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EFFECT OF FEED FORWARD ON PFC BASED OF SINGLE-PHASE UNINTERRUPTIBLE POWER SUPPLY

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Abstract- An uninterruptible power supply (UPS) is used to prevent interruption by providing energy to the load for a certain period of time despite grid interruptions. The main points to consider when designing any UPS system are the input power factor ratio and distortion harmonics. For this reason, UPSs are generally designed with power factor corrected (PFC) circuits. PFC based UPSs eliminate harmonics originating from the load and enable them to draw currents with high power factor ratio from the grid. PFC controllers with feed forward content are used to reduce the effect of input voltage dynamics in active PFC circuits. In this study, the effects of the feed forward PFC circuit on UPS were investigated. In the proposed study, Matlab/Simulink program was used, and the results obtained from here were evaluated.

Keywords: UPS, PFC, Feed Forward, THD.

1. INTRODUCTION

UPS systems have two functions to solve the problems caused by the network. The first is to provide frequency fluctuations, voltage fluctuations, power factor correction from the grid and regulate their harmonics. The second is to continuously provide emergency back-up power to critical loads in case of grid-related outages. UPSs provide their secondary functions with the batteries they contain. Therefore, a UPS has limited time to power critical loads.

As usual, most of the systems are supplied by AC main power. Today using of power converter rapidly increased. However, the power converter makes pulsating input current from the utility grid, which decreases the power factor. One of the biggest problems by such kind of devices is the efficiency and the power factor ratio because it contains rectifier and coils, which make more AC main line power distortions [1]. A PFC circuit which is a device or power system includes an AC to DC converter that should have a power factor correction circuit to comply with the requirements of National and international standards (IEC 1000-3-2 and IEEE-519) can decrease the number of current harmonics, electromagnetic interfacing (EMI) and make the power factor nearly unity. We can get all these by using active PFC circuits. A boost type PFC circuit with an average current mode controller (ACMC) is one of the best topologies compare with another type of active PFC circuits.

The design and topologies of the UPS is the most effective factor to reduce the losses and THD. One of the big problems of normal UPS is the efficiency of the UPS by low load and low power factor of the UPS [2].

Generally, in an UPS systems topology the UPS contains three main blocks, AC-DC converter, battery bank, and DC-AC converter; there is also a static switch that controls the direct line between the load and AC main power supply [3]. In addition, a passive low pass filters are necessary to be added to the output of the UPS to improve the quality of output power, therefore there is a reason to find off-line UPS presenting a square or semi-sinusoidal waveform output voltage [4].

AC-DC converters without PFC are generally containing rectifiers and capacitive filters cause nonlinear currents to be drawn from the grid and therefore generate input current with low input PF containing harmonics, causing pollution of the electricity grid. These non-linear currents drawn from the network not only increase the size of the devices used, but also cause the distortion of the grid voltage due to their harmonic content and negatively affect other users fed from the same network. Therefore, there is a need for PFC circuits which are generally boost type DC-DC converters to regulate the input current power factor and harmonics in devices with AC-DC conversion [6]. Input feed forward is used in PFC controllers to reduce the effect of input voltage dynamics.

In this study, the effects of the feed forward PFC circuit on UPS were investigated. Boost type active PFC circuit has been used at the input side to prevent generating harmonics by the load. The boost type PFC topology is studied with and without feed forward. MATLAB/Simulink model of the designed system were comprehensively verified under different working situations to validate the suitability of the system.

2. DESCRIPTION OF PFC BASED UPS SYSTEM

The input side of on-line or off-line UPS systems includes AC-DC circuit and a battery charging circuit as shown in Figure 1. The input side is connected to the AC main power source (220 Vrms / 50 Hz). The output side of the UPS systems (output-controlled inverter with transformer and LC filter) is connected with the load. To be clearer we explain each part separately in details.

