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THREE-PHASE PWM BOOST RECTIFIER OPERATING UNDER DIFFERENT INPUT VOLTAGE CONDITIONS

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Abstract: In this paper, a proposed control strategy is presented to improve the performance of the pulse width modulation (PWM) boost rectifier when operating under different supply voltage conditions (balanced, unbalanced, and distorted three-phase supply voltages). The proposed control strategy is divided into two parts, the first part is voltage controller and the second part is current controller. In the voltage controller, Proportional-Integral (PI) controller is used to regulate the output dc voltage at any desired level and Low Pass Filter (LPF) to reduce the even order harmonics which appear in the regulated output dc voltage due to unbalanced input supply voltages. LPF also reduces the even order harmonics which appear in the reflected dc current (I_{MAX}), this leads to reduce the odd order harmonics which appear in the input currents. While in the current controller, Enhanced Phase Locked Loop (EPLL) technique is used to obtain sinusoidal and balanced three phases, to construct the reference currents, which are in phase with the fundamental supply voltages Therefore, the supply-side power factor is kept close to unity. A proportional controller is used to give excellent tracking between the line and the reference currents. The complete system with the proposed control strategy is simulated using Matlab/Simulink (Version 2012). The results for the complete system using proposed voltage controller are obtained and compared to the results of the system with the conventional voltage controller (proportional-integral (PI) is used without LPF). THD_s for three-phase input line currents are better when using the proposed voltage controller (less than 5%).

Keywords*: Three-phase PWM boost rectifier, Low Pass Filter, Proportional-Integral controller, Enhanced Phase Locked Loop*

المقوم ثلاثي الاطوارالمضمن بعرض النبضة نوع رافع للجهد والذي يعمل تحت مصدر تغذية متغير الحالات

الخلاصة: هذا البحث يقدم استراتيجية سيطرة لتحسين اداء مغير القدرة المضمن بعرض النبضة رافع للجهد تحت تأثير عدة عوامل بالجهد الداخل (العوامل هي اتزان، عدم اتزان و تشويه بالجهد الداخل). هذه الاستراتيجية يمكن تقسيمها الى قسمين هما: القسم الاول هو مسيطر للجهد بينما القسم الثاني هو مسيطر للتيار. في القسم الاول، مسيطر نسبي وتكاملي لتنظيم الجهد الخارج المستمر عند اي قيمة مع استخدام مرشح مرور الترددات الواطئة لتقليل التوافقيات الزوجية التي تظهر في الجهد الخارج المستمر بسبب عدم الاتزان في الجهد الداخل. مرشح مرور الترددات ايضا يقوم بتقليل التوافقيات الزوجية التي تظهر في التيار المستمر المنعكس (I_{MAX}) وهذا يؤدي الى تقليل التوافقيات الفردية التي تظهر في التيارات الداخلة. بينما في القسم الاخر من هذه الاستراتيجية هو مسيطر التيار الذي يستخدم تقنية معزز دائرة قفل الطور (EPLL) للحصول على موجات ثلاثية الطور جيبيه ومتزنة لبناء التيارات الاساسية التي تكون متطابقة بالطور مع المركبة الاساسية للجهد الداخل لتحسين عامل القدرة. مسيطر نسبي يستخدم في مسيطر التيار لتحسين التتبع بين التيارات الاساسية والتيارات الداخلة.

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النظام مع هذه الاستراتيجية تنفذ باستخدام البرنامج الحاسوبي MATLAB/SIMULINK (اصدار ٢٠١٢). نتائج النظرية باستخدام المسيطر النسبي والتكامل مع مرشح مرور الترددات (الطريقة المقترحة) تقارن مع النتائج النظرية باستخدام المسيطر النسبي والتكاملي (الطريقة التقليدية). تشويه التوافقيات الكلي (THD) للتيارات الداخلة تكون افضل باستخدام الطريقة المقترحة (تكون اقل من ٠،٠٥).

1. Introduction

The boost PWM rectifier has been increasingly employed in recent years since it offers the possibility of a low distortion line current with near unity power factor for any load condition. Another advantage over traditional phase-controlled thyristor rectifiers is its capability for nearly instantaneous reversal of power flow. Unfortunately, the features of the PWM boost type rectifier are fully realized only when the supply three phase input voltages are balanced. It has been shown that unbalanced input voltages cause an abnormal second harmonic at the output dc voltage, which reflects back to the input causing third-order harmonic current to flow. Next, the third order harmonic current causes a fourth-order harmonic voltage on the dc bus, and so on. This results in the appearance of even order harmonics at the output dc and odd order harmonics in the input currents. An attempt was made to reduce low order harmonics at the input and the output of the PWM boost rectifier under unbalance input voltages [1]. H.S.Song and K.Nam [2] used two synchronous reference frames: a positive-sequence current regulated by a proportional integral (PI) controller in a positive synchronous reference frame (SRF), and a negative sequence current regulated by a PI controller in a negative SRF. S.C.Ahn and D.S.Hyum [3] proposed a new control scheme to minimize harmonic distortions of the input current and dc-link voltage in the converter. X. H. Wu and J. X. Xu [4] proposed a hybrid digital repetitive controller (RC) scheme to minimize the line-side current harmonics and the dc link voltage harmonics under the distorted and unbalanced operating conditions. But these strategies require a series of frame transformation and calculation which increase the complexity of implementation. A.V.Stankovic and Ke Chen [5] present a new control method for input-output harmonic elimination of the pulse width modulation (PWM) boost-type rectifier under conditions of both unbalancedinput voltages and unbalanced input impedances. But in this method, hysteresis current controllers are used to regulate the actual three-phase currents, these controllers produce drawbacks such as a variable switchingfrequency and an irregularity of the position of modulation pulses. These drawbacks provide high current ripples, acoustic noise, and difficulty in designing of input filter.

In this paper, the proposed method can be divided into two parts, the first part is voltage controller (PI controller with LPF) to produce the magnitude of the reference currents (I_{MAX}) without even order harmonics. The second part is current controller (Enhanced phase locked loops with using proportional controllers) to produce pure and balanced sine waves, these sine waves multiplied by the output of the voltage controller (I_{MAX}) to complete the reference currents. Finally after completing the reference currents, proportional controllers are used to force the line currents to follow these references.

2. Modeling of Three-Phase PWM Boost Rectifier Under Balanced Sinusoidal Input Voltage Condition

The main circuit of the three phases PWM ac to dc converter is shown in Fig.1. Three-phase line voltages and the fundamental line currents are:

$e_1=E_m \sin(\omega t)$ (1a)

$e_2=E_m \sin(\omega t-120)$ (1b)

$e_3=E_m \sin(\omega t+120)$ (1c)

Assume unity power factor

$i_1=I_m \sin(\omega t)$ (2a)

$i_2=I_m \sin(\omega t-120)$ (2b)

$i_3=I_m \sin(\omega t+120)$ (2c)

Where E_m (I_m) and ω are amplitude of the phase voltage (current) and angular frequency, respectively. For phase 1: [6]

$$L \frac{di_1}{dt} + R_L i_1 = V_{AD} = e_1 - (V_{DN} + V_{NO}) \quad (3)$$

When switch S_1 is ON and switch S_1' is OFF, the switching function is:

$d_1=1$ and $d_1'=0$

And

$$V_{DN} = i_1 R_S + V_o \quad (4)$$

Where R_S is equivalent resistance of a switching device. When switch S_1' is ON, the switching function is:

$d_1=0$ and $d_1'=1$ and

$$V_{DN}=i_1 R_S. \quad (5)$$

Therefore, (3) becomes:

$$L \frac{di_1}{dt} + R_L i_1 = e_1 - [(i_1 R_S+V_o)\, d_1 + (i_1 R_S)\, d_1' + V_{NO}] \quad (6)$$

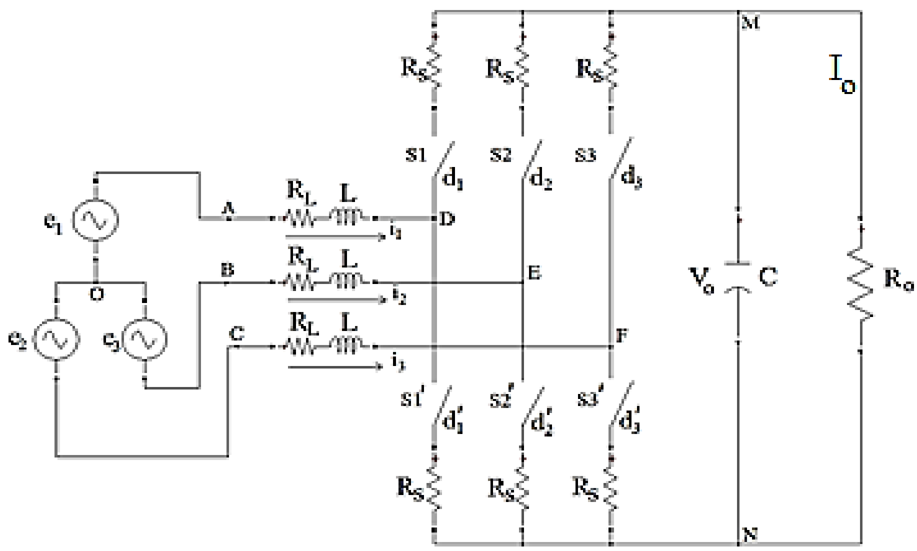

Figure 1: Circuit of the three-phase PWM rectifier

Because either S_1 or S_1' is conducting and only one of them is allowed to conduct in any moment, i.e. :

