1/3V_{dc}$	$\sqrt{2/3}V_{dc}$	0
2	$1/3V_{dc}$	$1/3V_{dc}$	$-2/3V_{dc}$	$1/\sqrt{6}V_{dc}$	$1/\sqrt{2}V_{dc}$
3	$-1/3V_{dc}$	$2/3V_{dc}$	$-1/3V_{dc}$	$-1/\sqrt{6}V_{dc}$	$1/\sqrt{2}V_{dc}$
4	$-2/3V_{dc}$	$1/3V_{dc}$	$1/3V_{dc}$	$-\sqrt{2/3}V_{dc}$	0
5	$-1/3V_{dc}$	$-1/3V_{dc}$	$2/3V_{dc}$	$-1/\sqrt{6}V_{dc}$	$-1/\sqrt{2}V_{dc}$
6	$1/3V_{dc}$	$-2/3V_{dc}$	$1/3V_{dc}$	$1/\sqrt{6}V_{dc}$	$-1/\sqrt{2}V_{dc}$

It can be noted that the vector of the voltages is dependent on the discrete commutation states of the PWM converter, as shown by the equation 8:

$$\begin{bmatrix} U_{e\alpha} \\ U_{e\beta} \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \tag{8}$$

2.2 Proposed Controller

Many significant advances in the design of nonlinear systems for a wide range of practical applications have occurred in recent decades. Several inspiring approaches, such as optimal control, nonlinear feedback control, adaptive control, sliding mode control, nonlinear dynamics, fuzzy logic control, fuzzy adaptive control, fractional order control, and robust control, as well as their integrations, have been proposed (Khamis et al., 2022, 2021; Sain et al, 2022; Ajeil et al., 2020a,b; Ibraheem et al., 2020a,b; Ammar et al., 2019, 2018; Ammar & Azar, 2020; Barakat et al., 2020; Ananth et al., 2021; Vaidyanathan and Azar, 2020; Azar and Kamal, 2021; Ajel et al., 2021; Al-Qassar et al., 2021a,b; Bansal et al., 2021; Azar et al., 2022, 2021a,b,c,d,e,f,g,h,i,j, 2020a,b,c,d; Najm et al., 2022, 2021a,b 2020; Elkholy et al., 2020a,b; Mohamed et al., 2020; Ibrahim et al., 2020; Sayed et al., 2023, 2020; Samanta et al., 2018 ; Mukherjee et al., 2014; Fekik et al., 2022. 2021a,b,c, 2020a, 2019, 2018a,b,c; Daraz et al., 2022, 2021; Pilla et al., 2021a,b, 2020, 2019; Abdul-Adheem et al., 2022, 2021, 2020a,b; Liu et al., 2020; Bouchemha et al., 2021; Gorripotu et al., 2021, 2019; Drhorhi et al., 2021 ; Alimi et al., 2021 ; Kumar et al., 2018, 2021; Acharyulu et al., 2021; Hamiche et al., 2021; Mittal et al., 2021; Pham et al., 2021, 2018, 2017a,b; Sambas et al., 2021a,b; Khan et al., 2020a,b; Khennaoui et al., 2020a,b; Kammogne et al., 2020; Alain et al., 2020, 2019, 2018; Rana et al., 2021; Sallam et al., 2020; Ouannas et al., 2021, 2020a,b,c,d,e,f, 2019a,b,c, 2017a,b,c,d,e,f,g,h,i,j,k, 2016; Bansal et al., 2021; Amara et al., 2019; Meghni et al, 2023, 2017a,b, 2018; Singh et al., 2018a,b,c, 2017; Singh & Azar, 2020a,b).

The conditions of passage from one stage to another are named" Transition" They are widely used in logical design to describe the state mechanism governing the operation of the system. It can be used a Petri nets in power electronics to describe the different states of a component. For example, a signal (g) can control an ideal switch. If the switch is closed(g), it closes and imposes a zero voltage on these terminals. If the switch is opened, $(\bar{g})$ imposes a zero current in the branch in which it is inserted. Figure 4 describes an ideal switch per Petri net.

A suggested controller based on Petri nets is used in the DPC based on Petri nets to replace the hysteresis comparators and the standard switching table, as shown in Figure 2. The errors of the active power $P = P_{ref} - P_{est}$, the reactive power $Q = Q_{ref} - Q_{est}$, the angle of the voltage n, and the errors tolerances of the active and reactive powers 1 and 2 are the inputs to. The switches of the PWM-rectifier, Sa, Sb, and Sc, are controlled by this controller's outputs. The Petri net graph in Figure 5 displays the structure of the suggested technique while taking into account the discrete states of the system.

