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An Energy Storage Integration Circuit for Improving AC Line Condition Applied in the 18-Pulse Converter System

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Abstract:

In this paper, a new compensation strategy for receiving clean power of a conventional 18-pulse ac/dc converter formed by three 6-diode bridges is proposed. According to the proposed strategy, a three-phase current-controlled inverter injects the compensation currents into the three positive terminals of the three six diode bridges. The goal of injecting currents at dc side is to improve the quality of the ac line currents. Compared to the conventional active filter deployed at the ac side, the three-phase inverter used in this paper is with lower kVA rating, and the 18-pulse converter draws nearly sinusoidal currents from the ac main by the proposed compensation strategy.

The theoretical compensation command is derived in this paper, and then an approximate approach is recommended to simplify the calculation. A digital-signal processor is employed as a digital controller to calculate the compensation command, and a 3-kW prototype including the 18-pulse converter and the current-controlled inverter is built for evaluation and measurement. Moreover, the performance affected by unbalanced ac source is investigated. The experimental results demonstrate that the proposed method not only improves the line current quality but also mitigates the effects caused by unbalanced source voltage.

INTRODUCTION:

In high electric power conversion applications, single-phase or three-phase full-bridge rectifiers have been the most popular converter as the first stage connected to the utility. Unfortunately, these rectifiers drew non sinusoidal currents from the utility and led to harmonic pollution on the grid. To regulate these problems and maintain power quality, some recommended standard which listed the acceptable distortion levels for different utilities, were published for industry to follow. Many strategies and topologies have been proposed to deal with these problems so as to meet the requirement of the standards.Among them, multipulse schemes played an important role due to their reliability, compactness, and effectiveness. Another advantage of multipulse methods was that they could only be implemented by uncontrollable semiconductor devices, i.e., diodes.The basic configuration of multipulse ac/dc converters is to connect multiple rectifier bridges together, either in parallel or in series at the dc side, so that some lower order characteristic harmonics produced by one rectifier can be canceled by other rectifiers.Thus, in practical situation, multipulse transformers always accompanied to provide the phase-shifted power supplies for the multiple rectifiers. Also in multipulse transformers with different configurations were introduced and investigated. Moreover, in parallel multipulse methods, an interphase transformer (IPT) was needed at the dc side to average the output voltage of each rectifier.To improve line current quality further, some modified IPTs cooperated with semiconductor switches were proposed. An IPT with taps connected to thyristors was proposed to improve line condition of an 18-pulse converter system by trigging the thyristors at predetermined angles.

Then, similar strategy was proposed with replacing thyristors by diodes . Although the performance of the latter was not better than the former, it promised the advantages of reliability, simplicity, and cost effectiveness. However, the improvement in line current conditions by these multitaped IPT methods was limited. , an ac-side current injection mechanism was proposed to improve the line conditions of a three-phase diode bridge.The main advantage was only passive elements were used to achieve the control goal. Although the performance could compete with 18-pulse converter, the total harmonic distortion of line currents was highly dependent on the output load with high THDi at low load.The input current shaping method was proposed for a 18-pulse rectifier, in which a line IPT was deployed at the ac side and two single switch boost-type switching-mode rectifiers were parallel at the dc side. Both sinusoidal input currents and output-voltage regulation were achieved through complex control scheme.

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The concept of an active IPT was first proposed in 18-pulse converter, which improved the line quality by injecting compensation current into the extra winding of the IPT with a low kilovolt-ampere rating inverter. However, the control strategy used in only improved one phase line current of the three-phase source while the other two phase line currents were still highly distorted. In another active IPT, which resulted in balanced line currents with improved quality, was proposed in a 24-pulse converter system. Moreover, the performance of different load arrangement was investigated and discussed as well. It has to be noted that,the active IPTs configured extra windings for injecting the compensation currents. Thus, the IPTs in the original multipulse converters had to be replaced by IPTs with extra windings.

A dc-side injection method applied to a conventional 18-pulse converter was proposed in an earlier version of this paper, in which the ac main currents were improved by directly injecting the compensation currents into three positive terminals of the three six-diode modules. The term “directly injecting” means that the proposed method provided the compensation currents without modifying any parts of the 18-pulse converter, even the IPT.