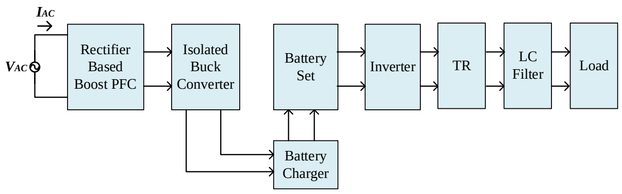

Figure 1. Block diagram of UPS system with PFC

The input side of the UPS system contains three subsystems which are PFC based boost converter, isolated buck converter and battery set with charger. The AC main power source is directly connected to a full-bridge rectifier to convert the AC sinusoidal waveform to a 311 DC volt. The rectifier is connected a controlled boost converter to fix and boost the voltage to 400 DC volt, and to control shape of input signal to correct the power factor and reduce the input current THD. The isolated buck converter is connected with battery charge to charge the batter and protect the battery set from overcharging.

The active methods of PFC, which contain the shaping of the line current, using switching devices such as MOSFETs or IGBTs, is a result of advances in power semiconductor devices. In the low-frequency active methods of PFC, the circuit is included a conductor, diode, capacitor and a transistor with a gate controller [7]. This solution is to control the output voltage within certain limits. It is a simple, reliable, low-cost transistor required, and switching losses are very low, but the output voltage regulation is slow, and it required a large inductance L_d [8].

The boost converter is the most common design topology used for PFC, and it is a step-up converter. It means the output voltage always higher than the input voltage. This type of converter can operate in two modes, Continuous Conduction Mode (CCM), and Discontinuous Conduction Mode (DCM) [8].

The controlled PFC based boost converter for input PFC as shown in Figure 2, consists of an IGBT switch transistor, inductance coil (L), Resistor (R), Diode D, voltage sensor, current sensor, transistors gate control circuit and a capacitor. The input of the circuit will be supplied with 311 DC volts, and through duty cycle of the switch it steps up the voltage to 400 DC volts. The duty cycle of the transistor gate will be controlled by a controlled circuit to correct input power factor and reduce input current total harmonics distortions by using average current control method. The parameters of these elements are: L = 3 mH, R = 0.3 Ω, C = 1000 µF with initial voltage of 310 V. The IGBT parameters are internal Resistance R_{on} = 0.001 Ω, Snubber Resistance R_s = 1MΩ; Snubber Capacitance C_s = INF. For the diode, the diode impedance is infinite on off-state mode; Resistance, R_{on} = 0.0001 Ω; Forward Voltage V_f =0.8 V; Snubber Resistance R_s = 50000 Ω; and Snubber Capacitance C_s =250 nF.