Table 3 present the Place definition of the Petri Nets for PWM rectifier to control of the switching cells. The transitions for the switching table shown in Table.1 are given in Table 4.

Three black points in place P_0 correspond to the chips and tokens when moving to another place in the Petri network, the transition that corresponds to it is valid and implies that the switch is activated. For example, if all the conditions for the transition T_{01} to be crossed are satisfied, a token will move to the place P_1. Thus, the switch S_a switches from the inactive state 0 to the activated state (1). On the other hand, if the transition T_{10} can be crossed (all the conditions are satisfied), the token that is in the place P_1 will move to P_0 what the switch S_a means from an active state to an inactive state. In the same way for all other switches.

Figure 4. Description of an ideal Petri net switch

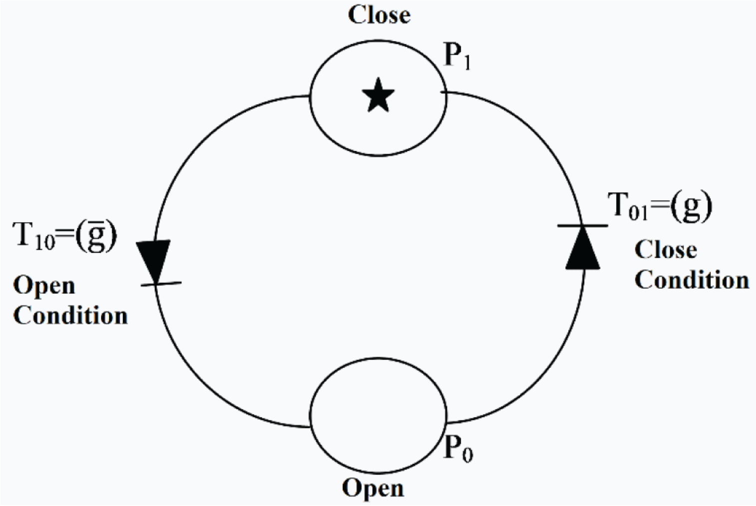


Figure 5. Graphic of Petri net for a PWM rectifier with three switching cells

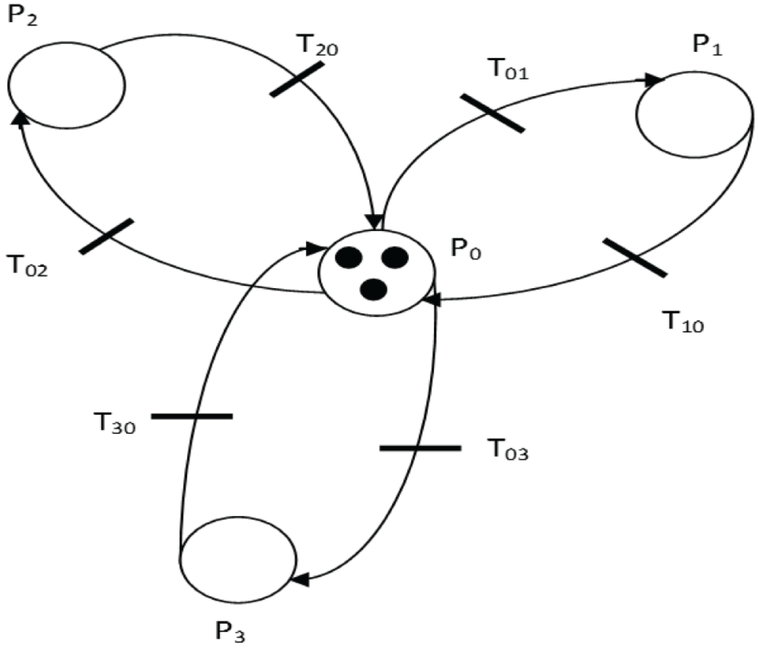


Table 3. Place definition

Place	Designations
P_0	Matches all switches are disabled S_a=0, S_b=0, S_c=0
P_1	Matches to the switch S_a activate S_a=1
P_2	Matches to the switch S_b activate S_b=1
P_3	Matches to the switch S_c activate S_c=1

3. RESULTS OF THE SIMULATION

The simulation’s findings, which are depicted in Figures 6 and 7, show that the viability and performance of the suggested DPC configuration at the Petri net base are assessed in response to a request to change the reference DC voltage at time t = 0.5s from V_{dcref} = 300V to 350V. Figure 6 displays the DPC-simulation Rdp’s findings for a network voltage that is solely sinusoidal. As shown in Figure 6.a, the active and reactive powers are perfectly balanced throughout all sectors. Table 5 lists the electrical circuit’s specifications.