$d_1 + d_1' = 1$ so

$$L\frac{di_1}{dt} + R_L\, i_1 = e_1 - [i_1 R_S\, d_1 + V_o\, d_1 + i_1 R_S d_1' + V_{NO}] \tag{7}$$

$$L\frac{di_1}{dt} + R_L\, i_1 = e_1 - [i_1\, R_S\, (d_1 + d_1') + V_o\, d_1 + V_{NO}] \tag{8}$$

$$L\frac{di_1}{dt} + R_L\, i_1 + R_S\, i_1 = e_1 - [V_o\, d_1 + V_{NO}] \tag{9}$$

$$L\frac{di_1}{dt} + R\, i_1 = e_1 - [V_o\, d_1 + V_{NO}] \tag{10}$$

Where $R=R_L+R_S$, the total series resistance in one phase. Similarly, for phase 2 and 3: [6]

$$L\frac{di_2}{dt} + R\, i_2 = e_2 - [V_o\, d_2 + V_{NO}] \tag{11}$$

$$L\frac{di_3}{dt} + R\, i_3 = e_3 - [V_o\, d_3 + V_{NO}] \tag{12}$$

For a three-phase system without neutral line,

$$i_1 + i_2 + i_3 = 0 \tag{13}$$

The sum of three-phase supply is

$$e_1 + e_2 + e_3 = 0 \tag{14}$$

The voltage V_{NO} can be obtained by adding (10), (11), and (12)

$$L\frac{di_1}{dt} + L\frac{di_2}{dt} + L\frac{di_3}{dt} + R\,(i_1+i_2+i_3) = e_1 + e_2 + e_3 - V_o\,(d_1+d_2+d_3) + 3V_{NO} \tag{15}$$

$$0 = V_o\,(d_1+d_2+d_3) + 3V_{NO} \tag{16}$$

$$V_{NO} = \frac{-1}{3} V_o \sum_{k=1}^{3} d_k \tag{17}$$

Substitute (17) in (10), (11), and (12), the result will be

$$L\frac{di_1}{dt} + R\, i_1 = e_1 - u_{s1} \tag{18}$$

$$L\frac{di_2}{dt} + R\, i_2 = e_2 - u_{s2} \tag{19}$$

$$L\frac{di_3}{dt} + R\, i_3 = e_3 - u_{s3} \tag{20}$$

Where

$$u_{s1} = V_o\left(\frac{2d_1 - (d_2+d_3)}{3}\right) \tag{21}$$

$$u_{s2} = V_o\left(\frac{2d_2 - (d_1+d_3)}{3}\right) \tag{22}$$

$$u_{s3} = V_o\left(\frac{2d_3 - (d_1+d_2)}{3}\right) \tag{23}$$

In the Fig. 1, another differential equation can be written as:

$$C\frac{dV_o}{dt} = i_1\, d_1 + i_2\, d_2 + i_3\, d_3 - \frac{V_o}{Ro} \tag{24}$$

A block diagram of the PWM rectifier with ABC model is presented in Fig. 2.

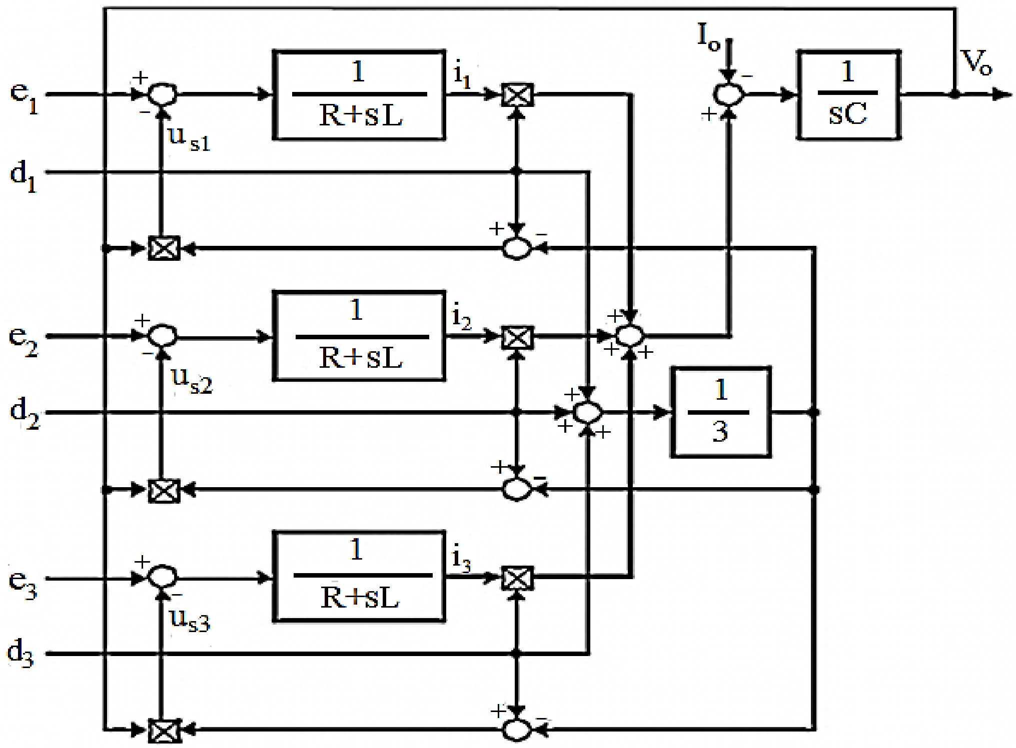

Figure 2: Three-phase PWM rectifier in ABC-model

3. Analysis of Three-Phase PWM Boost Rectifier Operating Under Unbalanced Input Voltage Condition

In Fig.1, it is assumed that the PWM rectifier is supplied by unbalanced input voltages but balanced input impedances. The assumptions used in the following derivation are

1) The system losses are very small and can be neglected.

2) The switching functions used to represent switching action of the converter are unbalanced but contain no zero sequence.

3) Only fundamental components of switching functions and input currents are taken into account (PWM switching harmonics are not considered).

4) There is no phase difference between the fundamental components of the switching functions and the input currents. Sothat the fundamental components of the switching functions can be written as

$d_{f1}= A_1 sin(\omega t)$ (25)

$d_{f2}= A_2 sin(\omega t - 120)$ (26)

$d_{f3}= A_3 sin(\omega t + 120)$ (27)

Three-phase unbalanced input line currents are

$i_1=I_{m1}\sin(\omega t)$ (28)

$i_2=I_{m2}\sin(\omega t-120)$ (29)

$i_3=I_{m3}\sin(\omega t+120)$ (30)

The output dc current is

$i_{dc} =\overline{T}.\,\overline{i}$ (31)

The converter transfer function vector $\overline{T}$ is composed of three switching functions [6]

$\overline{T}= [\ d_{f1}\ d_{f2}\ d_{f3}\ ]$ (32)

And the current $\bar{i}$ vector is

$$\bar{i} = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \qquad (33)$$

The three-phase unbalanced input currents can be presented as a sum of two balanced sets of positive and negative sequence component

$$\bar{i} = \overline{i_p} + \overline{i_n} \qquad (34)$$

$$\overline{i_p} = \begin{bmatrix} I_p\, sin(\omega\, t) \\ I_p\, sin(\omega\, t - 120) \\ I_p\, sin(\omega\, t + 120) \end{bmatrix} \qquad (35)$$

$$\overline{i_n} = \begin{bmatrix} I_n\, sin(\omega\, t) \\ I_n\, sin(\omega\, t + 120) \\ I_n\, sin(\omega\, t - 120) \end{bmatrix} \qquad (36)$$

Similarly the converter transfer function can be decomposed into two balanced sets of positive and negative sequence components under unbalanced voltages that is

$$\bar{T} = \bar{T}_p + \bar{T}_n \qquad (37)$$

$$\bar{T}_p = \begin{bmatrix} A_p\, sin(\omega\, t) \\ A_p\, sin(\omega\, t - 120) \\ A_p\, sin(\omega\, t + 120) \end{bmatrix}^T \qquad (38)$$

$$\bar{T}_n = \begin{bmatrix} A_n\, sin(\omega\, t) \\ A_n\, sin(\omega\, t + 120) \\ A_n\, sin(\omega\, t - 120) \end{bmatrix}^T \qquad (39)$$

Now from (34) to (39), the resultant output dc current (31) under unbalanced input voltages becomes [6]

$$i_{dc} = (T_p + T_n)\,(i_p + i_n) \qquad (40)$$

$$i_{dc} = T_p\, i_p + T_p\, i_n + T_n\, i_p + T_n\, i_n \qquad (41)$$

Equation (41) represents the general expression for the converter output current i_{dc} under unbalanced voltages in term of positive and negative sequence components of the converter transfer function and the input currents respectively.

$$T_p\, i_p = \frac{3A_p\, I_p}{2} \qquad (42)$$

$$T_n\, i_n = \frac{3A_n\, I_n}{2} \qquad (43)$$

$$T_p\, i_n = \frac{-3A_p I_n}{2} cos(2\omega t) \qquad (44)$$

$$T_n\, i_p = \frac{-3A_n I_p}{2} cos(2\omega t) \qquad (45)$$

$$i_{dc} = \frac{3A_p\, I_p}{2} + \frac{3A_n\, I_n}{2} - \frac{3A_p I_n}{2} cos(2\omega t) - \frac{3A_n I_p}{2} cos(2\omega t) \qquad (46)$$

The cross product ($T_p\, i_n$) and ($T_n\, i_p$) yield the abnormal second harmonics components.