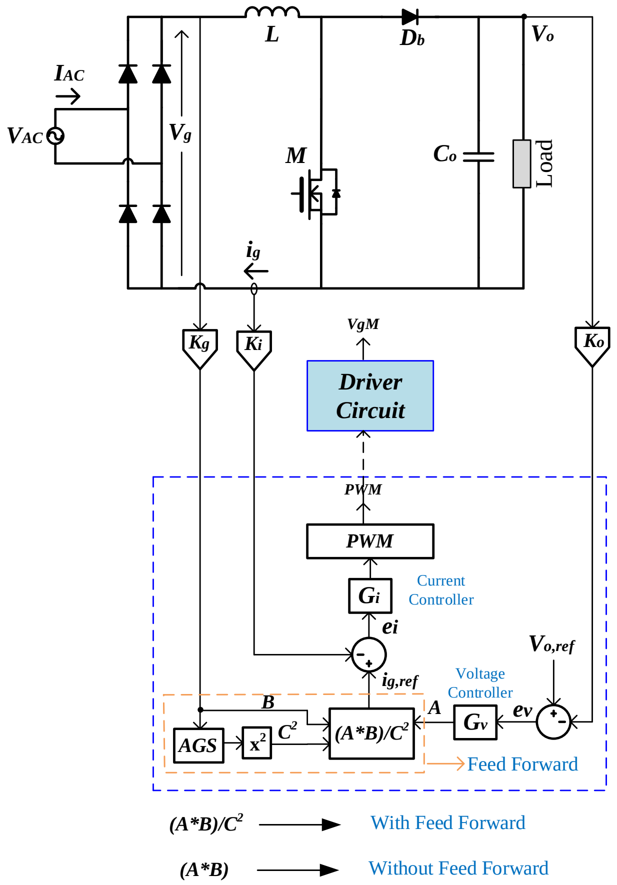

Figure 2. Controlled PFC based boost converter for UPS

The PFC control block as shown in Figure 2, consists of two PI controllers. One of them to fix the output voltage by comparing the circuit output voltage V_{out} and a reference voltage V_{ref} and the error of first PI will be multiplied with the input voltage V_{in}, to be compared with input current by second PI controller to find the delay angle in between input current and voltage, and finally both of PI controller correct the output voltage and input current shifting to get a nearly unity power factor and therefore reducing the input total distortion harmonics. In addition, feed forward controller block can be used to reduce the effect of input voltage dynamics.

The parameters of the control circuit are: Repeating sequence parameters; time value = [0 0.00002] = 50 KHz; Output value = [0 1]. The Voltage Reference: 400V, gain block (K_{out}) = 2.5/400 and K_{in} = 1/311.

Table 1. The parameters of the current controller for PFC boost

Parameter	Value
Time Domain	Continuous time
Proportional (P)	1.2998
Integral (I)	3164
Output saturation Limit / Upper saturation limit	0.98
Output saturation Limit / Lower saturation limit	0.02
I product/ Inherit via internal rule	Min. = -1 ; Max. = 1

The current PID controller compares output of voltage PI controller with main input current shape to find error of delay in between the inputs current and the voltage. The parameters of the current PI controller are shown in Table 1. The voltage PI controller compares the output voltage with the reference voltage and then sends errors to the current PI controller. The parameters of voltage PI controller are as in (Table 2). When the feed forward is used to reduce the effect of input voltage dynamics, the output of the feed forward block is multiplied with the output of the voltage controller to obtain current reference.

Table 2. The parameters of the Voltage controller for PFC boost

Parameter	Value
Time Domain	Continuous time
Proportional (P)	1.2881
Integral (I)	352
Output saturation Limit / Upper saturation limit	100
Output saturation Limit / Lower saturation limit	-100
I product / Inherit via internal rule	Min. = -10 ; Max. = 10

The PFC based boost converter directly provides 400 DC volt to the Isolated Buck converter. This voltage is too high for 24 V batter bus voltage, and normally buck converter couldn't step down the voltage with this ratio. Therefore, we should use an Isolated Buck converter with a high-frequency transformer. The circuit as shown in Figure 3, is consisting of four (MOSFET) as transistor switches, high frequency transformer with double winding, two diodes, inductor, capacitor and control circuit which content one PI controller, two sawtooth generators, and two relays.

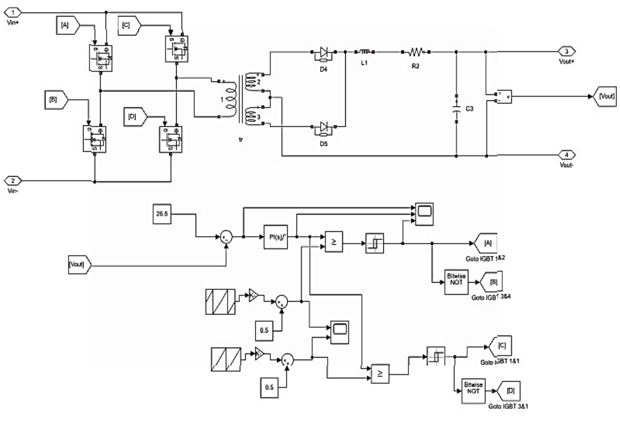

Figure 3. The Isolated Buck converter with control circuit

The output voltage of the isolated buck converter is compared with the reference voltage to fix correct the error of the output voltage through the duty cycle of the switches. The PI controller sends the pulse to all switches after correction of the output error. The parameters of elements in the isolated buck converter are given in Table 3. The parameters of PI controller and the high frequency transformer of Isolated Buck converter are also shown in Table 4.

