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Improvement of the Performances of the Direct Power Control Using Space Vector Modulation of Three Phases PWM-Rectifier

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Abstract: In this work, a method of control of three-phase PWM-rectifiers will be studied, in order to remedy the drawback of the conventional direct power control with variable switching frequency, called direct power control with Space vector modulation. In the direct Power control the switching states are selected from a switching table based on the digitized errors between the estimated active and reactive powers and their references respectively, and thus the angular position of the voltage. In the direct power control with Space vector modulation, the hysteresis regulators are replaced by PI regulators and the switching table with a vector modulation block to have a constant switching frequency, and in order to improve the quality of the current absorbed by the PWM-rectifier. The simulation results show that when using DPC-SVM method is better those obtained by a conventional DPC

Keywords: Direct power control (DPC), instantaneous active and reactive power, pulse width modulated (PWM) rectifier, switching table, Space Vector Modulation (SVM), Switching frequency, Total Harmonics Distortion (THD)

1. INTRODUCTION

Static converters know for a long time, a considerable development, and offer huge potential for the conversion of electrical energy. Research in the field of converters, considers several aspects including the topologies of these converters, the structures and performances of power switches and the control techniques[1],[2].

Static converters can induce a very high total harmonic distortion (THD) under certain operating conditions[1],[2]. For this reason, international standards are adapted such as IEEE standard 519 and IEC 61000 which impose limits to current and voltage THDs within the power supply network. In order to limit the harmonic perturbation rate caused by non-linear loads or power electronics connected to the grid, a more interesting

method of harmonic reduction is proposed. It is based on the use of rectifiers with PWM either with current or voltage structure. Among the most common and the most attractive structures is the PWM voltage rectifier. It has the capacity to control the currents absorbed and to operate under a unit power factor, it also ensures a bidirectional transfer of the power flow. In recent years, technical variants were proposed in the literature for controlling the AC / DC converters with PWM strategy, all of these strategies aim to achieve the same objectives namely the power factor and a current wave form close to a sinusoid. A various control strategies have been proposed in recent works[3],[4]. They can be classified according to their use of current loop controllers [5], or active/reactive power controllers[4],[6], Voltage-oriented control (VOC), which provides a good dynamic response by an internal current control loop [7]. An interesting emerging control technique, direct power control (DPC), was developed analogously with the well-known direct torque control (DTC) [4]. In DPC scheme, there are no internal control loops and the converter switching states are appropriately selected by a switching table based on the instantaneous errors between the controlled and estimated values of instantaneous active and reactive powers and the voltage vector position[4], [7]. However, among the well-known disadvantages of the DPC scheme, we can enumerate: variable switching frequency. To eliminate the above difficulties and drawbacks, space vector modulated direct power control (DPC-SVM), is presented in recent works [4] in DPC–SVM method, the switching states of the converter are generated by a SV-PWM modulator block operating with constant switching frequency.

This paper presents Improvement of the performances of the Direct Power control using the Space vector Modulation of three phases PWM-Rectifier, which achieves a unity power factor, by the direct control of the instantaneous active and reactive powers.

This strategy is compared to the classical direct Power control with switching table, both strategies are modeled and then a simulation is undertaken under Matlab environment. The comparative analysis shows that the performances using the Space vector modulation are slightly better than those obtained using a simple direct power control. In fact, the output voltage contains fewer harmonics reducing the THD ratio.

2. MODELING OF THREE PHASES RECTIFIER

2.1. General Structure

The power circuit of the PWM rectifier contains a bridge of six power transistors with anti-parallel diodes, which is used to carry out the PWM generation as well as the power bidirectional conversion, the general diagram of the PWM rectifier is shown in Figure 1. The converter is supplied by a voltage source in series with an inductance and a resistance, which model the network. Generally, the network inductance is insufficient to eliminate all the harmonics present in the current and voltage [8], [9], [11].

To attenuate the ripples due to the switching operation of the PWM rectifier, a series filter having a more significant inductance is needed. A load and a capacitor are connected simultaneously at the output of the converter. The capacitor is used as a voltage source and allows the rectifier to also operate as an inverter [8], [9], [11].