$$i_{dc} = I_{dc} + i_{sh} \qquad (47)$$

Where

$$I_{dc} = \frac{3A_p\, I_p}{2} + \frac{3A_n\, I_n}{2} \qquad (48)$$

$$i_{sh}=\frac{-3A_pI_n}{2}cos(2\omega t)-\frac{3A_nI_p}{2}cos(2\omega t) \qquad (49)$$

$$I_o = i_{dc} - C\frac{dV_o}{dt} \qquad (50)$$

$$I_o = I_{dc} + i_{sh} - C\frac{dV_o}{dt} \qquad (51)$$

$$V_o = R_o\, I_o \qquad (52)$$

Where V_o and R_o are the output dc load voltage and the resistive load

$$V_o = R_o\,[I_{dc} + i_{sh} - C\frac{dV_o}{dt}] \qquad (53)$$

$$V_o= \underbrace{[R_oI_{dc} - R_oC\frac{dV_o}{dt}]}_{constant\ (pure\ dc\ value\ V_{dc})} + \underbrace{R_oi_{sh}}_{second\ harmonic(V_{sh})} \qquad (54)$$

$$V_o = V_{dc} + v_{sh} \qquad (55)$$

Due to the unbalanced input voltages, the output dc voltage will contain dc term as well as ac term (100 Hz second frequency for 50 Hz supply).For a desired level V_{REF}, PI controller is used to regulate the output dc voltage at this level (V_{REF}). But due to existing the second harmonic voltage (v_{sh}) in V_o, the output from PI controller (I_{MAX}) will contain dc term (I) as well as the ac term ($I_c\cos(2\omega t)$) sothat

$$I_{MAX}= I + I_c cos\ (2\omega t) \qquad (56)$$

I_{MAX} used as magnitude for the reference currents sothat

For phase1, the reference current is

$i_{r1} = I_{MAX}\sin(\omega t)$

$i_{r1} = I\sin(\omega t) + I_c\cos(2\omega t)\sin(\omega t)$

$$i_{r1}=I\sin(\omega t)-\frac{I_c}{2}(\sin(\omega t)-\sin(3\omega t)) \qquad (57)$$

The second order harmonic in the output dc bus causes third order harmonic in the input current (see (57)). This interaction continues and results in the appearance of even order harmonics at the dc link voltage and odd order harmonics in the input currents.

4. Control Strategy

The proposed control strategy is divided into two parts; the first partis voltage controller includes proportional integral (PI) Controller to regulate the output dc voltage at any desired level and Low Pass Filter (LPF) to reduce the second order harmonic in output dc bus. The second part is current controller which includes reference current extraction control using PLL synchronization technique withinner current control using proportional controller only. Fig.3 shows the control strategy with voltage and current controllers together. The next sections will explain each part of the proposed control strategy in details.

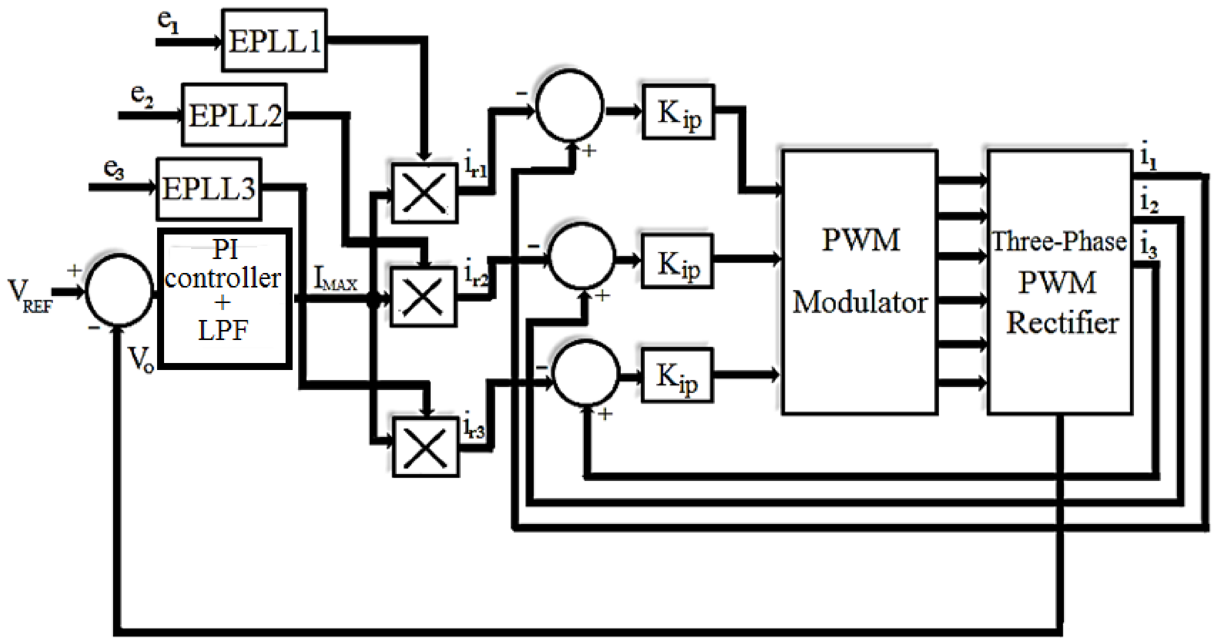

Figure3: Block diagram of the proposed control strategy

4.1 Voltage Controller

The dc side capacitor voltage is sensed and compared with a reference value.The PI controller is used to control the dc side capacitor voltage of the PWM-rectifier at the reference voltage.With the help of low pass filter (LPF), the second harmonic (100Hz for 50Hz supply) appeared in the output of PI controller (56) will be reduced by setting the cutoff frequency (f_c) of LPF at 50 Hz. The PI controller is a linear combination of the P, and I controllers. Its transfer function can be represented as

$$G_c(s) = K_{Vp} + \frac{K_{Vi}}{s} \qquad (58)$$

Where G_c (s) is the transfer function of the PI controller, K_{VP} is the proportional constant that determines the dynamic response of the dc-bus voltage control, K_{Vi} is the integration constant that determines it's settling time.

4.2 Current Controller

a) Enhanced Phase Locked Loop (EPLL):

The EPLL enhances the standard PLL by removing its main drawback that is the presence of double-frequency errors. It achieves this task by means of estimating the amplitude of the input signal. Thus, in addition to removing the ripples, the EPLL provides an estimate of the input signal magnitude and a filtered version of the input signal. This makes the EPLL function as a filter and as a controller too. The block diagram of the EPLL is shown in Fig.4. The EPLL comprises a PLL (shown in the box on the bottom of Fig.4) and also a branch that generates a signal y that is the filtered version of the input signal u. Thus, Y estimates the peak value of the input signal, and ϕ estimates its phase angle. The frequency is estimated at ω. The signal ψ is unity sinusoidal signal in phase with the input signal, and this represents a stable synchronizing reference. [7]

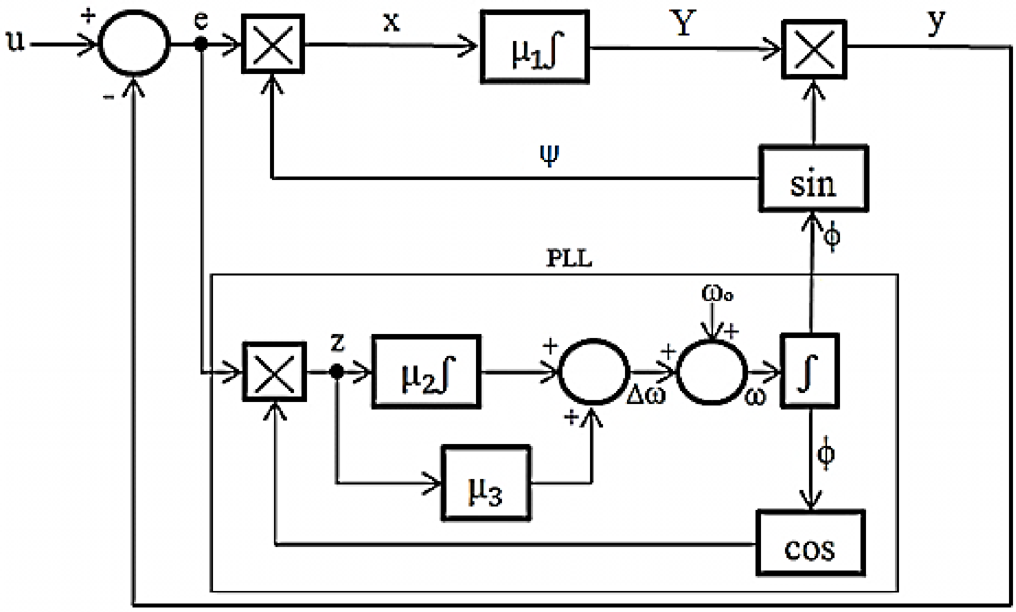

Figure4: EPLL block diagram

Assume (u=U sin θ, where θ=ωt)and (y= Ysinϕ). Obviously, when (Y = U and ϕ= θ), the EPLL is in a steady situation, and the error signal e = (u – y) is zero. If this steady situation is stable, then it means that the EPLL approaches the correct solution. For (u = U sin θ) and (y = Y sinϕ), the error signal is (e = u – y) =(Usinθ – Ysin ϕ). The output of phase detector (PD) (the multiplier in PLL) in figure4 is equal to

$$z = e\cos\phi = (U\sin\theta - Y\sin\phi)\cos\phi$$

$$= \frac{U}{2}sin(\theta-\phi) + \underbrace{\frac{U}{2}sin(\theta+\phi) - \frac{Y}{2}sin\,2\phi}_{high-frequency} \quad (59)$$

Assuming that the steady situation (i.e., Y = U and ϕ = θ) is stable, the high-frequency term approaches zero as the system approaches to the steady situation. This means that the high- or double-frequency term keeps being removed from the loop and the frequency and phase angle estimations will carry no double-frequency ripple as they approach their steady values. The output of the top multiplier in Fig.4 is equal to

$$x = e\sin\phi = (U\sin\theta - Y\sin\phi)\sin\phi$$

$$= \frac{U}{2}cos(\theta-\phi) - \frac{Y}{2} + \underbrace{\frac{Y}{2}cos(2\phi) - \frac{U}{2}cos(\theta+\phi)}_{high-frequency} \quad (60)$$

As the system approaches the steady condition, the high frequency term approaches zero. Therefore, there will be no double-frequency ripple on the estimated peak value. The selection of the parameters in Fig. 4 (μ1, μ2, and μ3) depends on the following observation:

- Increasing the value of μ_1 will increase the speed of estimating of the magnitude. However, it creates oscillations in the response. There is a tradeoff between speed and accuracy (or smoothness).
- Decreasing μ_1, μ_2, and μ_3 yield an estimation of the peak, and phase which is insensitive/robust to the undesirable variations and noise in the input signal.