The battery charging circuit consists of a control circuit, inductor L, and a diode. The control circuit of the charger is consisting of an ideal switch and a Relay. The ideal switch cut off the charging process to avoid overcharging of the batteries. The Inductor reduces the ripple of current through the charger to supply the battery with a smooth charging current. The parameters of the diode and the relay are listed in the.

Table 3. The parameters of Isolated Buck converter, PI Controller and High Frequency Transformer

Parameter	Value
Inductor (L)	2e3 H
Capacitor (C) with an initial voltage of 24V	470 e^{-6} F
PI controller: Time Domain	Continuous time
Source	Internal
Proportional (P)	0.15
Integral (I)	100
Output saturation Limit / Upper saturation limit	0.49
Output saturation Limit / Upper saturation limit	0.01
I product/ Inherit via internal rule	Min.= -1 Max.=1
Parameters of the High Frequency Transformer	
Nominal Power and frequency "P_n(VA) F_n(Hz)"	1000 20000
Winding 1 Parameter "V_1(V_{rms}) R_1(ohm) L_1(H)"	395 0 0
Winding 2 Parameter "V_2(V_{rms}) R_2(ohm) L_2(H)"	27 0 0
Winding 3 Parameter "V_3(V_{rms}) R_3(ohm) L_3(H)"	27 0 0
Magnetization resistance and inductance "R_m(ohm) L_m(H)"	Inf 0.001

The battery bank consists of two batteries lead-acid; each one is 12 Volt with 7 Ah. Both batteries will be connected in series to get 24 Volte and 14 Ah. When the AC main power source is available, the battery will be fully charged to be ready to supply the inverter in case of any main power supply interruption. The totally power of fully battery set is about 336 VA for an hour, but the UPS power is designed to supply a load with 800 VA, it means battery set have enough power to supply load for about 20 minutes. Parameters of the battery are as in Table 4.

Table 4. The parameters of the Battery of UPS system

Parameter	Value
Nominal Voltage	24 V
Rated capacity	14 Ah
Initial state charge	50%
Battery response time	10 mS
Discharge parameters of the Battery	
Maximum capacity (Ah)	14.5833
Cut-off Voltage (V)	18
Fully charged voltage (V)	26.1216
Nominal discharge current (A)	2.8
Internal resistance (Ohms)	0.0017143
Capacity (Ah) at nominal voltage	4.3439
Exponential zone "Voltage (V), Capacity (Ah)"	6.5 13 32.5

The output side of our UPS system is containing of three parts included a controlled Inverter, output Transformer, and a LC filter. The input port of the inverter is connected through a bypass switch with the battery set to supply the load in case of AC main source interrupting. The battery bus-bar voltage of the system is 24 Volts, it means the inverter will convert the battery set DC voltage to 24 AC voltages and then the Transformer will step up the voltage to 311 volts to supply the load through the LC filter. The filter will absorb noises coming from inverter switching and harmonics form nonlinear load.

The inverter consists of four similar IGBT switch transistors connected as H-bridge topology to invert 24 DC volt supplies from the battery to 24 AC volts and forward to the step-up transformer to provide the load through LC filter with 311 AC volts. The switching of the circuit will be controlled from a gate control circuit. The two input ports of the circuit are connected directly with the battery, and the two output ports connected directly with the output transformer. All IGBT switch transistors are similar and have parameters as: IGBT Internal Resistance R_{on} = 1mΩ; Snubber Resistance R_s =MΩ; Snubber Capacitance C_s = 1 nF.

The gate of the switch transistors gets duty cycle signal from Inverter controller to convert a DC voltage to an AC sinusoidal waveform voltage. The control circuit consists of a control loop block, PI controller, and saturation block.