However, the paper did not investigate the performance of the compensation strategy under unbalanced power supply. Following the concept in this paper proposes a strategy to improve the line condition of a conventional 18-pulse diode converter by injecting compensation currents at the dc side of the converter and the performance of the proposed scheme under unbalanced source is investigated through the experimental results. Availability of reliable and inexpensive semiconductor devices has led to numerous power electronics intensive industrial loads requiring dc power supply for operation. When a number of dc-powered loads are in proximity, it becomes viable for them to share a common dc bus.

Many such systems benefit from local dc storage to perform the following: 1) reduce the power demand from the grid; 2) provide backup power; and 3) store locally generated renewable power rather than feeding it back to the grid. Local dc distribution has been considered for data centers dc-level plug-in vehicle charging stations more electric ships, and aircrafts. The 18-pulse rectifier is a common, simple, and cost effective method to provide a stable dc supply while at the same time minimizing the grid-side harmonics.

The 18-pulse rectifier is a good tradeoff between harmonic reduction and subsystem complexity and is commonly used in the industry. However, the 12-pulse rectifier alone does not sufficiently reduce the ac harmonics to a level prescribed by relevant standards. A standard way to eliminate ac-side harmonics is to use active, passive, or hybrid power filters . Although these methods are well understood and widely used, passive filters are bulky, while active filters require complex control and specialized power electronics. An alternative method controls n the current draw from the dc side so as to minimize the ac harmonics. Researchers have shown that, for the 18-pulse rectifier, the ac-side harmonics are minimized by shaping the two six-pulse rectifier output currents to be triangular and out of phase. The resulting total harmonic distortion (THD) is as low as. In the researchers exploit this property; while effective at reducing the harmonics, the circuitry used to shape the current is placed in path of the load current, resulting in substantial VA rating. Furthermore, the proposed approaches in are only effective for continuous rectifier currents and are not capable of dc storage integration.

In this paper, we propose a new method of profiling the dc-side rectifier current by using current sources placed in parallel with each six-pulse rectifier bridge to inject current and shape the rectifier output current. The method is simple to implement and makes use of standard series-connected isolated gate bipolar transistor or metal oxide semiconductor field-effect transistor (MOSFET) modules. The property of the resulting current sources is that they are able to deliver power to the load, allowing for the integration of an energy storage system on the dc side. The VA rating required to profile the current is substantially reduced by a proper choice of the dc-side LC filter parameters. The remainder of this paper is organized, we review the proposed methods for harmonic reduction by shaping the rectifier output curren, we establish the proposed harmonic reduction topology and control strategy. We present simulation and experimental results and close with conclusions in Section.

Active power filters:

An explosive growth in consumer electronics and domestic appliances has generated a major concern in the electricity supply industry,. Due to its interface circuit (a diode bridge, followed by a large DC capacitor), these appliances draw current only near the peak of the mains voltage.

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Like this circuit other power electronics based applications draw non-sinusoidal currents, despite the applied voltage being sinusoidal. Due to the non-ideal characteristics of the voltage source, harmonic currents create voltage distortion. Non-linear loads such as rectifiers, cyclo converters, variable speed drives and arc furnaces, large decaying DC components, asymmetrical loads and other electrical equipment can cause high disturbances in the power supply system. The harmonics generated by the most common non-linear loads have the following properties: • lower order harmonics tend to dominate in amplitude; • if the waveform has half-wave symmetry there are no even harmonics; • harmonic emissions from a large number of non-linear loads of the same type will be added. The major problems caused by the mains harmonic currents are those associated with the harmonic currents themselves, and those caused by the voltage waveform distortion resulting from the harmonic currents flowing in the supply source impedance. This distortion of the voltage waveform can cause, e.g. serious effects in direct on-line induction motors, ranging from a minor increase in internal temperature through excessive noise and vibration to actual damage; electronic power supplies may fail to operate adequately; increased earth leakage current through EMI filter capacitors due to their lower reactance at the harmonic frequencies. To minimize these effects in electricity distribution systems (non-sinusoidal voltages, harmonic currents, unbalanced conditions, power de-rating, etc) different types of compensators have been proposed to increase the electric system quality,one of those compensators is the active power filter This Chapter is organized as follows, it is presented a brief review of power quality and harmonic emission standards, addresses main active filter topologies, control methods and performance indexes. It is developed a prototype of an APF for demonstration purposes, including the operating principle of the current controlled filter and includes the design of the filter's passive elements. Simulation and experimental results in different operating conditions are presented , including performance evaluation. It discusses conclusions related to the presented work and indicates some future research needed in this area.