The DC bus voltage responses, active and reactive instantaneous power, and absorption currents during a transient regime are shown in Figure 6 (a, b, c, and d). The active power does indeed rise with a higher reference voltage for the DC bus. A good follow-up of the reference of the active power supplied by the regulator PI is ensured by direct POWER control using Petri nets. It maintains the reactive power in the vicinity of zero; that is to say, operation under a power factor of unity and sinusoidal current is ensured during its transient period.

It can also be noted that the DPC based on Petri Nets guarantees better control of the instantaneous powers, which are mainly reactive, and that the absorbed currents have become better for twelve sectors than for six sectors (THDi = 1.84%, illustrated in Figure 6. (e)). It should be noted that the proposed

Table 4. Transitions definition of switching table

Transition	Designation
T_{01}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_4 or θ_5 or $\theta_{12}\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_2$ or θ_3 or θ_4 or θ_5 or θ_6 or $\theta_7\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_6$ or θ_7 or θ_8 or θ_9 or θ_{10} or $\theta_{11}\}$
T_{02}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_4$ or θ_5 or θ_6 or θ_7 or θ_8 or $\theta_9\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_2$ or θ_3 or θ_4 or θ_5 or θ_6 or $\theta_7\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_6$ or θ_7 or θ_8 or θ_9 or θ_{10} or $\theta_{11}\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_{10} or θ_{11} or $\theta_{12}\}$
T_{03}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_8 or θ_9 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_6$ or θ_7 or θ_8 or θ_9 or θ_{10} or $\theta_{11}\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_2$ or θ_3 or θ_4 or θ_5 or θ_6 or $\theta_7\}$
T_{10}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_6$ or θ_7 or θ_8 or θ_9 or θ_{10} or $\theta_{11}\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_4$ or θ_5 or θ_6 or θ_7 or θ_8 or $\theta_9\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_8 or θ_9 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_4 or θ_5 or $\theta_{12}\}$
T_{20}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_1$ or θ_8 or θ_9 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_4 or θ_5 or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_4$ or θ_5 or θ_6 or θ_7 or θ_8 or $\theta_9\}$
T_{30}	$\Delta P<\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P<\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_1$ or θ_8 or θ_9 or θ_{10} or θ_{11} or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q<\delta_2$ and $\{\theta_n=\theta_1$ or θ_2 or θ_3 or θ_4 or θ_5 or $\theta_{12}\}$ or $\Delta P>\delta_1$ and $\Delta Q>\delta_2$ and $\{\theta_n=\theta_4$ or θ_5 or θ_6 or θ_7 or θ_8 or $\theta_9\}$

Table 5. System parameters

R	Line resistance	0.25 Ω
L	Line inductance	0.016 H
C	Capacitor	0.0047 F
R_d	Load resistance	100 Ω
e_{abc}	Peak amplitude of line voltage	120 V
f	Source voltage frequency	50 Hz
V_{dcref}	DC-Voltage Reference	300 V