The control loop circuit is responsible to create the duty cycle pulses for the gates of transistors of the inverter. The cycle frequency is generated by Sawtooth Generator with 20 KHz. The parameters of both circuit components are list in Table 5.

Table 5. Parameters of inverter controller

Parameter	Value
Inverter PI controller:	
Time Domain	Continuous time
Proportional (P)	25
Integral (I)	100
Output saturation Limit / Upper saturation limit	2.95
Output saturation Limit / Upper saturation limit	0.01
I product/ Inherit via internal rule	Min.= -3 ; Max.= 3
Sine wave Parameters:	
Amplitude	1
Bias	0
Frequency, rad/se	2P*50
Phase rade	0
Sample time	0
Saturation block	Upper limit = 2.5 / Lower limit = 1.5
Sawtooth Generator Parameters:	
Frequency	20 kHz

The output transformer steps up the inverter output voltage from 24 V to 311 V AC. It is also isolate the load from inverter switching noises. The output LC filter is to filter inverter switching noises and a current harmonics distortion occurs due nonlinear load. The parameters of LC filter are; Inductor (L) = 3 mH.; Resistor (R) = 10 µΩ; and Capacitor (C) = 1 µF.

3. RESULTS AND DISCUSSION

The proposed study has been verified via some simulation results which were obtained via Matlab/Simulink program. While all the results of the proposed system were observed, the main evaluation was focused on the results related feed forward for comparing the effect of input voltage dynamics.

The input voltage-current waveforms of the PFC based proposed system is given in Figure 4. It is seen that the current shape is sinusoidal, and it tracks the voltage shape. This due to the PFC controller. sine waves. The input current is around (8 A) by battery charging and full load, the input power factor is nearly unity, and the THD is less than 5% (3% to 4%) as required.

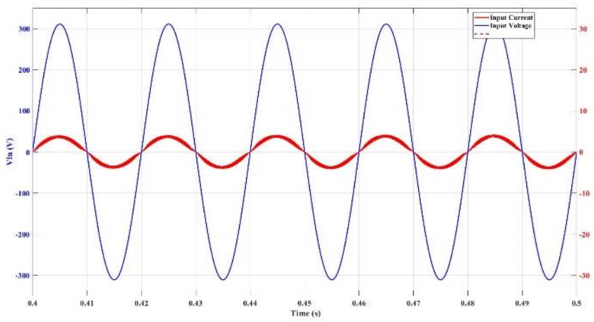

Figure 4. Input voltage-current waveforms of the UPS system

The input voltage-current waveforms of the proposed system based on feed forward are given in Figure 5 and Figure 6. While the Figure 5 shows input voltage-current waveforms with feed forward, the Figure 6 shows input voltage-current waveforms without feed forward. The effect of the feed forward is observed by changing the input voltage. The input voltage was changed from 220 V_rms to 110 V_rms. It is seen that the current shape tracks the voltage shape in a short time when the feed forward is applied.

