Improvement of Power Quality by Using 28-Pulse AC-DC Converter

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Abstract

With the fast growing information technologies, high efficiency AC-DC front-end power supplies are becoming more and more desired in all kinds of distributed power system applications due to the energy conservation consideration for the Power Factor Correction (PFC). For improving power quality in terms of Power-Factor Correction (PFC), reduced total harmonic distortion at input ac mains and precisely regulated dc output in buck, boost, buck–boost and multilevel modes with unidirectional and bidirectional power flow. This paper presents a new 28-pulse AC-DC converter for enhancing the power quality at the point of common coupling, while feeding a medium capacity Switched Mode Power Supply (SMPS). It consists of two series connected 14-pulse AC-DC uncontrolled converters fed by seven phase-shifted ac voltages. The proposed converter is found capable of suppressing up to 27 harmonic currents in the ac mains. The power factor is also improved to near unity over a wide operating range of the SMPS.

Keywords

28-Pulse Ac-DC Converter, Phase-Shift Transformer, Multiphase, Thd, Smps, Power Quality, Power Factor Correction (PFC)

I. Introduction

Electric Power quality is a term which has captured increasing attention in power engineering in the recent years. The measure of power quality depends upon the needs of the equipment that is being supplied. Usually the term power quality refers to maintaining a sinusoidal waveform of bus voltage at rated voltage and frequency [1]. The waveform of electric power at generation stage is purely sinusoidal and free from any distortion. Many of the Power conversion and consumption equipment are also designed to function under pure sinusoidal voltage waveforms [1-3]. However, there are many devices that distort the waveform. These distortions may propagate all over the electrical network. In recent years, there has been an increased use of non-linear loads which has resulted in an increased fraction of non-sinusoidal currents and voltages in Electric Network. Classification of power quality areas may be made according to the source of the problem such as converters, magnetic circuit non-linearity, arc furnace and also in telecom power supplies or by the wave shape of the signal such as harmonics, flicker.

Power supplies connected to ac mains introduce harmonic currents in the utility. It is very well known that these harmonic currents cause several problems such as voltage distortion, heating, noise and reduce the capability of the line to provide energy. This fact and the need to comply with “standards” or “recommendations” have forced to use power factor correction in power supplies. Unity power factor and tight output voltage regulation are achieved with the very well known two stage approach. Since the power stage is composed by two converters, size, cost and efficiency are penalized, mainly in low power applications. However, this is probably the best option for AC-DC converters due to the following reasons.

1. Sinusoidal line current guarantees the compliance of any regulation.
2. It gives good performance under universal line voltage.
3. It offers many possibilities to implement both the isolation between line and load, and the hold-up time.
4. The penalty on the efficiency due to the double energy processing is partially compensated by the fact that the voltage on the storage capacitor is controlled. The fact of having a constant input voltage allows a good design of the second stage. Normally, a PFC circuits are realized by cascading a diode-bridge rectifier with either a single DC-DC converter or two DC-DC converters [4].

Many of power supplies used in telecommunication applications should have stiffly regulated output voltages and galvanic isolation. Many researchers have worked on providing a simple utility interface to these power supplies circuits and yet meeting voltage regulation requirements successfully [5]. In fact, multi-pulse converters have been used as an improved power quality utility interface in a variety of applications such as telecommunication power supplies, electric aircraft applications and variable frequency induction motor drives.

It is observed that an AC-DC converter with number of phases which is not multiple of three is effective in reducing the line current harmonics. A combination of multiphase and multi-pulse technique for input line current harmonic reduction for drive applications has been proposed in the literatures [6]. This paper proposes a new 28-pulse AC-DC converter which is a combination of both multiphase and phase staggering technique for medium capacity SMPS. The proposed auto connected transformer based AC-DC converter is based on multiphase technique that produces seven-phases from three-phase input supply. The advantages of the present converter approach are that it is inexpensive, reliable and energy-efficient. Moreover, the THD of ac mains current is low and the power factor is well improved. Fig.1 presents a schematic diagram of a medium capacity SMPS using a full-bridge converter that has a 6-pulse converter at the front end [6].

Fig. 1: Schematic Diagram of a 6-Pulse AC-DC Converter fed SMPS

In this paper, an auto connected transformer based 28-pulse AC-DC converter is presented to improve the power quality at the utility interface to achieve a power factor close to unity. A detailed analysis and design methodology of the proposed auto connected transformer based 28-pulse AC-DC converter is also included in
the following sections. The operation of the AC-DC converter at constant dc load current is investigated.