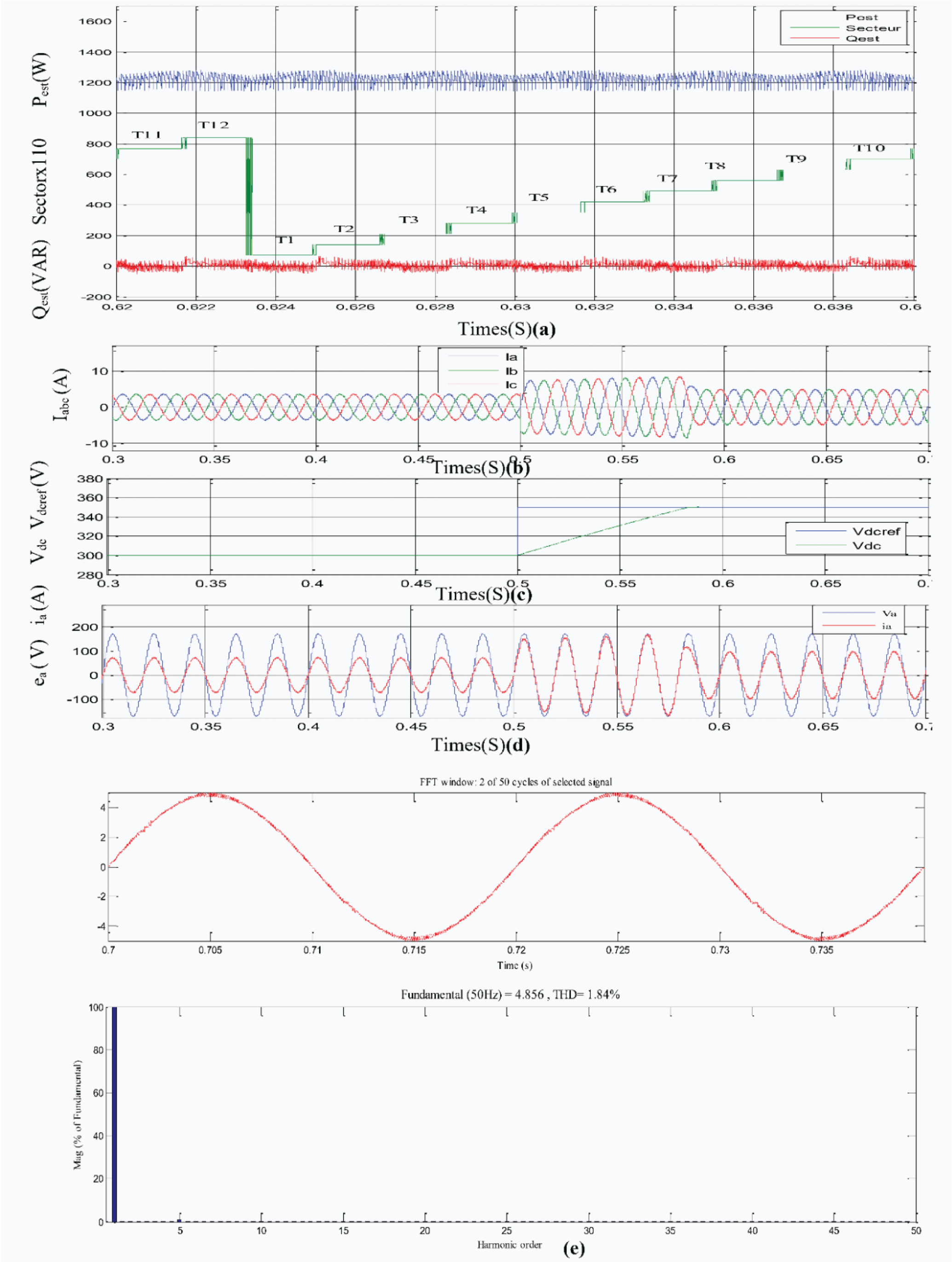
DPC based on Petri networks is capable of independently controlling the reactive power at a value other than zero, which allows the rectifier to exchange reactive power with the network absorption). This mode of operation allows the rectifier to function as a reactive compensator. Figure 7 shows an example of simulation results obtained. In this simulation test, the reactive power reference undergoes a step from 0 to 400 var. It can be noted that the reactive power follows its new reference without affecting the active power due to the perfect decoupling of the control of these powers.

4. EXPERIMENTAL RESULTS

The test bench consists of the following essential parts (8) the power map of the PWM rectifier, which is composed of the three arms of the converter consisting of six IGBTs and an anti-parallel diode reference SKM120 GB 123 type SEMIKRON. These modules support a voltage of 600V and a rated current of 120A and the numerated element as shown in Figure 8.

The DC bus voltage is measured using a sensor Hall effect of the LEM-LV 25-P variety. Line currents are measured using three LEM-LA 55-P Hall Effect Sensors. Utilizing Matlab / Simulink for

Figure 6. Permanent steady-state simulation results of DPC based on Petri nets and spectrum of absorbed currents, Qref = 0 and Vdcref = 300 to 350v at t = 0.5s



simulation and real-time implementation, and dSPACE, the control algorithm is developed (RTI1103). The three control signals of the arms of the IGBTs, which originate from the dSPACE, are inserted into a control card. The board is powered by a symmetrical source that outputs a voltage of 15V to

Figure 7. Simulation results of the DPC based on Petri Nets Vdcref = 300V and Qref = 0VAR at 400 VAR at t = 0.5s