Power quality and harmonic emissions standards:

With the increased use of electrical and electronic equipment, and telecommunication and broadcasting transmissions the electromagnetic spectrum is becoming saturated. The equipment within residential, commercial or industrial installations has become increasingly sensitive to some type of electromagnetic interference (EMI) both from internal or external sources, primarily because of the use of digital technology. So there is a need for control of electromagnetic environment, namely by limiting of the harmonic emissions caused by any type of electrical or electronic equipment. In the European Union, this problem has been addressed by the Directive 2004/108/EC - the Electromagnetic Compatibility Directive; in the United States the main guideline comes from the IEEE Standard 519. The EMC Directive incorporates standards mainly from the CISPR, the CENELEC, and the IEC organizations. The standards assist in achieving adequate power quality and in controlling it. They provide a framework within which the electricity distribution network environments, the susceptibility of equipment to low voltage quality, and the emissions from different types of equipment are all defined. Examples of standards relating to power quality characteristics and measurements are the EN 50160, the IEC 61000-4-30 and the IEEE Standard 1159.

The purpose of the EN 50160 standard is to specify the characteristics of the supply voltage with regard to the course of the curve, the voltage level, the frequency and symmetry of the three-phase network at the interconnecting point to the customer. The goal is to determine limiting values for regular operating conditions. However, facility defects may lead to major disturbances in the electricity distribution supply network. The complete breakdown of the network can no longer be described efficiently by limiting values. Thus there is no point in indicating actual limiting values. Accordingly, the standard establishes just these values as limiting values, which are not allowed to be exceeded or remained under during 95% of the controlled period. Rather than being an EMC standard the EN 50160 is a product standard giving the voltage characteristics which can be expected at the supply terminals.

The EN 50160 standard is becoming a kind of reference for what should be seen as good power quality. Like the EN 50160, the IEC 61000-4-30 and the IEEE 1159 are the first standards that define the characteristics of voltage waveform as obtained from measurements. The power quality parameters considered are grid frequency, magnitude of the supply voltage, flicker, supply voltage dips and swells, voltage interruptions, transients over voltages, supply voltage unbalance, voltage and current

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harmonics, voltage inter-harmonics and mains signalling on the supply voltage and rapid voltage changes. Depending on the purpose of the measurement, all of the phenomena on this list may be measured, or a subset of the phenomena on this list may be measured. It is in this scenario of voltage/power quality issues related to the grid connection of electric/electronic loads or sources that the APF is an important player.

APF control methods and performance
APF topologies

In some industrial and commercial applications, electric power is distributed through three phase four-wire systems. With incorrectly distributed or uncompensated loads such systems may suffer from excessive neutral currents caused by non-linear or unbalanced loads. In such conditions, a three-phase four-wire active filter can provide harmonic neutralization, (Aredes et al., 1997, Montero et al., 2007). The main converter topologies for three-phase four wire active power filters are the conventional three-leg converter with neutral point connection in the DC bus and the four-leg converter; the fundamental difference between them is the number of power semiconductor devices. In some conditions, even in three phase installations, single-phase compensation can be advantageous. In such cases, the single-phase shunt active filter is often used, (Komurcugil&Kruker, 2006). However, three-phase systems without neutral conductor are more general and will be the object of the present work.

Control methods and strategies:

Different approaches such as notch filter, (Newman et al., 2002), scalar control, (Chandra et al., 2000), instantaneous reactive power theory, (Furuhashi et al., 1990, Akagi et al., 2007), synchronous detection method, (Chen et al., 1993), synchronous d–q frame method, (Mendalek et al., 2003), flux-based control, (Bhattacharya et al., 1996), and closed loop PI, (Bhattacharya et al., 1996), internal model control, (Marconi et al., 2007), and sliding mode control, (Saetieo et al., 1995), can be used to improve the active filter performance. Also, the direct power control method has found application in active filters, (Chen &Joós, 2008). Specific harmonics can be cancelled out in the grid using the selective harmonic elimination method (Lascu et al., 2007). In all cases, the goal is to design a simple but robust control system for the filter. Usually, the voltage-source is preferred over the current-source to implement the parallel active power filter since it has some advantages, (Routimo et al., 2007). Using higher voltages in the DC bus is desirable and can be achieved with a multilevel inverter (Lin & Yang, 2004). In this Chapter it is used the voltage-source parallel topology, schematically shown in Fig. 1.