The logical states impose the rectifier input voltages, are given as:

$$\begin{aligned} u_{ea} &= S_a \cdot V_{dc} \\ u_{eb} &= S_b \cdot V_{dc} \\ u_{ec} &= S_c \cdot V_{dc} \end{aligned} \tag{1}$$

Thus the operation principle of the rectifier is illustrated by the following matrix system:

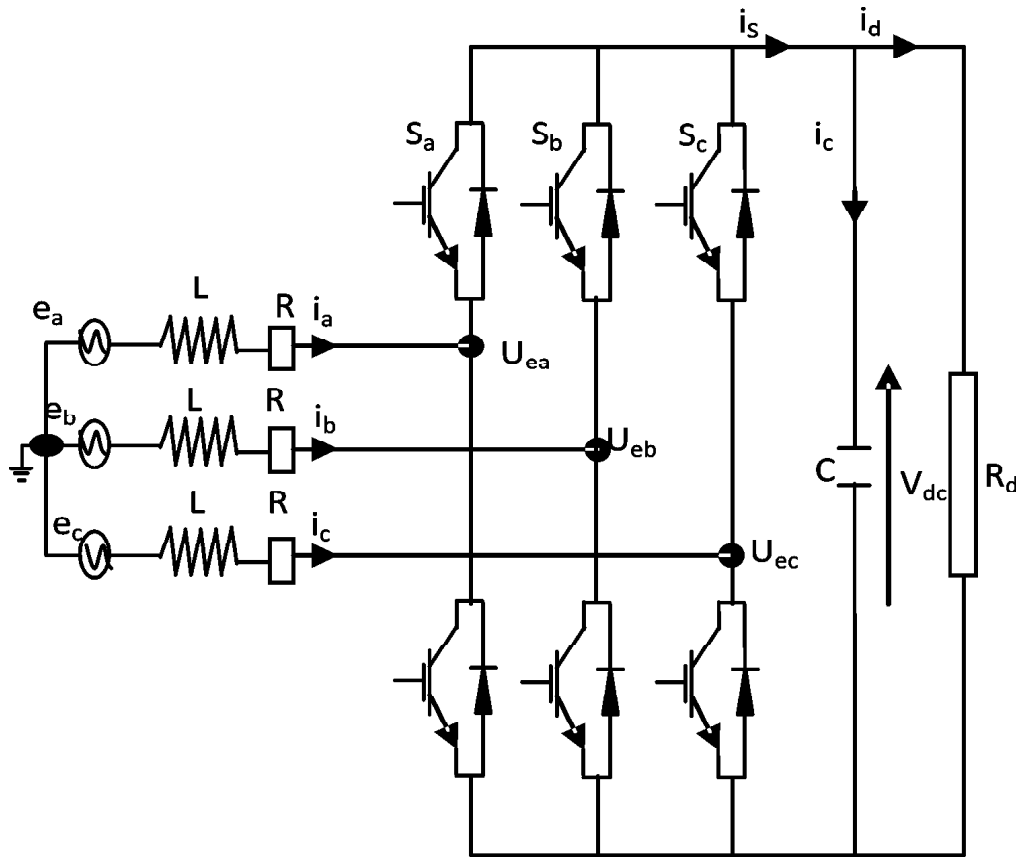


Figure 1: General Diagram of the PWM rectifier

$$\begin{bmatrix} u_{ea} \\ u_{eb} \\ u_{ec} \end{bmatrix} = V_{dc} \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & \frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{2}{3} \end{pmatrix} \begin{pmatrix} S_a \\ S_b \\ S_c \end{pmatrix} \quad (2)$$

The AC side can be modelled by the following equations [12].

$$\begin{cases} u_{ea} = e_a - Ri_a - L \frac{di_a}{dt} \\ u_{eb} = e_b - Ri_b - L \frac{di_b}{dt} \\ u_{ec} = e_c - Ri_c - L \frac{di_c}{dt} \end{cases} \quad (3)$$

AC currents i_a , i_b and i_c are generated by voltage drops at impedances network boundaries ($e_a - u_{ea}$), ($e_b - u_{eb}$) and ($e_c - u_{ec}$), and then these currents will be modulated through the switches to provide the D.C. current i_s such as:

$$i_s = S_a i_a + S_b i_b + S_c i_c \tag{4}$$

The voltages vectors generated by the rectifier can be given by Table 1:

Table 1
Different switches configurations and the corresponding voltage vectors

S_a	S_b	S_c	U_{ea}	U_{eb}	U_{ec}	V_i
0	0	0	0	0	0	V_0
0	0	1	$-\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{3}$	$\frac{2V_{dc}}{3}$	V_5
0	1	0	$-\frac{V_{dc}}{3}$	$\frac{2V_{dc}}{3}$	$-\frac{V_{dc}}{3}$	V_3
0	1	1	$-\frac{2V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	V_4
1	0	0	$\frac{2V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	V_1
1	0	1	$\frac{V_{dc}}{3}$	$-\frac{2V_{dc}}{3}$	$\frac{V_{dc}}{3}$	V_6
1	1	0	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{3}$	$-\frac{2V_{dc}}{3}$	V_2
1	1	1	0	0	0	V_7

i_d is the current absorbed by the load, its equation depends on the nature of this load [14].

No load

$$i_d = 0 \tag{5}$$

For a resistive load (R_d)

$$i_d = \frac{V_{dc}}{R_d} \tag{6}$$

For passive inductive load (L_d, R_d)

$$\frac{di_d}{dt} = \frac{V_{dc} - R_d i_d}{L_d} \tag{7}$$

For an active inductive load (L_d, R_d, E)

$$\frac{di_d}{dt} = \frac{V_{dc} - R_d i_d - E}{L_d} \tag{8}$$

In our the study load is considered to be purely resistance

2.2. Direct Power Control

DPC is based on the instantaneous active and reactive power control loops. In DPC there are no current control loops. As shown in Figure 2, and for the classical DPC, the converter switching states are selected by a predefined switching table based on the digitized signals S_p and S_q , of instantaneous errors of active and reactive power, respectively, provided by a fixed band hysteresis comparators and the power source voltage vector position θ_n [13], [16], [17].