Finally, the output of the EPLL (ψ in Fig.4) will be pure unit sinusoidal and synchronized with the voltage in each phase, therefore the reference currents are:

$$i_{r1} = I_{MAX}\, sin(\omega t) \tag{61}$$

$$i_{r2} = I_{MAX}\, sin(\,\omega t - 120) \tag{62}$$

$$i_{r3} = I_{MAX}\, sin(\,\omega t + 120) \tag{63}$$

b) Proportional Controller

The block diagram of the current control loop shown in Fig.5, gains and time constants associated with various elements of the this block diagram are as follow [8]

e_1 source voltage
u_{s1} converter input voltage
K_{ip} gain of the P controller
K_{PWM} gain of the PWM block
T_{RL} time constant of the plant = $\frac{L}{R}$
K_{RL} gain of the plant = $\frac{1}{R}$
i_1 line current
i_{r1} reference current

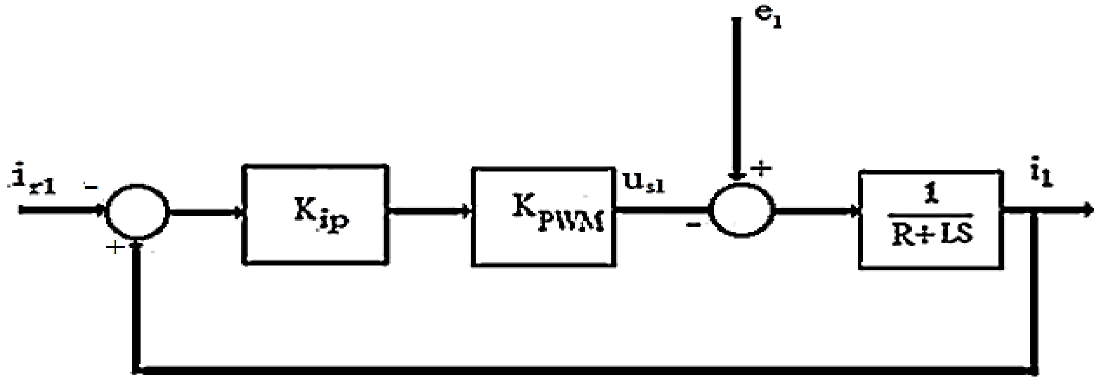

Figure 5: Block diagram of the current control loop in ABC model.

Forward transfer function = $\frac{K_{ip}K_{PWM}K_{RL}}{1+ST_{RL}}$

The closed loop transfer function is

$$\frac{i_1}{i_{r1}} = \frac{\frac{K_{ip}K_{PWM}K_{RL}}{1+ST_{RL}}}{1+\frac{K_{ip}K_{PWM}K_{RL}}{1+ST_{RL}}} = \frac{\frac{K_{ip}K_{PWM}K_{RL}}{1+ST_{RL}}}{\frac{1+ST_{RL}+K_{ip}K_{PWM}K_{RL}}{1+ST_{RL}}} = \frac{K_{ip}K_{PWM}K_{RL}}{ST_{RL}+K_{ip}K_{PWM}K_{RL}+1}$$

$K_{ip}K_{PWM}K_{RL} >> 1$, so the closed loop transfer function becomes

$$\frac{i_1}{i_{r1}} = \frac{1}{1+T_eS} \tag{64}$$

Where $T_e = \frac{T_{RL}}{K_{ip}K_{PWM}K_{RL}}$

5. Simulation Results

The operation of the three-phase PWM boost rectifier under extremely unbalanced and distorted operating conditions has been simulated in MATLAB Simulink by using SimPowerSystems toolbox. Eight different cases have been selected to verify feasibility and performance of the proposed control method (PI controller with using LPF) compared to the conventional one (without using LPF). The converter operates at near unity power factor with a stable behavior in spite of level of imbalance and distortion of the input conditions. The main electrical parameters of the power circuit and control data are given in Table 1.

Table. 1: Electrical parameters of power circuit

Switching Frequency(f_S)	10000Hz	dc-output voltage V_o	300V
Resistor of reactor(R_L)	0.01 Ω	Input voltage(V) and supply frequency(F)	120V, 50Hz
Inductance of reactors (L)	5 mH	K_{Vp} K_{Vi}	1, 66
dc-bus capacitor (C)	1000 µF	K_{ip}	133
Load resistance R_o	100 Ω	μ_1, μ_2, μ_3	18,0.1,0.1

The cases are

CASE 1:

In this case, the operation of the three-phase PWM boost rectifier is simulated under balanced input voltages condition. Fig.6 shows three-phase input voltages condition of this case, where e_1=e_2=e_3=120V. Fig. 7 shows the steady-state three-phase input currents and Fig. 8 shows the output dc voltage when using the proposed voltage controller (PI controller with using LPF).

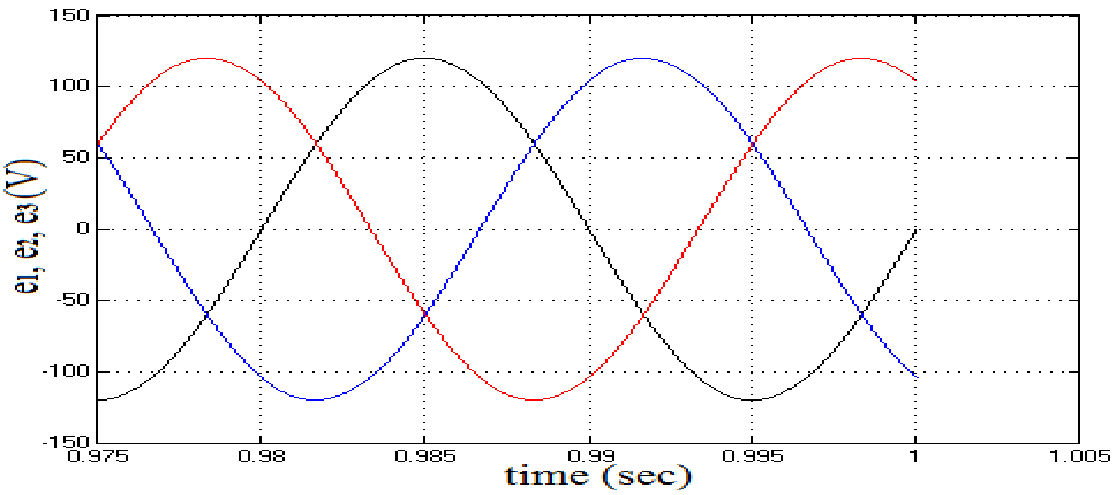

Figure 6: Input voltages of case 1

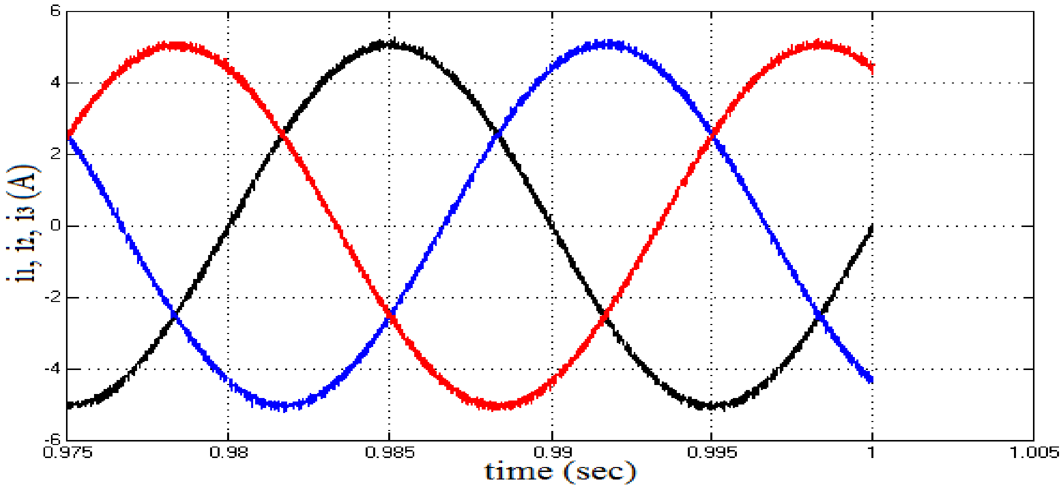

Figure 7: Input line currents when using the proposed voltage controller

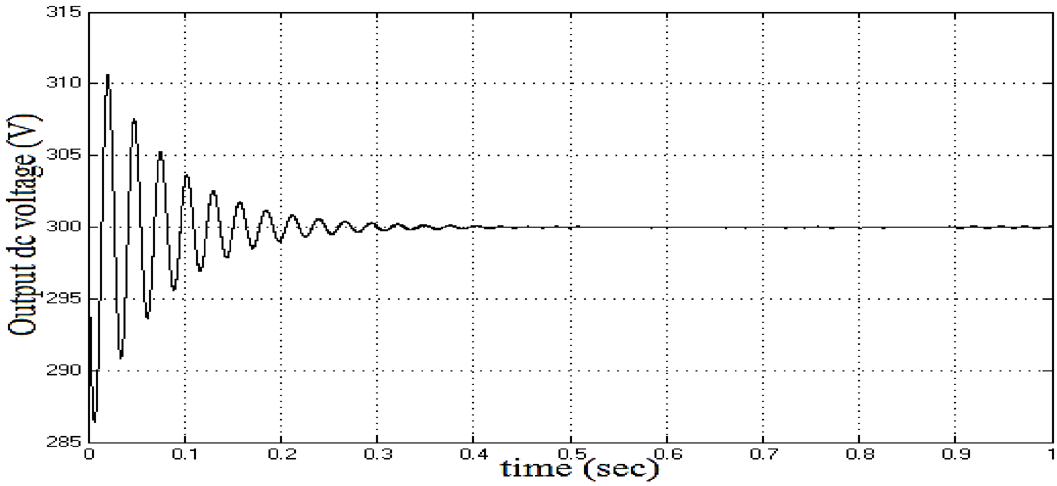

Figure 8: output dc voltage obtained when using the proposed voltage controller

CASE 2:

If the input supply voltages are e_1=190V, e_2=120V, and e_3=70V as shown in Fig. 9, then the input line currents obtained when using the proposed voltage controller are shown in Fig. 10.