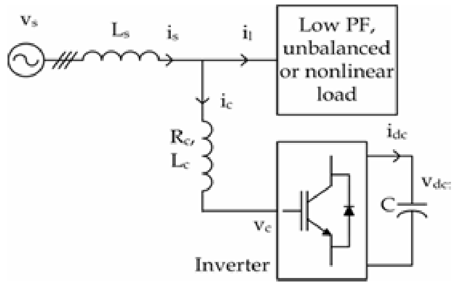

Fig1: Connection diagram of a voltage source active power filter

The filter generates currents in the connection point in order to: 1- cancel/minimize the harmonic content in the AC system, 2- correct the power factor at fundamental frequency, 3- regulate the voltage magnitude, and 4- balance loads. So, the AC distribution system only carries the active fundamental component of the load current. Very different current control algorithms can be applied to the active filter, (Akagi, 2005).

The current reference for the active filter connection node usually satisfies one of the two following strategies: 1- power factor correction, harmonic elimination, and load unbalance compensation or, 2- voltage regulation, harmonic elimination, and load unbalance compensation. The voltage regulation strategy is a concurrent objective faced to the power factor compensation because the two depend on the reactive current. However, any control algorithm has enough flexibility to be configured, in real-time, to either objectives or for the two, in a weighted form.

Even under the same compensation strategy, the filter can be controlled with different control algorithms. Two main approaches are common: voltage control, and current control. Both methods have advantages and weaknesses. In Fig. 2 it is represented a block diagram, with the variables shown in Fig. 1, of a voltage-based control algorithm of an active power filter implementing vector control.

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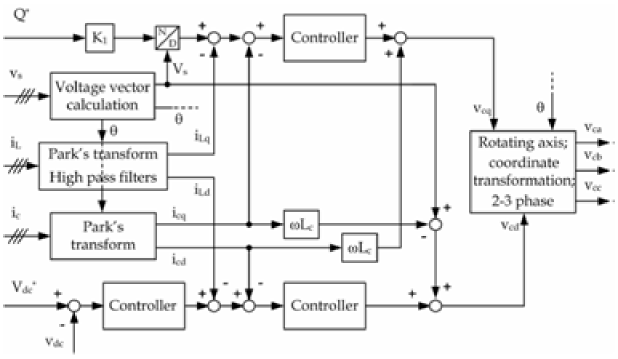

Fig2. Voltage control of the active power filter

In the presence of the power quality concern the mains current is the most important variable to be controlled. This method indirectly controls the mains current through the filter output voltage. In Fig. 3 it is shown a block diagram of a current-based control algorithm of an active power filter also capable of implementing different compensation strategies. This control method directly controls the mains current through the is Ref signals. However, it has slower dynamics than the voltage-based method (Chandra et al., 2000).

A static power converter, like the one shown in Fig. 1, capable of doing (almost) all the above referred functions is necessarily very complex. This complexity arises from the following considerations: • the converter dynamic behavior must be very fast in order to be capable of compensate currents in a large spectra, • the control algorithm must deal with a large number of variables such as mains voltages and currents, load currents,

DC voltage and current, and • high dynamic performance and better active and reactive power decoupling can demand direct and inverse coordinate transformation and a large amount of signal processing. So, fast power electronics semiconductors, with high switching frequencies, and powerful control platforms are needed to build this type of power electronics systems.