II. Structure of the Proposed System

Fig. 2 shows the overall system configuration. It is shown that the proposed auto connected transformer based 28-pulse AC-DC converter is feeding a 12kW SMPS load with the isolated full-bridge dc-dc converters. The proposed auto connected transformer secondary generates two sets of seven-phase voltage for the two seven-phase diode bridge rectifiers. The dc side of each seven-phase diode bridge rectifiers is connected to the isolated full-bridge dc-dc converters with a dc-link LC filter in between them. A DC link LC filter (Lf, Cf) is placed on each of the dc-links to filter out the harmonics which are multiples of 2nd order. The electrical isolation between the input-output is provided by the high frequency transformer.

Each transformer has two secondary windings, which are connected as shown in fig. 2. The secondary winding sides of the two high frequency transformers are connected in series to achieve DC link current balancing. Thus, rectified output voltage is the sum of the secondary voltages of high frequency transformers and each secondary voltage corresponds to its respective dc output voltage of each converter. The overall output voltage characterizes a two 14-pulse AC-DC converter output consisting of the sum of the two secondary winding voltages. Further, the stresses on the devices and the conduction losses in the diodes are reduced by choosing a center-tapped connection for the high frequency transformer. A Proportional-Integral (PI) controller regulates the DC output voltage and also provides gating signal to the isolated full-bridge DC-DC converter.

![Fig. 2: Block Diagram Representation of the Overall SMPS System Configuration](image)

III. Design of the Proposed 28-Pulse AC-DC Converter

The complete design and analysis of the proposed auto connected transformer based 28-pulse AC-DC converter is presented in this section. The AC-DC converter presented here is a combination of both multiphase and phase-staggering technique. In a multiphase system all the phases are distributed at same angle resulting in elimination of harmonics. In phase-staggering AC-DC converter technique, the phase angle displacement between AC supplies connected to bridges is given as,

\[ \text{Phase angle displacement} = \theta \]

No of six-pulse converters

Initially the design methodology of the proposed converter is carried out, and then analysis of the converter is performed to calculate the winding voltages and currents. Finally the auto connected transformer capacity is estimated from the winding voltages and currents which are explained in the following sections.

A. Design of an auto connected Transformer based 28-Pulse AC-DC Converter

Fig. 3(a) and (b) shows the winding and phasor diagram of the proposed auto connected transformer. The phasor diagram depicts the angular position of various phasor. It means that for a 12-pulse AC-DC converter of 30° and for an 18-pulse AC-DC converter of 20° is the phase displacement between the rectifier bridges. Similarly, if two seven-leg rectifier bridges are employed the phase staggering angle is considered as ((360°/14)/2) = 12.86°.

Therefore, two converters have a phase displacement of 12.86° between them. Thus, the phase angles of different phasor shown in Fig. 3b are given as \( \theta_1 = 6.43°; \quad \theta_2 = \theta_4 = \theta_9 = 38.57°; \quad \theta_3 = 05 = 08 = 12.86°; \quad \theta_6 = 10.71° \) and \( \theta_7 = 27.86° \). The two seven-leg diode bridge converters 1 and 2 are connected to two sets of seven-phase secondary winding output terminals of the auto connected transformer. The converters 1 and 2 have each seven sets of voltage as \( a', b', c', d', e', f', g' \) and \( a'', b'', c'', d'', e'', f'', g'' \) respectively. These two sets of converters are displaced by 12.86° from each other at -6.43° and +6.43° respectively from the input supply voltage of phase 'a'.

![Fig. 3: Winding and Phasor Diagram of Proposed Auto Connected Transformer Based 28-Pulse AC-DC Converter](image)

B. Analysis of an Auto Connected Transformer

A systematic analysis of winding currents, voltages is carried out to calculate the magnetic rating of the auto connected transformer based 28-pulse AC-DC converter in this section. Fig. 4 shows the circuit schematic used for the analysis. In this analysis some assumptions made to obtain the equations and values of the winding voltage/currents.

1. Input ac mains voltages are balanced.
2. Output dc current is ripple-free.
3. Current distribution between the two seven-phase diode bridges is equal.

C. Seven-Phase Diode Rectifier

The 14-phase voltages produced by the auto connected transformer are the inputs for the two seven-phase diode bridge rectifiers. The two sets of dc voltages produced by the diode bridge rectifier are also having a phase shift of ±6.43° between them. Further, it is observed the ‘a’ phase of converter-1, that is current Ia’ exists for a period of \( 2\pi/7 \) having a magnitude of Idc/2 starting from a period of \( 5\pi/14 \). The remaining other six phase currents of converter-1 have identical magnitudes of Idc/2 starting from la’ by a further delay of \( 2\pi/7 \) sequentially. The diode bridge rectifier currents ia’ and ia’.