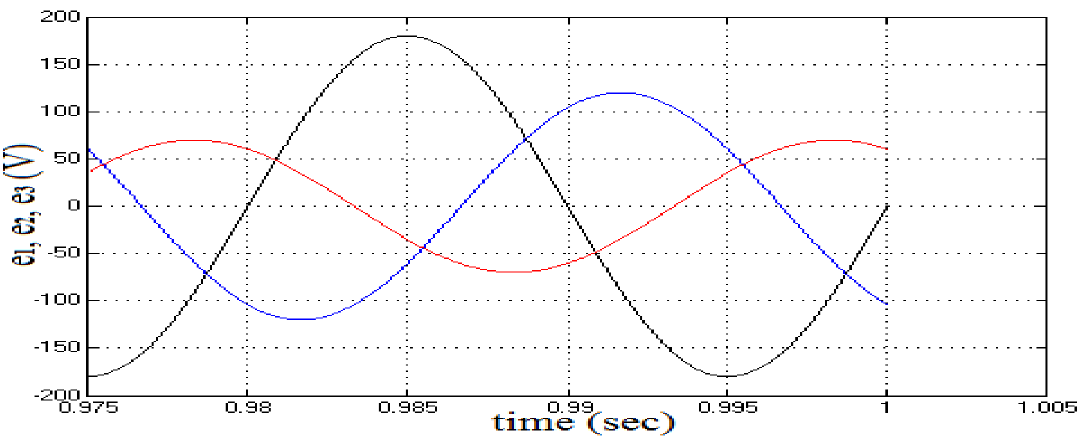

Figure 9: Input supply voltages of case 2

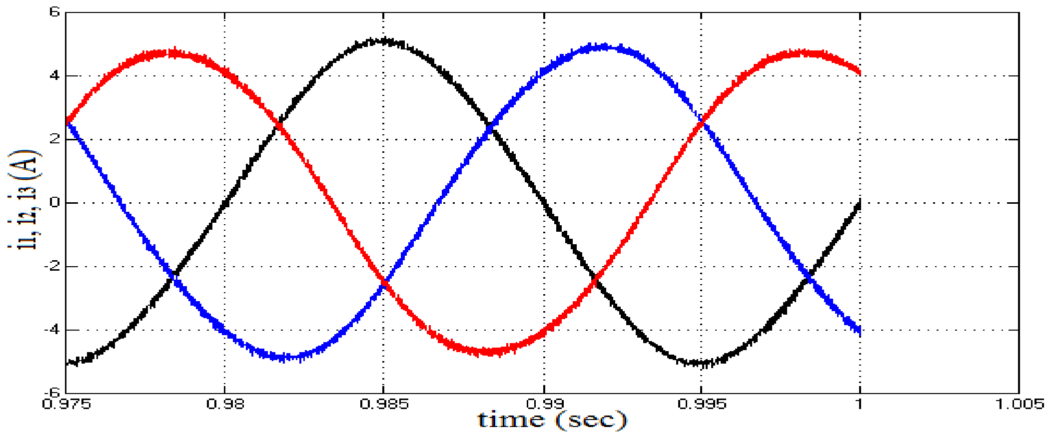

Figure 10: Input line currents when using the proposed voltage controller

Fourier analysis of the input line current for phase 1 is shown in Fig. 11, so that the third order harmonic currents in each phase are 0.097A, 0.1A, and 0.1A respectively. While the THD_s for three phases are 2.76%, 2.89%, and 3.07% respectively.

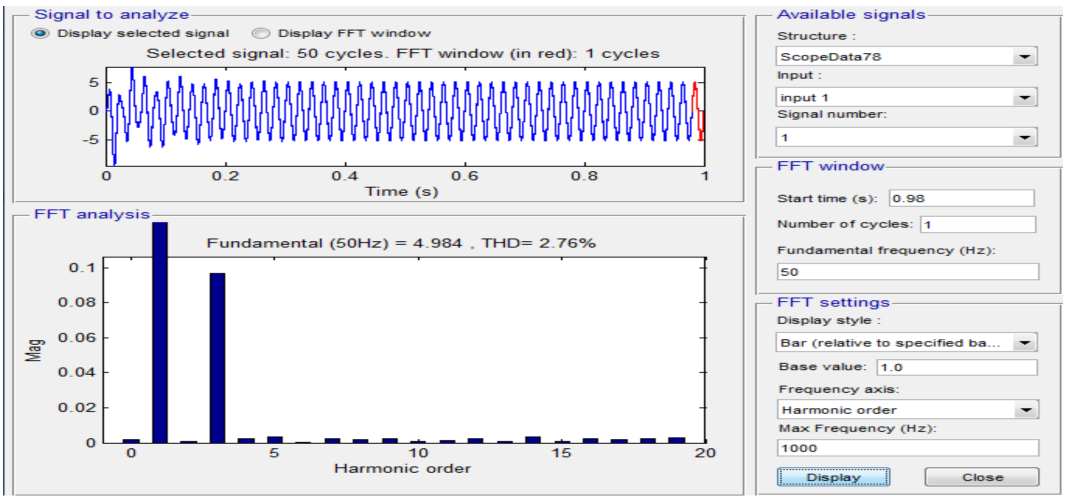

Figure 11: Fourier analysis of the input current for phase1 when using the proposed voltage controller in case 2

Fig. 12 shows the obtaining output dc voltage when using the proposed voltage controller. In this Figure, the second order harmonic in this voltage is 3V (Peak to peak (P.P)).

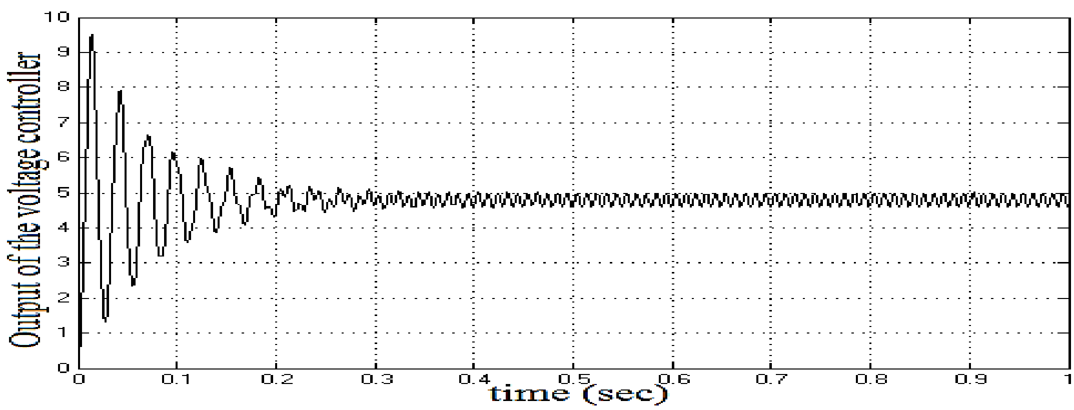

Figure 12: Output dc voltage obtained when using the proposed voltage controller

Fig.13 shows the three-phase input line currents obtained when using the conventional voltage controller (PI controller without using LPF).

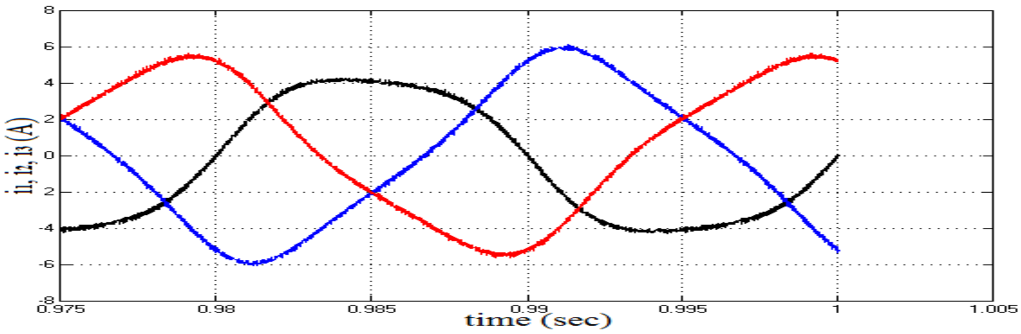

Figure 13: Input currents obtained when usingthe conventional voltage controller

Fig.14 shows Fourier analysis of the input line current for phase 1 when using the conventional voltage controller. From this Figure, the third order harmonic currents are 0.47A, 0.58A, and 0.54A. While the THD_s for three phases are 10.9%, 11.11%, and 11.09% respectively.