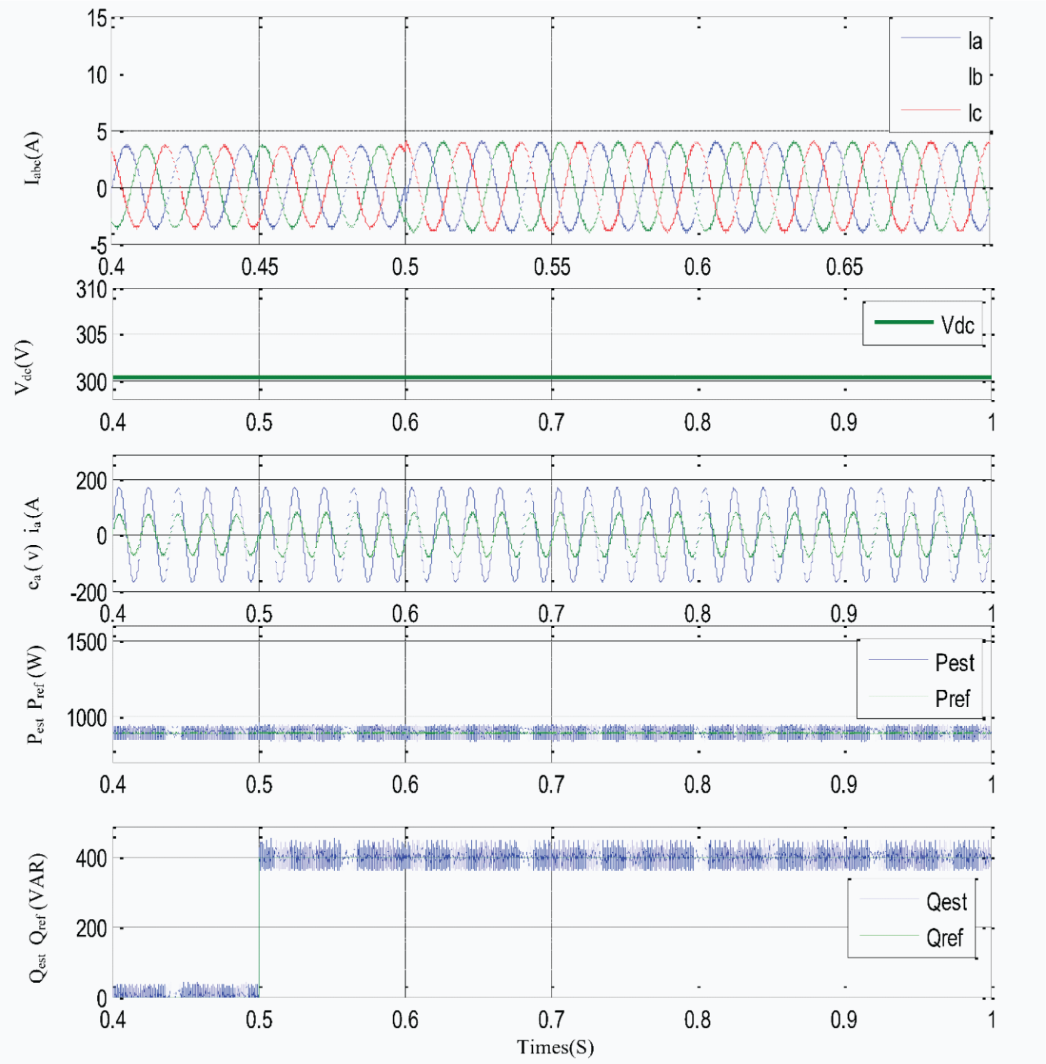
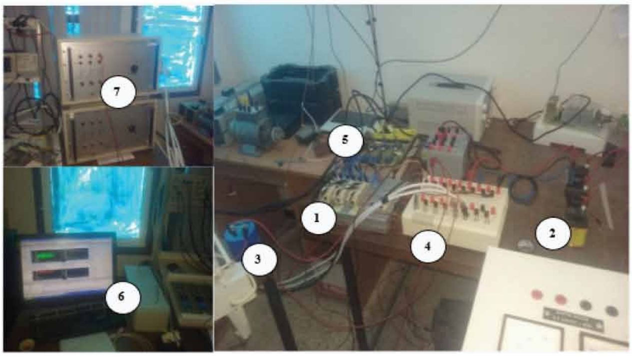


Figure 8. The implemented test bench



① PWM-Rectifier;
② Line inductor and resistance(L-R);
③ Capacitor ;
④ Current sensor; Voltage sensor;
⑤ Control card;
⑥ Dspace 1103;
⑦ Load resistance.

power the Optocouplers and Drivers. The IGBT is controlled by a Driver, which allows adapting the control signals to the characteristics of the switches. The IR2109 driver is an integrated circuit used to improve the switching times of power electronics switches. The output of the driver sends to the terminals of the switches of the module a variable DC voltage of 0-15 V (as shown in Figure 9). In order to ensure isolation between the control board and the power transistor, Opto-couplers (4N35) are used for which their outputs are connected to the drivers. This insulation protects the low-power electronic part and is less sensitive to noise generated by the power section.