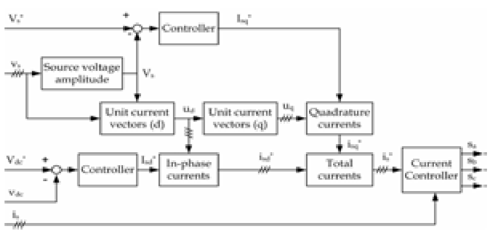

Fig3:Current control of the active power filter

Dc side current injection method:

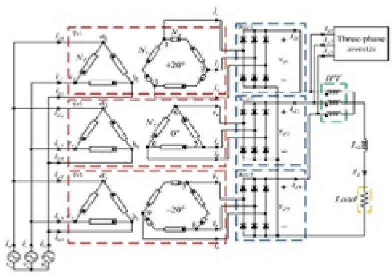

Fig 4:Scheme of the proposed injected method applied to an 18-pulse converter

In fig 4, the proposed scheme, which includes a set of multipulse transformers, three six-diode bridges, a threewinding IPT, and a three-phase current-controlled inverter. Th-set of multipulse transformers, including one delta–delta connection and two delta-polygon connections, provide three threephase sources for the three diode bridges with +20◦, 0◦, and –20◦ phase shift, respectively. It has to mention that even the delta-polygon connection are used in this paper, other isolated connections with identical phase shift also can be used in the proposed scheme, such as delta-fork connection .

The secondary sides of the three phase-shift transformers, denoted as Tr1, Tr2, and Tr3, connect to the three diode bridges, denoted as Rec1, Rec2, and Rec3, respectively. Then, all the negative terminals of the diode bridges connect together whil the three positive terminals connect to the three noncommon terminals of the IPT, respectively. The three output terminals of the three-phase current-controlled inverter directly connect to the three noncommon terminals of the IPT.

The inverter injects the compensation currents into these terminals according to the proposed strategy that leads to nearly sinusoidal ac line currents and will be detailed in next section. Through the direct connection, the proposed scheme can adapt easily to an existing 18-pulse converter system without any modification. Moreover, when the inverter is disconnected from the proposed system, the18-pulse converter still can resume it original performance

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Energy Storage Integration Circuit:

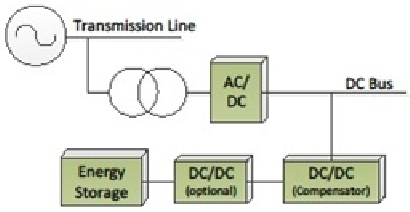

Fig 5:Proposed DC distribution system with energy storage integration and harmonic elimination

In this circuit, a new approach is proposed, to integrate energy storage and eliminate AC side harmonics, as depicted in Figure 3.8. The novelty is that the same DC/DC converter/compensator is used to integrate the energy storage, eliminate DC side ripple, and eliminate AC side harmonics. While the first two functions are considered the state of the art, the challenge is to use DC side compensator to eliminate AC side harmonics. It has been proposed to shape the rectifier output current in order to eliminate the AC harmonics. They generally rely on directly shaping the rectifier current or on inserting a voltage source between the capacitor bank and the rectifier . In the authors propose to directly shape the rectifier output current by the use of active switches to directly control the rectifier output current Since the entire rectifier output current has to be processed by the active switches, this method is not very efficient.

.INTRODUCTION TO MATLAB:

MATLAB is a software package for computation in engineering, science, and applied mathematics.It offers a powerful programming language, excellent graphics, and a wide range of expert knowledge. MATLAB is published by and a trademark of The Math Works, The focus in MATLAB is on computation, not mathematics: Symbolic expressions and manipulations are not possible (except through the optional Symbolic Toolbox, a clever interface to maple). All results are not only numerical but inexact, thanks to the rounding errors inherent in computer arithmetic. The limitation to numerical computation can be seen as a drawback, but it's a source of strength too: MATLAB is much preferred to Maple, Mathematical, and the like when it comes to numerics. On the other hand, compared to other numerically oriented languages like C++ and FORTRAN,MATLAB is much easier to use and comes with a huge standard library.1 the unfavorable comparison here is a gap in execution speed.

This gap is not always as dramatic as popular lore has it, and it can often be narrowed or closed with good MATLAB programming (see section 6). Moreover, one can link other codes into MATLAB, or vice versa, and MATLAB now optionally supports parallel computing. Still, MATLAB is usually not the tool of choice for maximum-performance Computing.

The MATLAB niche is numerical computation on workstations for non-experts in computation. This is a huge niche—one way to tell is to look at the number of MATLAB-related books on mathworks.com. Even for supercomputer users, MATLAB can be a valuable environment in which to explore and fine-tune algorithms before more laborious coding in another language. Most successful computing languages and environments acquire a distinctive character or culture.