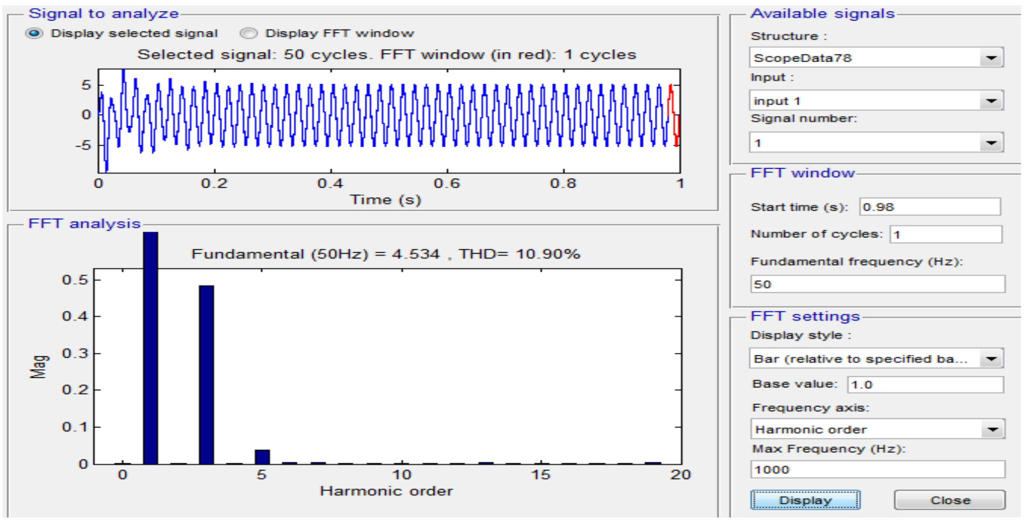

Figure 14: Fourier analysis of the input line current for phase 1 when using the conventional voltage controller

Fig.15 shows the obtaining output dc voltage when using the conventional voltage controller. In this Figure, the second order harmonic in the output dc voltage is 2.1V (P.P).

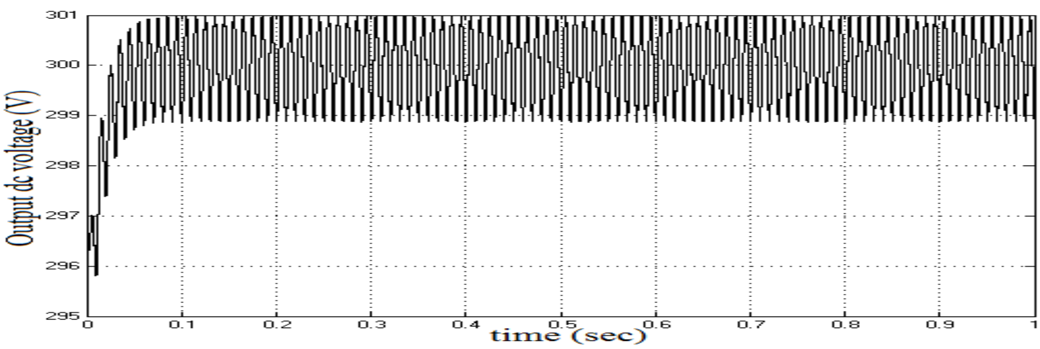

Figure 15: Output dc voltage obtained when using the conventional voltage controller

From comparisons between the conventional and the proposed voltage controllers, it can be seen that THD_s for the input line currents are better when using the proposed method. The reason of the improvement in THD is that Fig.16 shows the output of the voltage controller I_{MAX} (second order harmonic is 0.6V (P.P)) when using LPF. While Fig.17 shows I_{MAX} (second order harmonic is 2V (P.P)) without using LPF. I_{MAX} is multiplied by the outputs of the $EPLL_s$ to produce the reference currents (see equations 61, 62, and 63), the reference currents have fewer harmonics when using the proposed method, and therefore THD_s is improved. Better THD_s means pure and more sinusoidal input line currents. Finally for two cases, the obtaining power factor is0.9839.

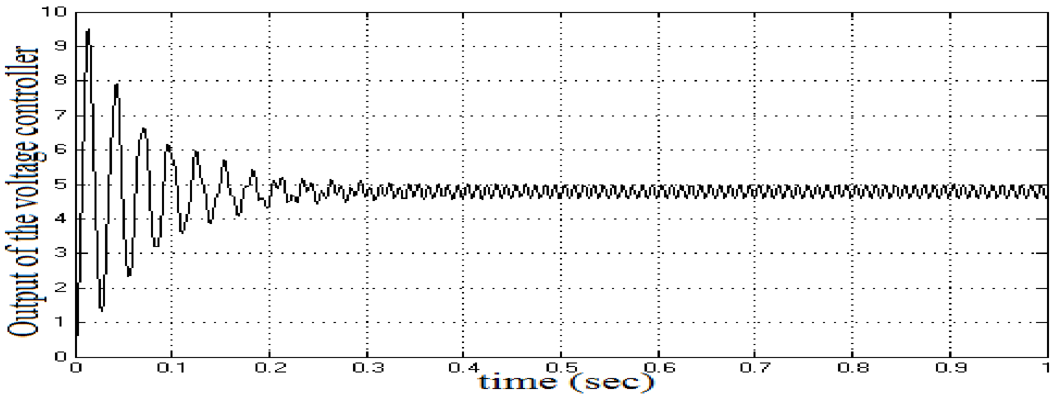

Figure 16: Output of the voltage controller obtained when using LPF

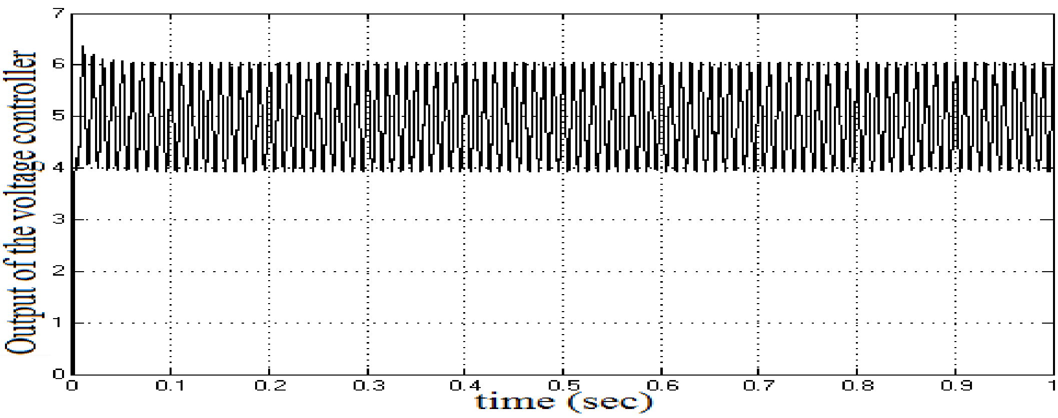

Figure 17: Output of the voltage controller obtained without using LPF

CASE 3

In this case, a 5th order harmonic of 25% distorts unbalanced input voltages (e_1=150V, e_2=120V, and e_3=80V). Fig.18 shows the input voltages of this case, while the input currents obtained when using the proposed voltage controller in this case are shown in Fig.19.

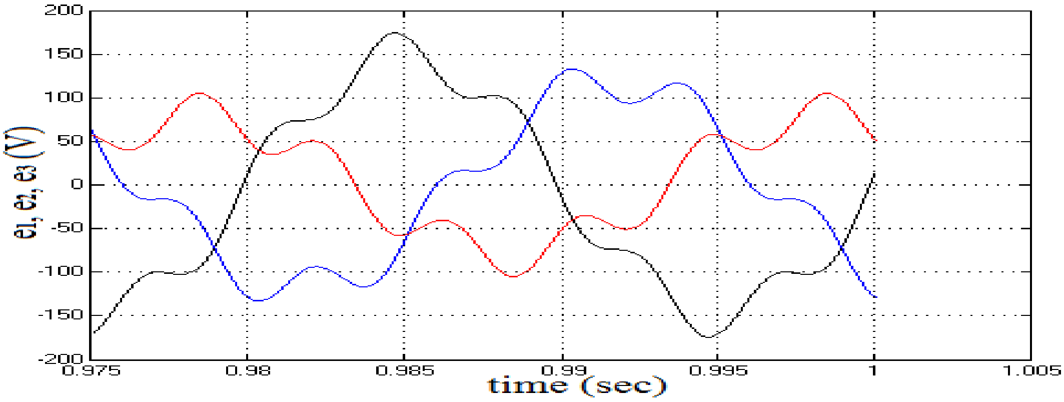

Figure 18: Input supply voltages for case 3

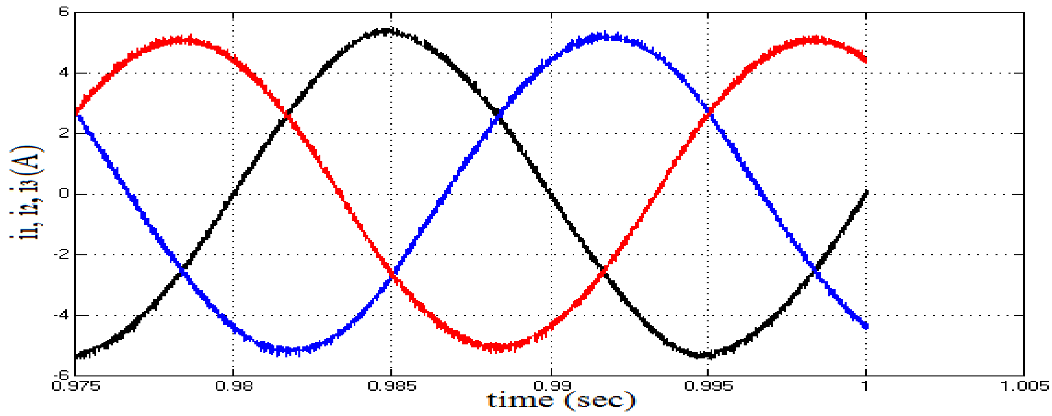

Figure 19: Input line currents obtained when using the proposed voltage controller

Fig.20 shows Fourier analysis of the input line current for phase 1. In this Figure, the third order harmonic currents in each phase line currentwhen using the proposed method are 0.07A, 0.06A, and 0.06A respectively. While the fifth order harmonic currents are 0.03A, 0.03A, and 0.03A. The seventh order harmonic currents in these line currents are 0.01A, 0.01, and 0.01A respectively. THD$_s$ for three phases when using the proposed method are 2.53%, 2.28%, and 2.41%.