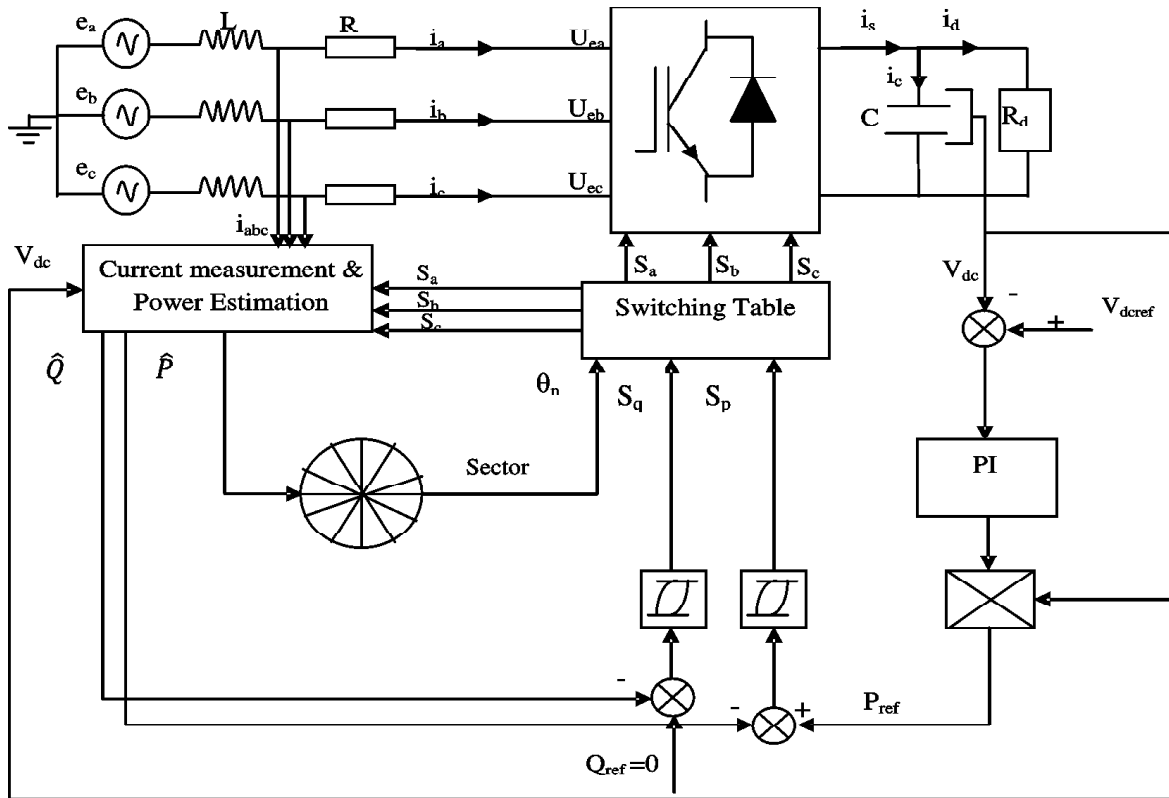


Figure.2: Configuration of DPC with switching table of PWM rectifier

2.2.1. Instantaneous Power Estimation

The estimation of instantaneous active and reactive powers is carried out by equation (9):

$$\hat{P} = L\left(\frac{di_a}{dt} + \frac{di_b}{dt} + \frac{di_c}{dt}\right) + V_{dc}(S_a i_a + S_b i_b + S_c i_c) \quad (9)$$

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

2.2.2. Voltage Estimation

To achieve voltage sensor less operation, using the following equation:

$$\begin{bmatrix} \hat{e}_\alpha \\ \hat{e}_\beta \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} i_\alpha & -i_\beta \\ i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} \hat{P} \\ \hat{Q} \end{bmatrix} \quad (10)$$

2.2.3. Line Voltage Vector Position

The phase of the power-source voltage vector is converted to the sector signal. For this purpose, the stationary coordinates are divided into 12 sectors, as shown in Figure.3 and the angle can be deduced from equation (11).

$$\theta_n = \arct\left(\frac{e_\beta}{e_\alpha}\right) \tag{11}$$

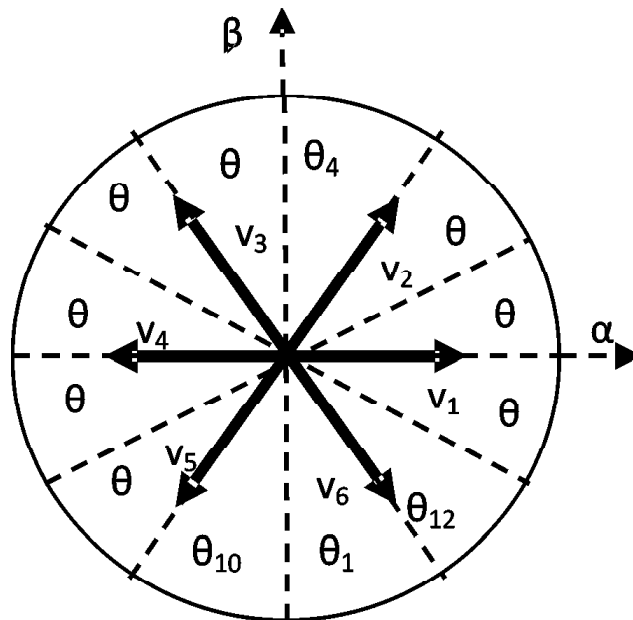


Figure 3: Voltage vector in stationary coordinates with twelve sectors

2.2.4. Switching Table

The selection of the adequate vector is determined by the following table according to the variation in the active and reactive power with the position of voltage vector.

Table 2
Switching table of DPC

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_6	V_7	V_1	V_0	V_2	V_7	V_3	V_0	V_4	V_7	V_5	V_0
1	1	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0	V_7	V_7	V_0	V_0

$V_1(100), V_2(110), V_3(010), V_4(011), V_5(001), V_6(101), V_0(000), V_7(111)$

2.3. Direct Power Control with Space Vector Modulation

The DPC-SVM with constant switching frequency uses closed-loop power control, as shown in Figure 4. The control reactive power Q_{ref} set to zero for unity power factor operation and delivered from the outer PI dc-voltage controller. The reference active power P_{ref} and reactive power Q_{ref} which are in the DC frame and flowing between

$$\begin{aligned} e_d &= E = \sqrt{\frac{3}{2}} E_m \\ e_q &= 0 \end{aligned} \tag{12}$$