In MATLAB, that culture contains several elements: an experimental and graphical bias, resulting from the interactive environment and compression of the write-compile-link-execute analyze cycle; an emphasis on syntax that is compact and friendly to the interactive mode, rather than tightly constrained and verbose; a kitchen-sink mentality for providing functionality; and a high degree of openness and transparency (though not to the extent of being open source software).

The fifty-cent tour:

When you start MATLAB, you get a multipaneleddesktop. The layout and behavior of the desktop and its components are highly customizable (and may in fact already be customized for your site). The component that is the heart of MATLAB is called the Command Window, located on the 1Here and elsewhere I am thinking of the "old FORTRAN," FORTRAN 77. This is not a commentary on the usefulness of FORTRAN 90 but on my ignorance of it.

SIMULATION AND EXPERIMENTAL RESULTS:

Two systems are presented in this paper: We analyze a large industrial 1-MVA system and validate the proposed concept on a smaller experimental setup. The main limitation of the experimental setup is the high leakage inductance and the high ESR of the transformer.

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A. Simulation Results:

We model the 1-MVA rectifier using Sim-Power-Systems Toolbox in Simulink. The specifications of the setup are given in Table I. The LC filter ESR is optimized according to (10) to give the minimum current source VA rating at RL= 0.5 Ω (with RL= 0.37 Ω corresponding to full load resistance).To assess the required current source ratings, we subtract the actual rectifier current from the ideal triangular waveform. Simulation results summarized in Fig. 11 show that the rms current of current source normalized by the load current reaches a minimum at RL= 0.54 Ω which is close to the designed value of RL= 0.5 Ω. The small difference comes from the omission of higher order harmonics in the original analysis and neglected.

B. Experiment Results:

A small-scale experiment setup is built to verify the functionality of the proposed system. The specifications of this setup are given in Table II. The three-phase transformer consists of three single-phase transformers (VPT48-10400), and the secondary windings are rewound to get the desired voltage level. The 12-pulse diode rectifier consists of two three-phase diode bridges (SC50VB80). Two inductors are connected in series to get Lf . The filter inductors were hand wound around a ferrite E80 core. The MOSFETs used for the buck-and-boost converters are IXFH40N50Q2. We used the TDS5034B oscilloscope from Tektronix and associated measurement and analysis software to capture the experimental waveforms and perform power quality analysis.Experimental setup.

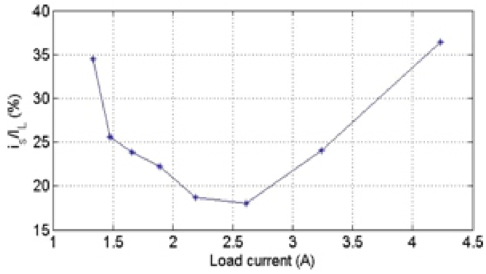
TABLE-I: PARAMETERS OF THE AC/DC RECTIFIER FOR EXPERIMENT

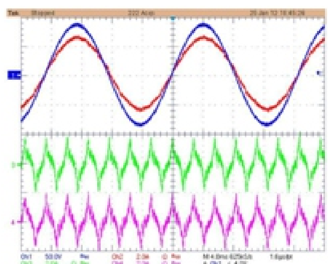
PARAMETER	VALUE
Output power	270 W
Transformer primary voltage (L-L RMS)	60 V
Transformer secondary voltage (L-L RMS)	25 V (two in series)
Transformer leakage inductance	0.3 mH
ESR of upper/lower transformer (equivalent)	(0.28/0.31)Ω
DC-side inductor (L_{f1},L_{f2})	2.6 mH
Rectifier output capacitor (C_{f1},C_{f2})	66 μF
ESR of L_{f1}/ C_{f1}/ L_{f2}/ C_{f2}	(0.52/0.015/0.48/0.015)Ω
Buck-and-boost switching frequency	20 kHz
Buck-and-boost DC link voltage	130 V
Buck-and-boost output filtering inductor	2 mH

The experiment setup has some limitations. First, based on the analysis , the setup requires a high current injection from the current sources due to the relatively high leakage inductance and ESR of the transformers. The experimentally obtained waveforms with and without the compensation current when the load current ILis 4.2 A.