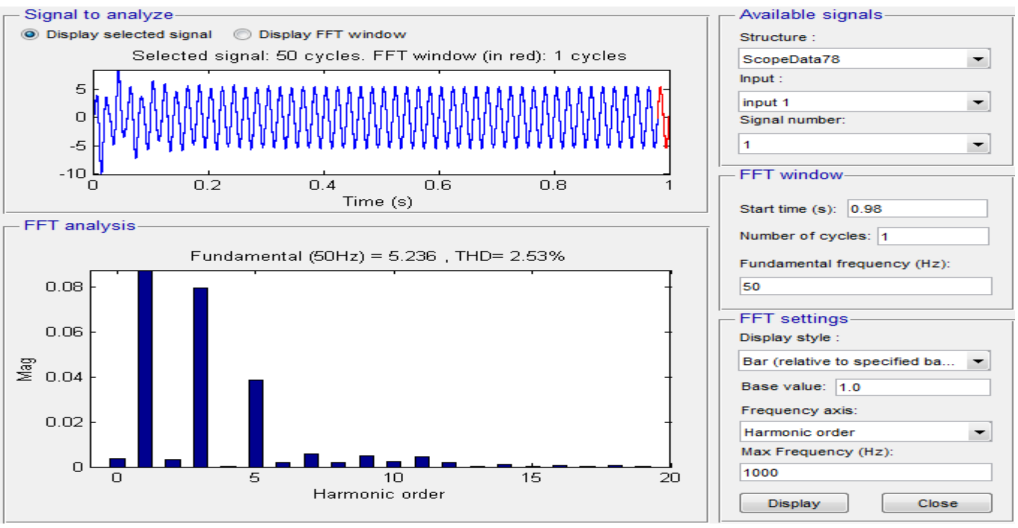

Figure 20: Fourier analysis of the input line current for phase 1 when using the proposed voltage controller

Fig.21 shows the obtaining output dc voltage when using the proposed voltage controller. In this Figure, the second order harmonic is 2V (P.P)

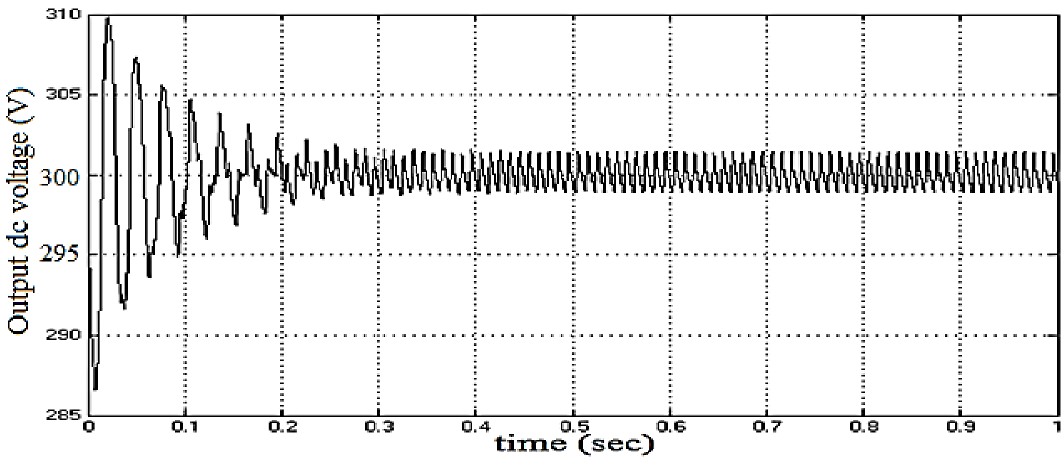

Figure 21: Output dc voltage obtained when using the proposed voltage controller

Fig.22 shows the three-phase input line currents when using the conventional voltage controller. While Fig.23 shows Fourier analysis of the input line current in the phase 1.

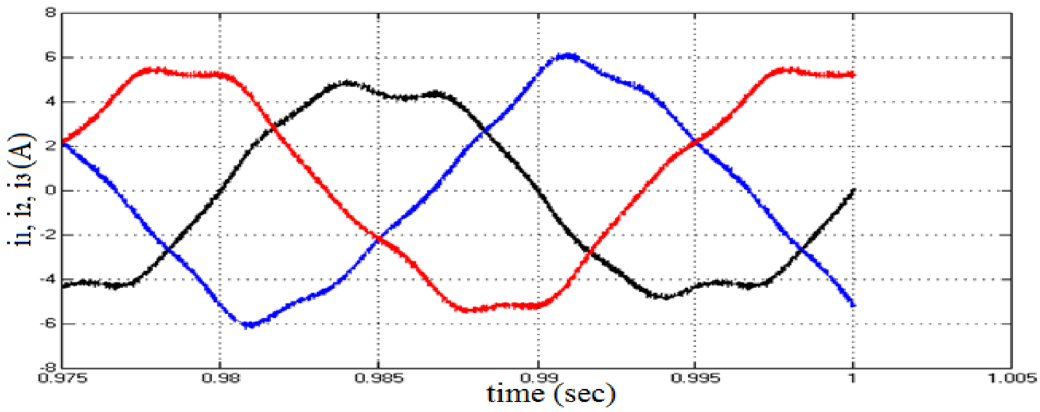

Figure 22: Input line currents obtained when using the conventional voltage controller

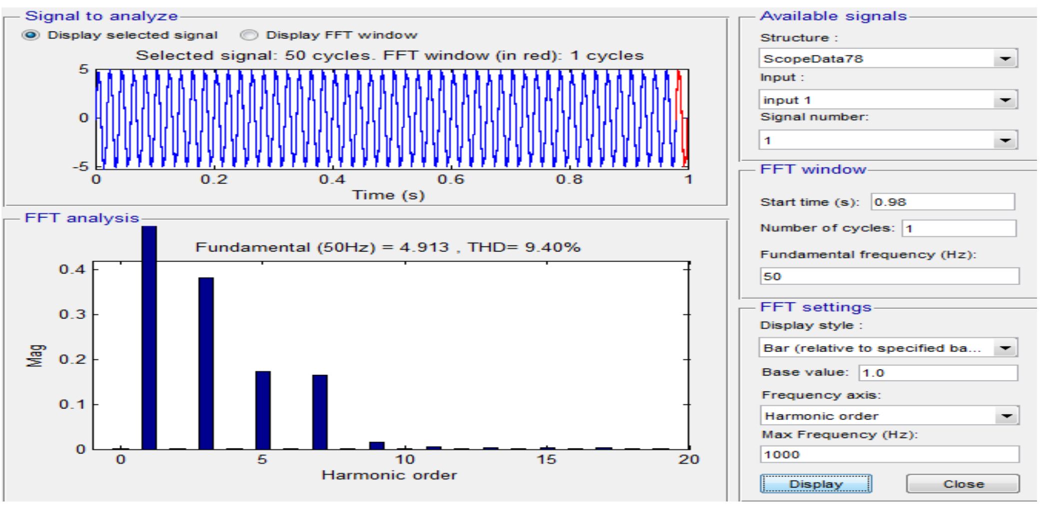

Figure 23: Fourier analysis of the input line current for phase 1 when using the conventional voltage controller

The third order harmonic currents in each phase line current when using the conventional method are 0.38A, 0.36A, and 0.31A respectively. While the fifth order harmonic currents are 0.17A, 0.14A, and 0.21A. The seventh order harmonic currents in these line currents are 0.16A, 0.17, and 0.18A respectively. THD_s for three phases when using the conventional method are 9.40%, 8.31%, and 7.98% . Finally, the obtaining power factor for this case is 0.9717.

CASE4:

In this case, a 7^{th} order harmonic of 25% distorts unbalanced input voltages (e_1=150V, e_2=120V, and e_3=80V). Fig.24 shows the waveforms of the input voltages of this case.

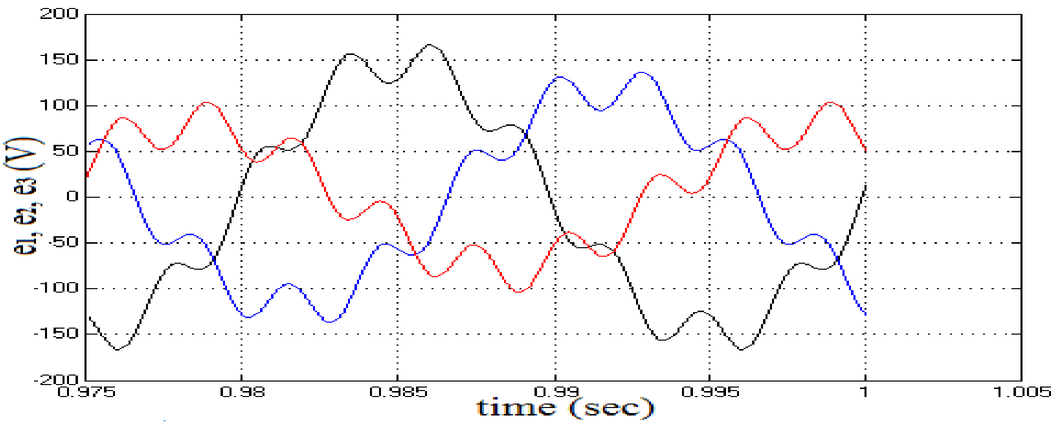

Figure 24: Input supply voltages for case 4

Fig.25 shows the three-phase input line currents when using the proposed voltage controller. While Fourier analysis of the input line current for phase 1 is shown in Fig.26.