And

$$\begin{aligned} e_d &= Ri_d + L \frac{di_d}{dt} - \omega Li_q + u_{ed} \\ 0 &= Ri_q + L \frac{di_q}{dt} + \omega Li_d + u_{eq} \end{aligned} \tag{13}$$

The expressions of active and reactive powers in synchronous coordinates are:

$$\begin{aligned} P &= E i_q \\ Q &= E i_d \end{aligned} \tag{14}$$

The parameters of the PI Controller can be adjusted based on the superposition theorem. The figure.6. Shows the simplified block diagram of the instantaneous active power control loop

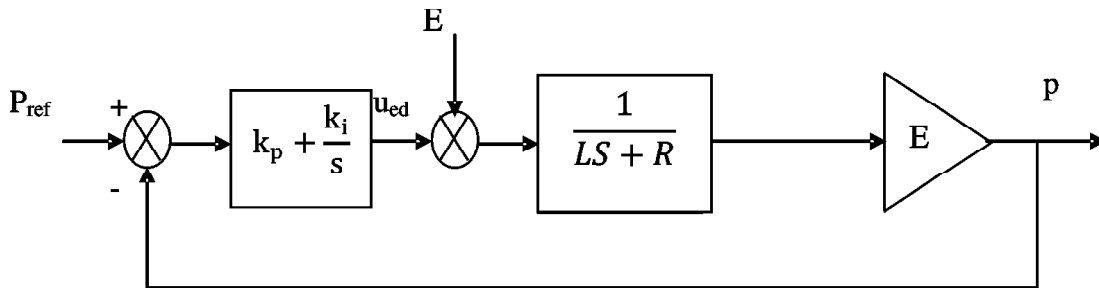


Figure 6: Active power controller

The line voltage is considered as a constant disturbance and must be compensated for by the integral part of the corrector PI. The closed loop transfer function of the system is given by:

$$FTBF = \frac{E(k_p s + k_i)}{Ls^2 + (Ek_p + R)s + Ek_i} \tag{15}$$

The transfer functions of a second order system in a closed loop:

$$F(s) = \frac{1}{s^2 + 2z_n \omega_n s + \omega_n^2} \tag{16}$$

By analogy between expressions (15) and (16), we find:

$$k_p = \frac{2Lz_n \omega_n - R}{E} \quad k_i = \frac{L\omega_n^2}{E} \tag{17}$$

It should be noted that equation (17) is valid for both regulators

3. SIMULATION RESULTS

Both strategies, was simulated using Matlab / Simulink software. The parameters used are shown by table.3. The DC voltage control system for both strategies is tested as well as the DPC and DPC-SVM method following a DC voltage step variation occurred at $t=0.5s$ from 300V to 350V (parameters given in table.3).

Table 3
System Parameters

R	line resistance	0.25	Ω
L	line inductance	0.0016	H
C	DC-capacitor	0.0047	F
R_d	Load resistance	100	Ω
e_{abc}	Voltage line	120	V
f	Source voltage frequency	50	Hz
f_c	Switching frequency(DPC-SVM)	30	KHz
V_{dcref}	DC-Voltage Reference	300	V

Figure 7-A and Figure 8-A show the DC link capacitor voltage, when a step voltage is applied at $t=0.5s$, we can see, that the DPC-SVM structure need 0.1s to attend the references value. Figure 7-B and Figure 8-B show the behaviours of the instantaneous active under step variation, between 0.9 and 1.2 kW we can see that the responses of both structure provides an excellent performances.