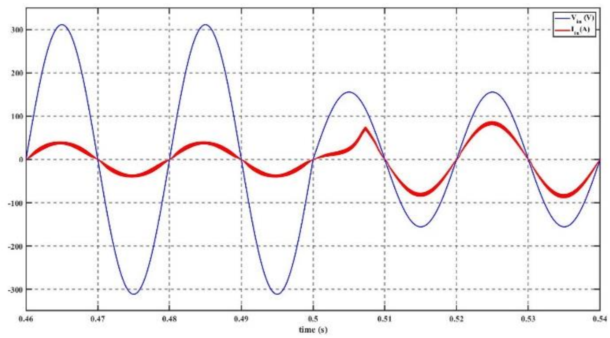

Figure 5. Input voltage-current waveforms with feed forward

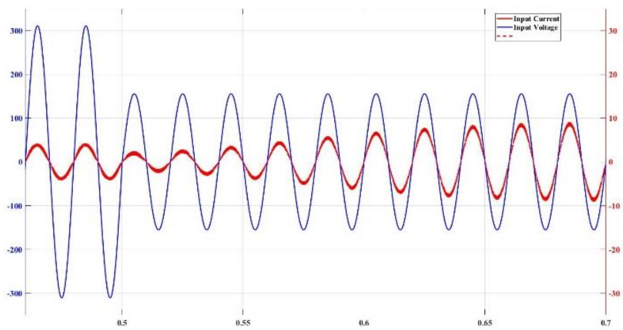

Figure 6. Input voltage-current waveforms without feed forward

The output voltage waveform of the boost PFC which is a part of the proposed system based on feed forward are given in Figure 7 and Figure 8. While the Figure 7 shows the output voltage waveform of the PFC with feed forward, the Figure 8 shows the output voltage waveform of the PFC without feed forward. The effect of the feed forward is observed by changing the input voltage. The input voltage was changed from 220 V_rms to 110 V_rms. It is seen that the ripple of the output voltage shape is lower when the feed forward is applied.

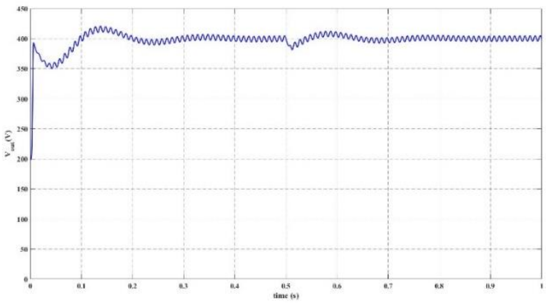

Figure 7. The output voltage waveform of the boost PFC with feed forward

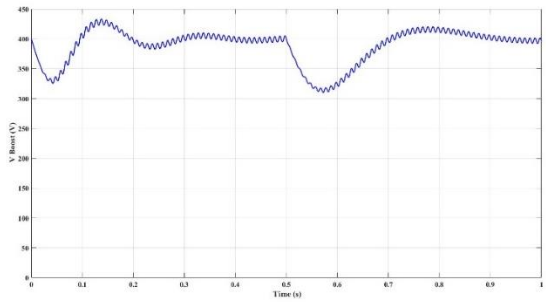

Figure 8. The output voltage waveform of the boost PFC without feed forward

The output voltage waveform of the isolated buck converter is fixed as required with a little ripple voltage as shown in Figure 9. The battery charger provides the power to the battery and charge the battery smoothly. The charging process is shown in Figure 10.

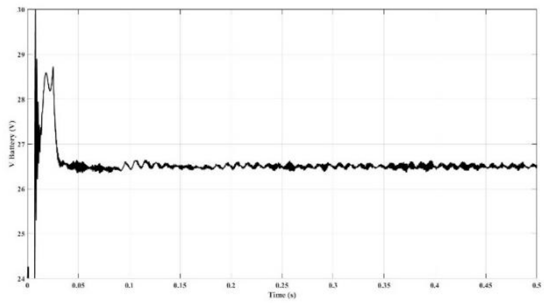

Figure 9. The output voltage of isolated buck converter

The second part of the UPS system is the inverter side. The inverter takes energy from the battery and converts 24 DC volts to 24 AC volts. Then it provides the step-up transformer directly to make 311 AC volts, and then the load will be supplied through the LC filter. The LC filter absorbs any noises or harmonics produced by the inverter switching process. Figure 11 shows the output waveform of the transformer and the output waveform of the system which is supplied to the load. The power factor of system outputs is nearly unity and the output THD ratio are less than 5% as required, by full load.