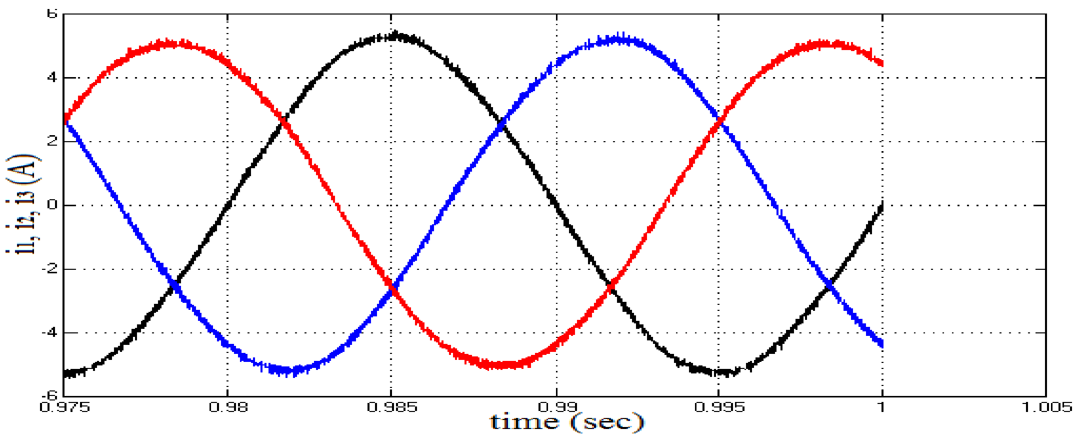

Figure 25: Input line currents obtained when using the proposed voltage controller

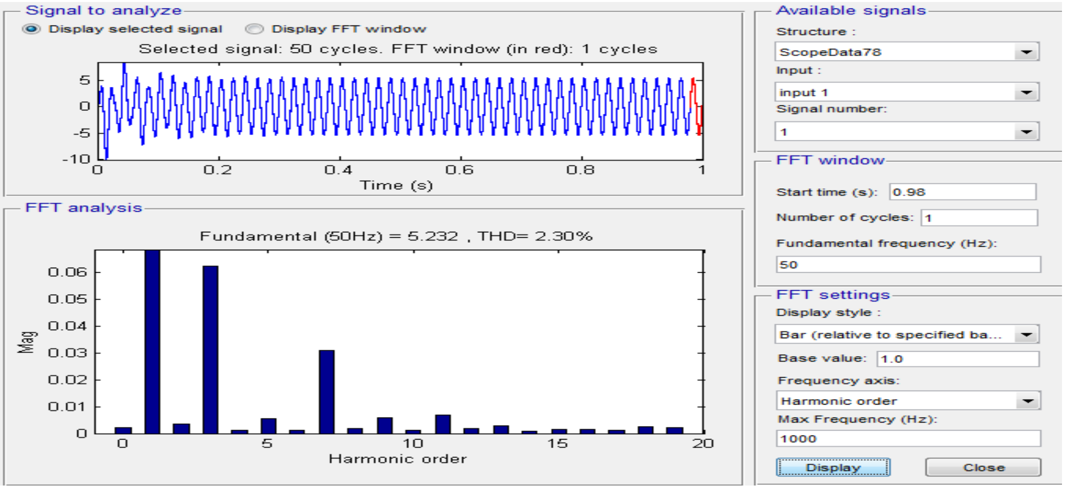

Figure 26: Fourier analysis of the input line current for phase 1 when using the proposed voltage controller

In this Figure, the third order harmonic currents in each phase line current when using the proposed method are 0.06A, 0.06A, and 0.06A respectively. While the seventh order harmonic currents in these line currents are 0.03A, 0.02, and 0.03A respectively.THD_s for three phases when using the proposed method are 2.30%, 2.22%, and 38%. Fig.27 shows the output dc voltage when using the proposed method. The second order harmonic in this voltage is 2.2V (P.P).

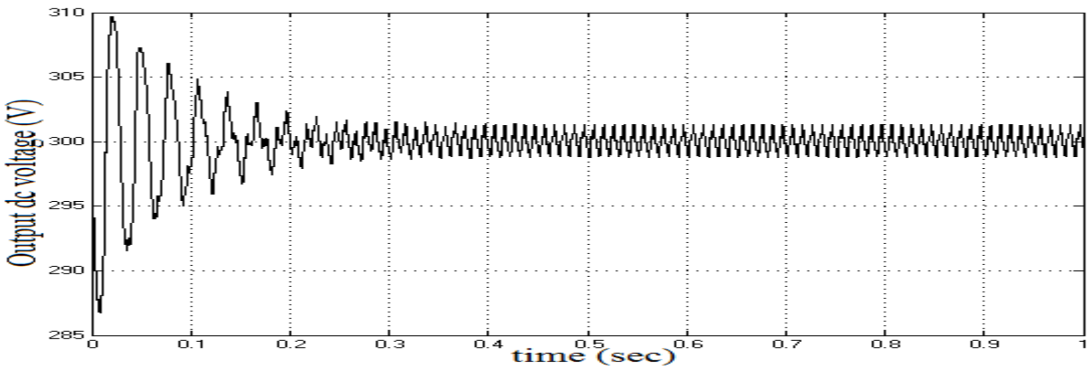

Figure 27: Output dc voltage obtained when using the proposed voltage controller

Fig.28 shows the three-phase input line currents obtained by using the conventional method.

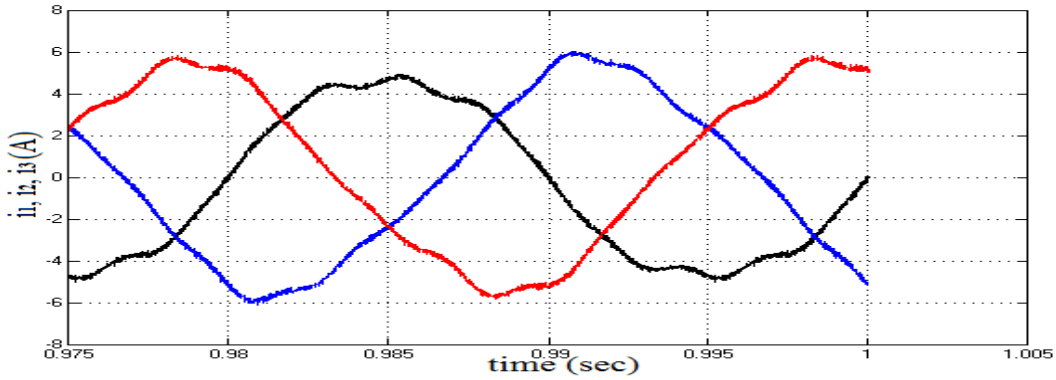

Figure 28: Input line currents obtained when using the conventional voltage controller

While Fig.29 shows Fourier analysis of the input current in phase 1. In this Figure, the third order harmonic currents in each phase line current when using the conventional method are 0.34A, 0.37A, and 0.36A respectively. While The seventh order harmonic currents in these line currents are 0.14A, 0.1, and 0.16A respectively. THD_s for three phases are 8.38%, 7.76%, and 8.02% respectively. Finally, the obtaining power factor is 0.9717.

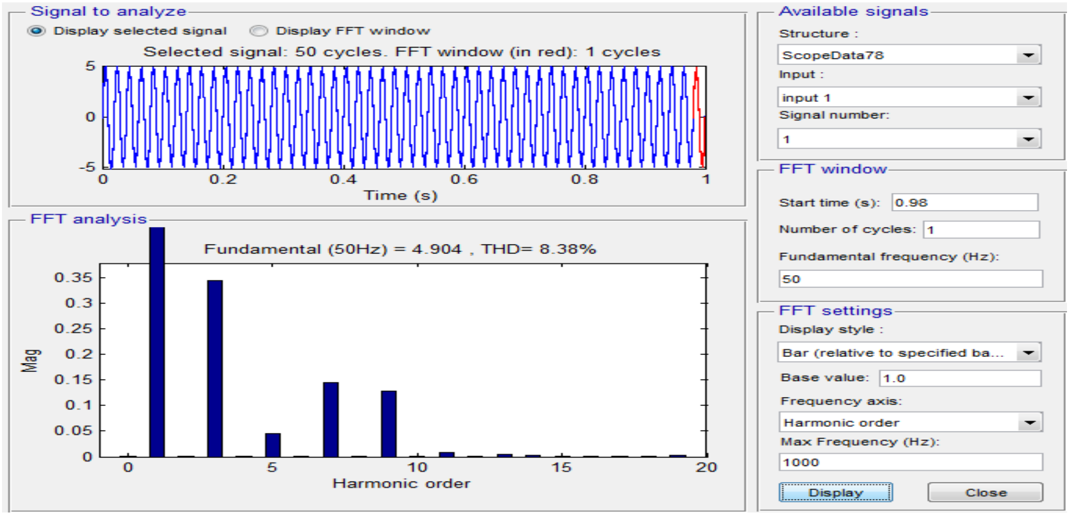

Figure 29: Fourier analysis of the input line current for phase 1 when using the conventional voltage controller

6. Conclusions

This paper proposed control strategy (PI controller with using LPF areused in the voltage controller, and EPLL with proportional controller are used in the current controller) on a three-phase PWM boost rectifier, to achieve input-output harmonic reduction under different input supply voltage conditions. It is concluded from the analysis of the PWM rectifier that when the input supply voltages are unbalanced a second order harmonic appears at the output dc voltage and this result in a third order harmonic in the input currents. The performance of reduction these harmonics for both the proposed method and the conventional method is evaluated. The proposed control method (PI controller with using LPF) produces less second order harmonic in the reflected dc current I_{MAX}, this reduces the third order harmonic in the input currents and improves the THD_s (less than 5%), less third order harmonic in the input currents results in reducing the second order harmonic in the output dc voltage. While if the conventional method is used, I_{MAX} has higher second order harmonic and this makes the THD higher than 5%. Simulation results in this paper are discussed in the steady state response under different input voltage supply conditions. In the steady state response, four different cases were performed to verify the feasibility of PWM rectifier with the proposed control strategy.The advantages of using the proposed method are:

1- Balanced three-phase sinusoidal input currents.
2- The power factor is kept close to unity.
3- The output dc voltage can be regulated at any desired level.

While when the conventional method (PI controller without using LPF) is used, non-sinusoidal input line currents are obtained. The power factor obtained when using the conventional method is also kept close to unity.

7. References

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