Figure 7-C and Figure.8-C show that the quick variation of the active power does not affect the reactive power which is keep at its reference (value 0 VAR), thus, decoupled control between active and reactive power is achieved. To compare the DPC and the DPC-SVM strategie the harmonic spectrums of the current are given in Figure 7-E and Figure.8-E. It is shown that the DPC-SVM is better than the DPC strategy as far as the harmonic content is concerned (THD= 2,05 with a DPC-SVM compared to THD=4,29 with a DPC)

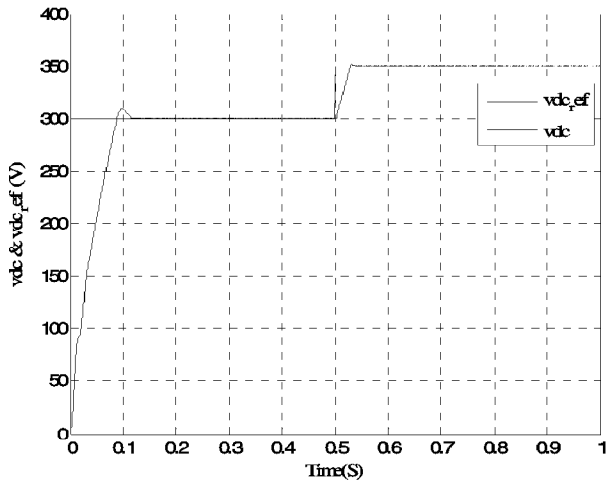
4. CONCLUSION

This paper present improvement of the performances of the Direct Power control using Space vector Modulation of three phases PWM-Rectifier, which achieves a unity power factor by the direct control of the instantaneous active and reactive powers. This strategy is compared to the classical direct Power control with switching table.

In DPC the active and reactive power can be regulated directly by hysteresis comparators of the power. In this configuration, the errors between the power control signal and the feedback signals are compared by the hysteresis elements, and the specific switching state of the converter is appropriately selected by the switching table, so that the errors can be restricted within the hysteresis bands. In DPC-SVM method, the switching states of the converter are generated by a SV-PWM modulator block operating with constant switching frequency.

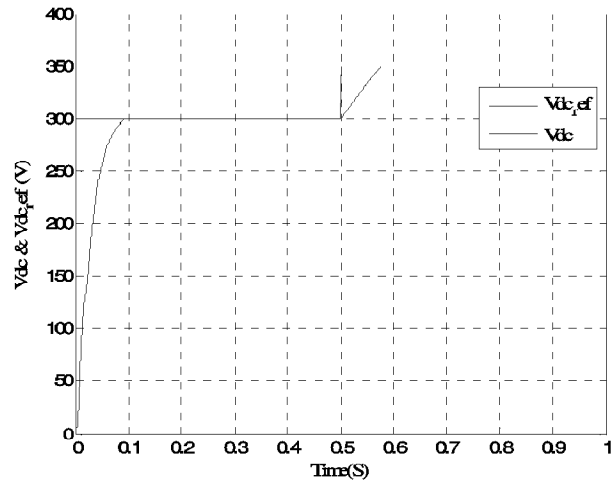
The DPC-SVM has proven excellent performances and verifies the validity of the proposed control system. The DPC-SVM system has the advantages having a lower sampling frequency, a lower THD, and constant switching frequency those obtained by classical DPC.

DPC

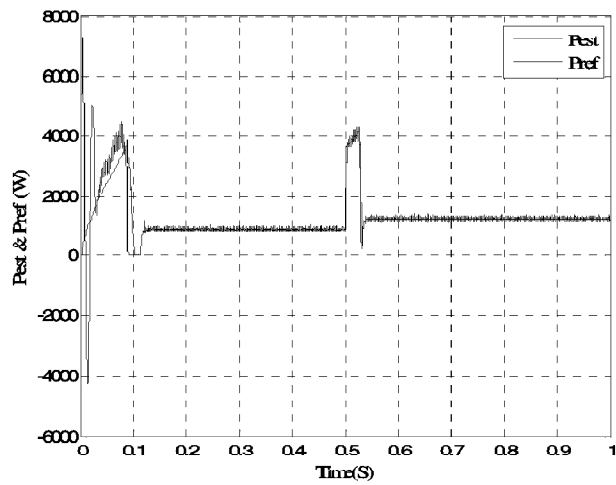


(A)