4.1 Static Study

Figures 10 and 11 show the experimental results for the proposed DPC based on Petri networks at the stationary state (a-d). These graphs show that the experimental results and the earlier simulated results are fairly similar. Using the suggested method, line currents ia is closer to a sinusoid (DPC-Rdp). Using the suggested control strategy, the unity power factor is successfully produced, as illustrated in Figure 10.(c). Given that the predicted voltage appears to match the measured voltage, Figure 10(d) demonstrates that the line voltage sensorless control is achieved. The analysis of the simulation findings as shown in Figure 10 explains why the suggested DPC greatly improves the active and reactive powers control (b).

4.2. Robustness Analysis

Robustness is commonly characterised as the bare minimum that a control system must meet in order to be usable in a real situation. Once created, the controller's settings do not alter, and control performance is assured (Ahmed et al., 2023a,b, 2022a,b; Sergiyenko et al., 2023 ; Kengne et al., 2023a,b ; Hashim et al., 2023 ; Hameed et al., 2023 ; Fekik et al., 2023a,b ; Zhang et al., 2023 ; Wang et al., 2023 ; Dendani et al., 2023 ; Toumi et al., 2022 ; Mahdi et al. 2022 ; Ali el al., 2022a,b ; Abdul-Kareem et al., 2022; Abed et al., 2022; Sekhar et al., 2022 ; Saidi et al., 2022; Al Mhdawi et al., 2022 ; Lajouad et al., 2021; El Kafazi et al., 2021 ; Sundaram et al., 2021 ; Alimi & Azar, 2021; Tolba et al., 2017a,b ; Soliman et al., 2017, 2020; Wang et al., 2017; Humaidi et al. 2022, 2021, 2020; Djeddi et al., 2019; Shukla et al., 2018; Khettab et al., 2018; Vaidyanathan et al., 2021a,b,c,d,e, 2019, 2018a,b,c,d, 2017a,b,c, 2015a,b,c; Vaidyanathan and Azar, 2021, 2020, 2016a,b,c,d,e,f, 2015a,b,c,d; Santoro et al., 2013).

Figure 11 depicts the DC link capacitor voltage; when a step voltage is applied at t=0.5s, it can be seen that the proposed DPC structure needs 0.05s to reach the references value. This was done to test the robustness of the proposed control, which was put to the test by our system being subjected to a DC voltage step at t = 1.5 s Vdcref = 300 to 350 V. Figure 11(b) depicts the instantaneous active power behaviour under step variation between 0.9 and 1.2 kW, and it is clear that the reaction performs admirably. Figure 11(b) demonstrates that the reactive power, which is maintained at its reference level, is unaffected by the fast variation of the active power (value 0 VAR). Decoupled control of active and reactive power is thus made possible.

Figure 9. The implemented test bench

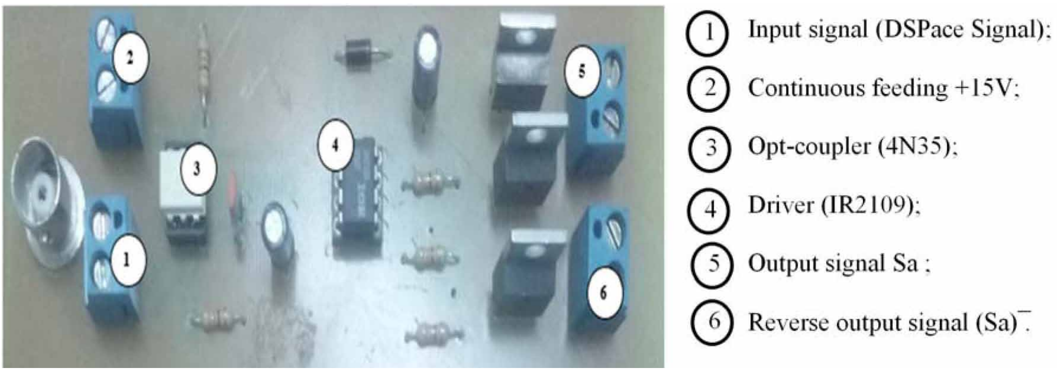


Figure 10. The experimental findings in steady state for the proposed DPC based on Petri nets: (a) DC-Voltage, (b) active and reactive Power reference and estimation value, (c) line current and voltage are in phase, (d) estimation and line voltage, Vdcref = 300 V, and Qref = 0 VAR