The compensation currents is1and is2at the same load. The improvement of the line currentharmonic level is apparent: The THD drops from 4.60% to 2.41%. The magnitude of each harmonic is plotted . It is interesting to note that even the initial harmonics are fairly low and much lower than for the 18-pulse rectifier with LC filter design for dc ripple minimization. This is due to the choice of the LC filter that amplifies the 360-Hz harmonic in the current. The results show that the rectifier current is successfully shaped into the triangular form.Further comparisons are shown,with different load conditions. The proposed method is effective at reducing the harmonics in the input line current even as the rectifier output current is becoming discontinuous.

The VA rating of the current sources at different load conditions . It can be seen that the optimized point (where the VA rating is minimized) is when the load current is 2.6 A (with load resistance as 25 Ω). On the other hand, according to (7) and (8) and Table II, the calculated optimal point is when the load resistance is 22 Ω. The VA rating is relatively high because of the high leakage inductance and ESR of the transformer. According to the current flow analysis described in the previous section, we can see that, for the filter parameters from Table I, only 57.1% and 56.1% of thecompensation current goes through loop I. Therefore, almost half of the compensation current goes toward reducing the LC filter current rather than toward shaping the rectifier current into the triangular reference.The active power injection function of the current source is3 is also verified in experiment. A dc source is connected





Ch1: line voltage (phase A), 50V/Div Ch2: line current (phase A), 2A/Div
Ch3:i_{s1}, 2A/Div Ch4: i_{s2}, 2A/Div

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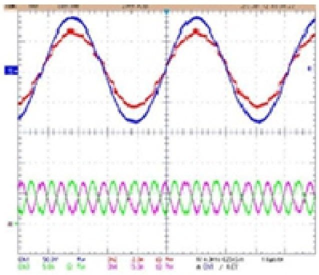
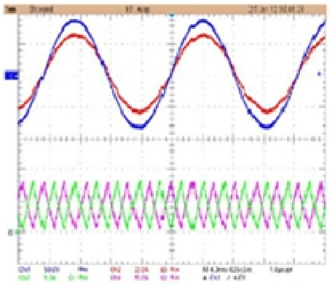
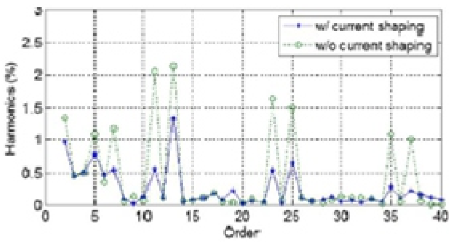


Ch1: line voltage (phase A), 50V/Div Ch2: line current (phase A), 2A/Div
Ch3: i_{uc1}, 5A/Div Ch4: i_{uc2}, 5A/Div
(a)



Ch1: line voltage (phase A), 50V/Div Ch2: line current (phase A), 2A/Div
Ch3: i_{rec1}, 5A/Div Ch4: i_{rec2}, 5A/Div
(b)



CONCLUSION:

This paper proposed a dc-side compensation strategy to improve the line current condition of an 18-pulse converter system formed by three six-pulse rectifiers. A three-phase current controlled inverter injects the compensation currents into the positive terminals of the three rectifiers to improve the quality of the ac source currents. The compensation strategy was analyzed and the injection commends were derived in this paper. An approximate method was recommended to simplify the calculation. The investigation of the performance under unbalance conditions showed that the proposed converter was able to mitigate the current UBFs which were proved by experimental results. It has to be noted that the quality of the ac currents of each rectifier was worse than the conventional when applied the proposed method. Nevertheless, the overall ac line currents were nearly sinusoidal and the current unbalance can be mitigated under unbalanced source. The design criteria of the major components were given for applications.

The proposed method only needs a rather low rating (2.4%) three-phase inverter and when the inverter is disconnected, the proposed system still can work as a conventional 18-pulse converter properly. A DSP based digital controller was employed to calculate the current commands and inject the compensation currents into the 18-pulse converter by the three-phase current-controlled inverter.A 3-kW prototype was established for measurement and evaluation, and the experimental results demonstrated the correctness and validity of the proposed scheme. Finally, the performance of the proposed method under different unbalanced sources was investigated through experimental results, which showed that the proposed strategy not only can improve ac current conditions but also can mitigate the effects caused by non ideal sources with different unbalanced conditions.

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