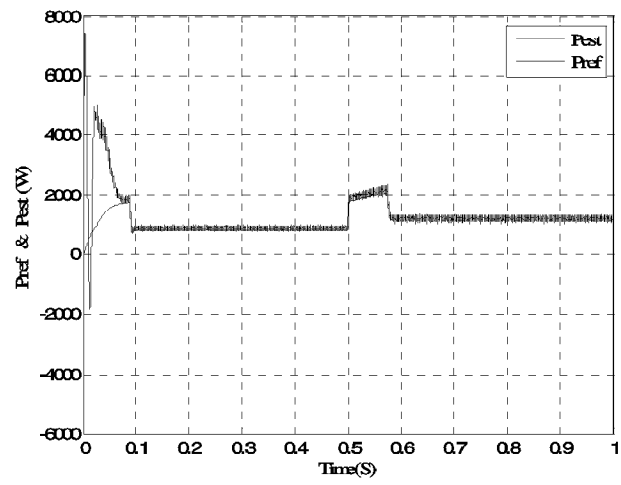
SVM-DPC



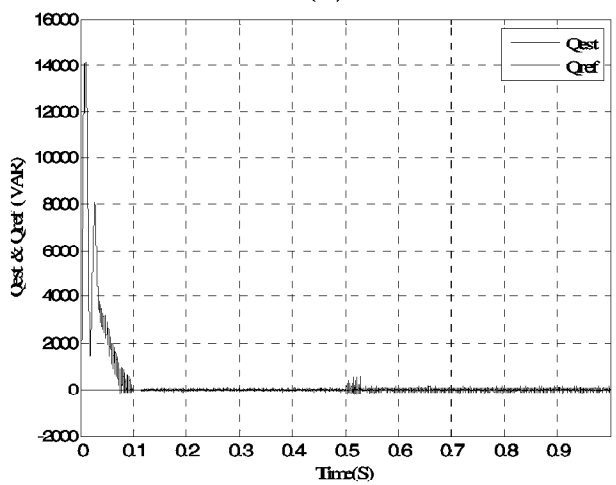
(A)



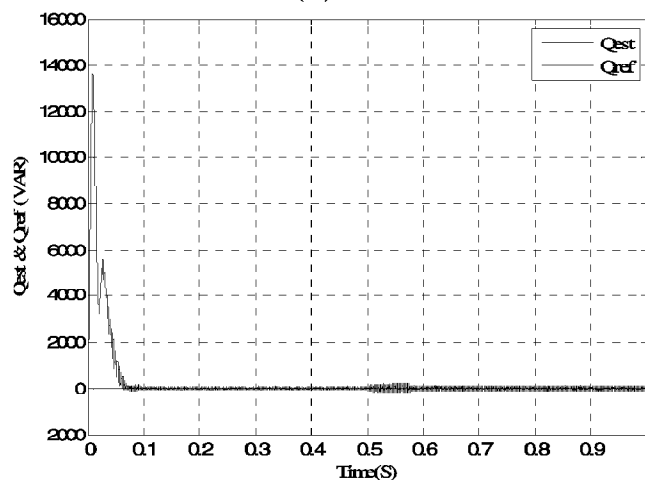
(B)



(B)



(C)



(C)