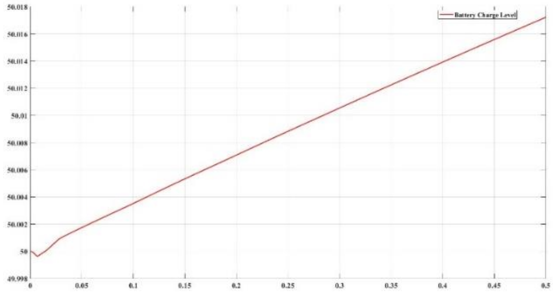

Figure 10. Battery charging process of the UPS system

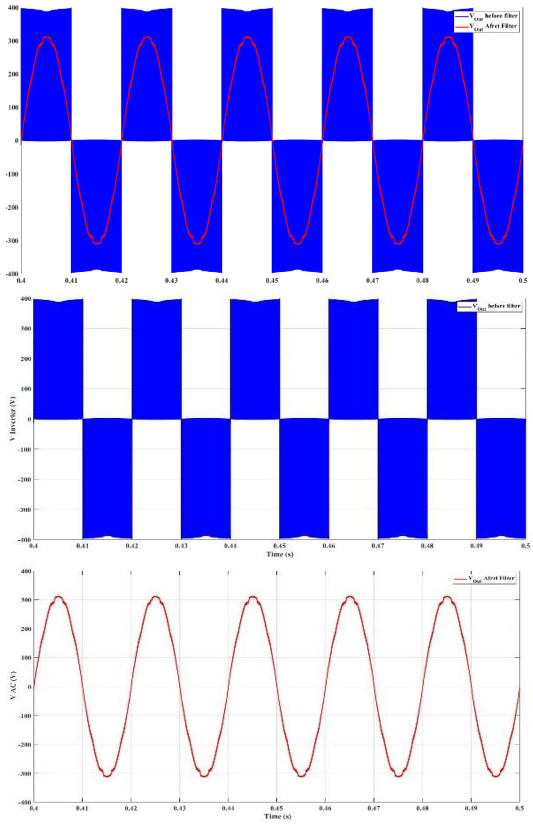

Figure 11. Output voltage waveforms of the proposed UPS

Table 6. The effects of feed forward

Outputs of the UPS System	With Feed Forward	Without Feed Forward
Input Line *THD* (%)	4.429	4.422
DC Output rise time	55 ms s	65 ms
DC output overshoot (%)	3.75	7.01
DC output undershoot (%)	4.75	21.75
PFC Output Voltage Ripple (%)	2.5	2.5
AC Current tracking time	8 ms	160 ms
Input Cos θ	1	1
Output Voltage *THD* (%)	2.96	2.91
Output *P* (VA)	1000	1000
AC Output Current	4.54	4.54
Output Cos θ	1	1

Table 6 shows the power factor and THD values in the case of using feed forward. It is seen that the THD in all cases still under 5%. However, it is seen that the input current reaches its steady-state value in a short time when the feed forward is applied. In addition, the feed forward affects the ripple of the output voltage shape. The ripple of the output voltage shape of the PFC is lower when the feed forward is applied.

4. CONCLUSIONS

Improving power factor and THD is important for any device and for the utility too. Using a boost type PFC converter with ACMC controller provides a good result of PF for the circuits and we achieved nearly unity of PF for design topologies, also the input current Harmonics and output THD are minimized to an extent (less than 5% for both sides). PFC based UPSs eliminate harmonics originating from the load and enable them to draw currents with high power factor ratio from the grid. PFC controllers with feed forward content are used to reduce the effect of input voltage dynamics in active PFC circuits. In this study, the effects of the feed forward PFC circuit on UPS were investigated. In the proposed study, Matlab/Simulink program was used, and the results obtained from here were evaluated. It is observed that the input current reaches its steady-state value in a short time when the feed forward is applied for the dynamic changes in the grid. In addition, the ripple of the output voltage of the PFC shape is lower when the feed forward is applied.

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BIOGRAPHIES

Ali Mamizadeh received his B.Sc. degree in Electrical Engineering from Sahand University of Technology, Tabriz, Iran in 2005. He received the M.Sc. and Ph.D. degrees in Electrical Engineering from Gazi University, Ankara, Turkey, in 2010 and 2016, respectively. His interests include power transformers, and power electronics.

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