![Fig. 4: Circuit Schematic of the Analysis System](image)
D. THD of Input Line Current

The input line current harmonics of the proposed 28-pulse auto connected transformer can be calculated by the relationship between the rms value of the input line current and the rms value of the fundamental frequency component. These values are obtained by analyzing the input line current (\(i_{ia}\)) waveform. Using the rms value of the input line current (\(I_{ia, rms}\)) is calculated from quarter wave symmetry as,

\[
I_{ia, rms} = \sqrt{\frac{2}{\pi} \int_0^{\pi/2} i_{ia}(t) \, d(\omega t)}
\]

The input line current has quarter wave symmetry. Hence all the even harmonics are absent and the cosine term in the Fourier series expansion is zero. Thus, the magnitude of the fundamental frequency component of the input line current (\(I_{1ia, max}\)) is calculated as:

\[
I_{1ia, max} = \left(\frac{4}{\pi}\right)^{\frac{1}{2}} \int_0^{\pi/2} i_{ia} \sin(\omega t) \, d(\omega t)
\]

The Total Harmonic Distortion (THD) of the input ac mains current is obtained as:

\[
\%_{THD} = \frac{\sqrt{I_{ia, rms}^2 - I_{1ia, rms}^2}}{I_{1ia, rms}} \times 100
\]

IV. Matlab/Simulink Modeling and Simulation Results

Here the simulation is carried out by two cases
1. Traditional 6-pulse AC-DC converter fed SMPS.
2. Proposed 28-pulse AC-DC converter fed SMPS.

Case 1: Traditional 6-pulse AC-DC converter fed SMPS:

![Fig. 4: Matlab/Simulink model of Traditional 6-pulse AC-DC converter fed SMPS](image1)

Fig. 4 Shows the Matlab/Simulink model of traditional 6-pulse AC-DC converter fed SMPS.

![Fig. 5: Simulated Waveforms of (a) Input Voltage (b). Input current, (c). DC- Link Voltage, (d). Current, (e). Output Current, (f). Output Voltage of 6-pulse AC-DC Converter fed SMPS](image2)

Fig. 5 Shows the Simulated waveforms of input voltage, input current, dc-link voltage/current, output current and output voltage respectively of traditional 6-pulse AC-DC converter fed SMPS.
Case 2: Proposed 28-pulse AC-DC Converter fed SMPS:

Fig. 6: THD Analysis of Phase A Source Current
Fig. 6 Shows the THD Analysis of Phase A Source Current, source current was distorted due to power electronic circuits, we get THD value is 26.60%.

Fig. 7: Matlab/Simulink model of proposed 28-Pulse AC-DC Converter fed SMPS
Fig. 7, Shows the Matlab/Simulink model of proposed 28-pulse AC-DC converter fed SMPS.

Fig. 8: Simulated Waveforms of Input Voltage, Input Current, DC-Link Voltage, DC Link Current, Output Current and Output Voltage of 28-Pulse AC-DC Converter fed SMPS.
Fig. 8 Shows the simulated waveforms of input voltage, input current, dc-link voltage, dc link current, output current and output voltage, respectively of proposed 28-pulse AC-DC converter fed SMPS.

Fig. 9: THD Analysis of Phase A Source Current of proposed 28-pulse converter
Fig. 9 Shows the THD Analysis of Phase A Source Current of proposed 28-pulse converter, source current was sinusoidal or undistorted due to increasing of pulse generation so, we get THD value is 2.35%.
V. Conclusion

A new auto connected transformer based proposed 28-pulse AC-DC converter has been presented. The behaviour of the converter is studied in MATLAB based simulation under various load conditions and also for varying leakage reactance of the auto connected transformer. The input ac mains current THD has been found less than 6% in the complete range of varying loads, with a power factor close to unity which meets the requirements of IEEE-519 standard. The observed performance of the 28-pulse AC-DC converter has demonstrated its potential to improve the power quality indices at ac mains in terms of THD of supply current and power factor. The THD value improves in 28 pulse conversion system compared to conventional converter, in conventional converter we get THD value is 26.60% and in proposed converter the THD value is 2.35%, As per IEEE standards THD value is less than or equal to 6% and improve the power quality terms.

References


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