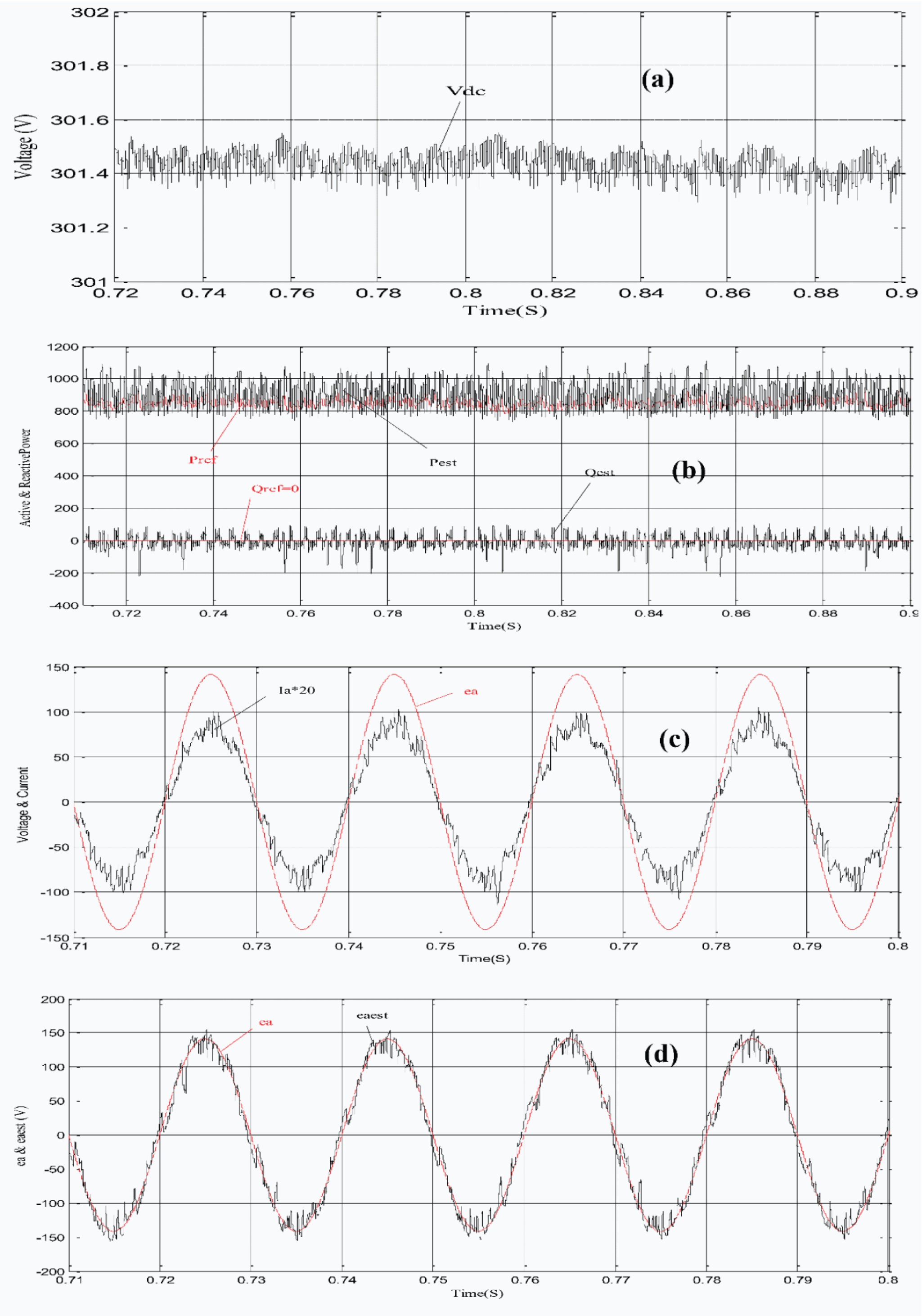
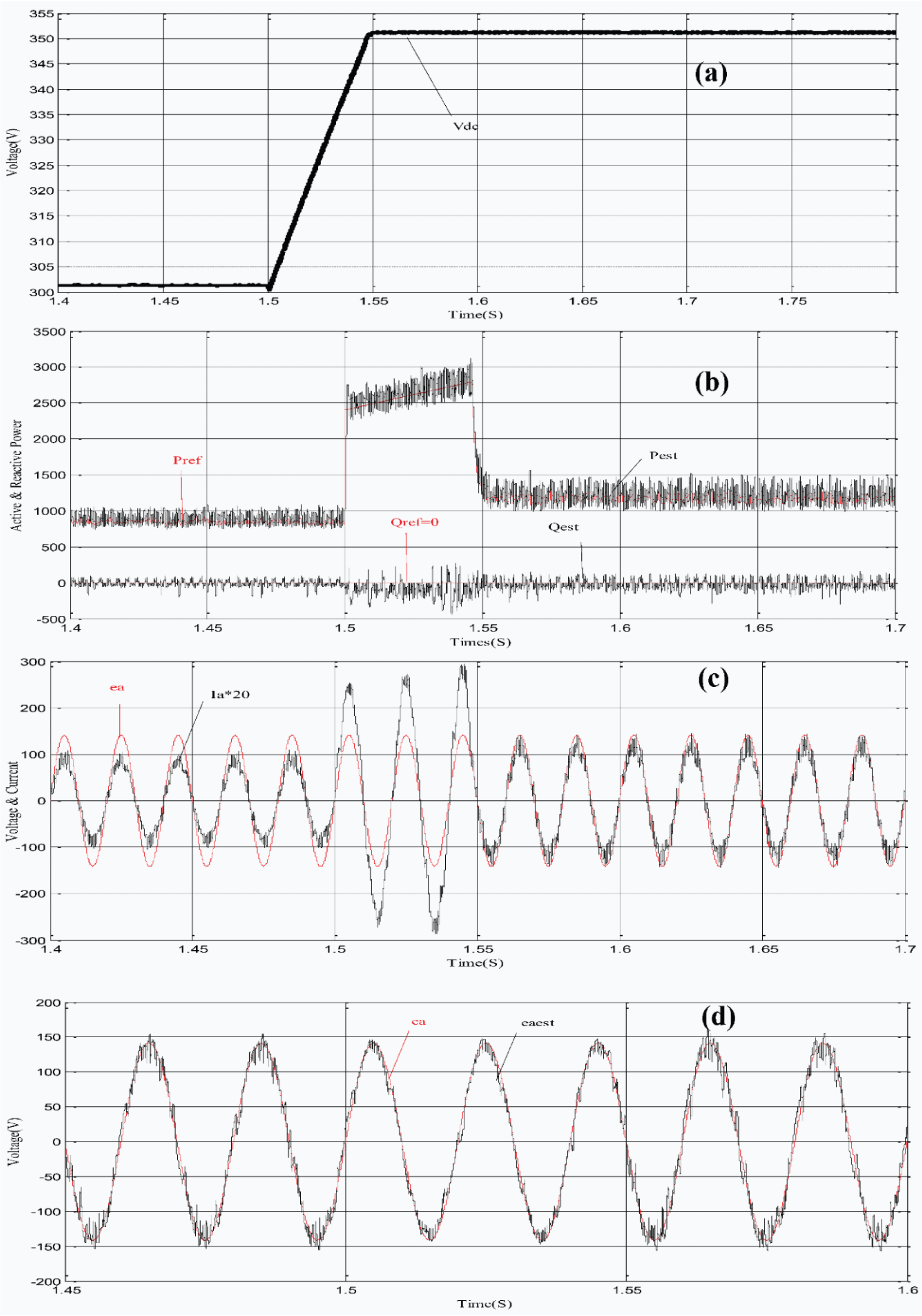


Figure 11. Experimental results in dynamics state for the proposed DPC based on Petri nets (a) DC-Voltage, (b) active and reactive Power reference and estimation value (c) line current and voltage are in phase (d) estimation and line voltage, Vdcref = 300 to 350V, Qref = 0 VAR



5. CONCLUSION

This study presented a Petri network-based direct power control technique for a three-phase power converter connected to the electrical grid. The main objective of the control system is to maintain the DC bus voltage at a required level using a traditional PI controller in the DC bus voltage control loop. To achieve a unit power factor, it is necessary to keep the input currents from the power supply sinusoidal and in phase with the respective voltages. In the suggested arrangement, the use of hysteresis comparators or a switching table is not required. The simulation and experimental testing results were presented and confirmed the findings. The suggested control technique provides highly dynamic performance and optimal behavior in steady-state operation.

As future perspectives:

- Exploring other intelligent DC bus voltage regulators such as fuzzy controllers or neural network-based controllers could be considered.
- Additionally, implementation on a fast platform such as an FPGA board could be explored.

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