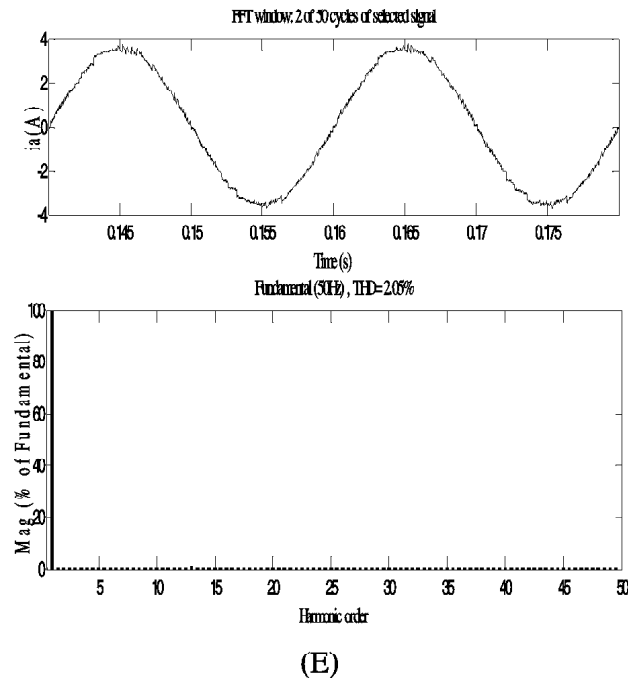
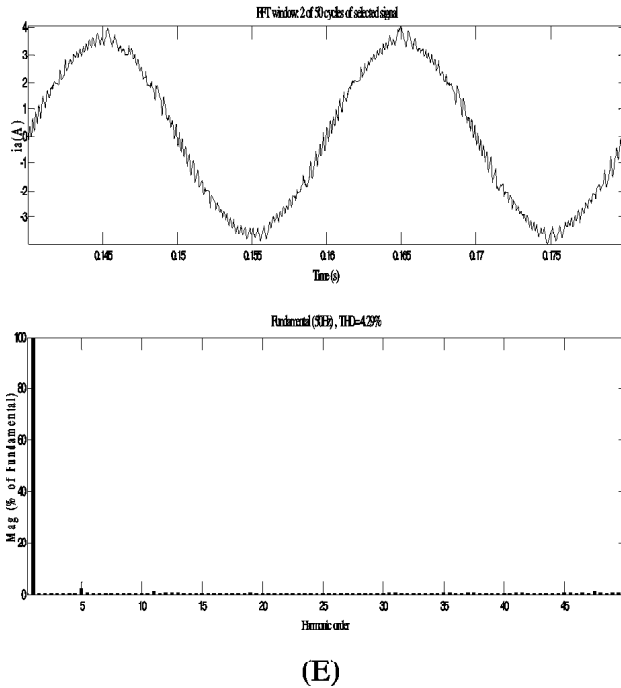
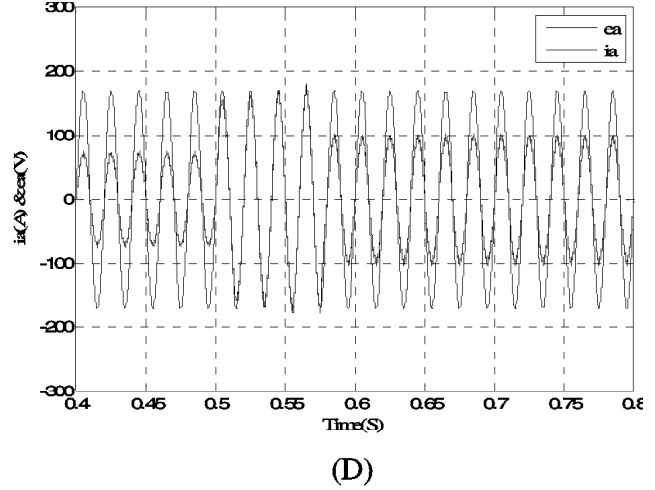
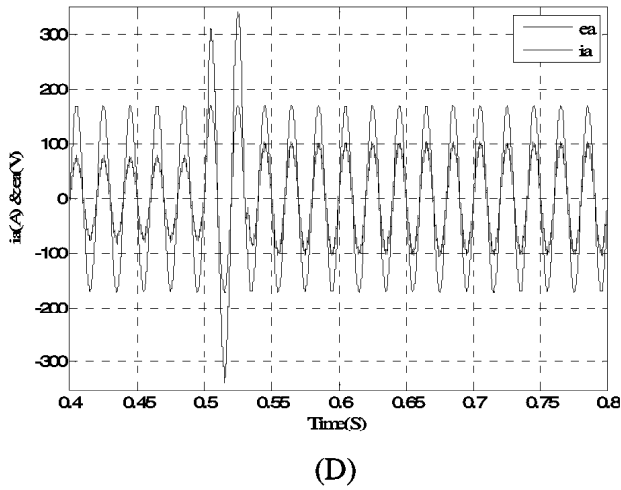


Figure 7: (A, B, C, D, E): Simulated basic signal waveforms and line current harmonic spectrum under purely sinusoidal line voltage for DPC. From the top: instantaneous active and reactive power, DC link voltage, line current, and harmonic spectrum of the line current (THD = 4.29%)

Figure 8: (A, B, C, D, E): Simulated basic signal waveforms and line current harmonic spectrum under purely sinusoidal line voltage for DPC-SVM. From the top: instantaneous active and reactive power, DC link voltage, line current, and harmonic spectrum of the line current (THD = 2.05%)

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