POTENTIAL APPLICATIONS AND EVALUATION OF AC-AC CONVERTER FOR RENEWABLE-ENERGY CONVERSIONS

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Abstract: Proposed is a new system scheme for future variable-speed wind turbines and micro-turbines. The scheme employs a PWM AC-AC converter with new capability of operating at variable and high frequency inputs. Simulation and experimental work are conducted to evaluate the feasibility of the proposed converter for the challenging OEM applications. Comparative study differentiates the performance of the AC-AC converter and conventional rectifier-inverter configuration. The proposed system potentially improves the efficiency and power density of future variable-speed wind turbines and micro-turbines.

1. Introduction

Our world today needs more than 10^{13} watts of reliable power to support our modern living standards and industries. With the ever increasing demand for more electrical power, many developed and developing countries have suffered continued electrical power shortages or energy crises, e.g. California of United States and other countries during the year of 2000 - 2001. As a result, developing alternative and renewable energy and higher energy-efficiency power conversion systems becomes crucial for our communities and industries.

Wind turbines and micro-turbines are very effective in producing renewable or alternative energy [1-3]. However, many modern commercial wind turbines run at fixed rates of rotation. Although it is easy to implement and control, a fixed rate of rotation does not optimize the capture of mechanical power from the wind. Variable-speed turbines are more desirable to improve the efficiency of energy conversion [2,3].

Furthermore, wind turbines and micro-turbines require solid-state power converters to convert the unregulated variable frequency (VF) electricity from the on-shaft alternator to a well regulated output electrical AC power that has a desirable frequency, voltage and phase angle within a tight tolerance band. The most popular industrial three-phase or single-phase power converters are voltage-source two-stage power conversion circuits. They follow two-stage power conversion principle and circuit topology: converting from an AC raw power to DC and then converting the DC power back to a regulated AC power for different load applications. From the point of view of circuit structure, such a converter is a combination of a front-end rectifier, DC-link capacitor filter and pulse width modulated (PWM) inverter. They are candidates today for the wind turbine and micro-turbine applications due to their simple structure and low cost. However, when driving popular AC motor loads, such two-stage conversion systems are less efficient at operating speeds other than the rated speed of the motor. For instance, if the motor speed is 50 percent of the rated rpm, the efficiency of these drives can drop as low as 50 percent. This is highly undesirable for the capture and conversion of mechanical power to electrical power. Also, such variable speed drives are often large. Additional disadvantages of this kind of power converters can be summarized below:

1. Rich in input current harmonics due to the front-end rectification of a diode bridge. This causes undesirable harmonic heating and unnecessary losses in the alternator stator winding.
2. Poor total input power factor due to the poor waveform power factor. Together with 1, this reduces overall efficiency of the power generation systems.
3. Large electrolytic capacitors exist at the DC-link that are bulky, temperature sensitive and have short service life time, resulting in penalties to the system's size, weight, cost and reduces reliable service lifetime.
4. Only one-directional power transfer (non-regenerative).

This paper proposes a new system scheme for future variable-speed wind turbines employing one-stage bi-directional power converters. The objective is to achieve high-energy-efficiency with reduced size and weight, and increased system reliability. The applications can be extended to future variable-speed micro-turbines.

2. System Configuration

Simplified system block diagram

Based on the proposed concept, a new architecture for more compact wind power systems is conceived and given in Figure 1. The proposed PWM AC-AC converter must be able to accept a wide variable frequency (VF) power input that is in proportion to the shaft rotating speed of the alternator as shown in Figure 1. This converter is, therefore, a new breed of VF-VF one-stage power converter, differentiating from the conventional matrix converter [4 -7] that accepts a constant frequency input.

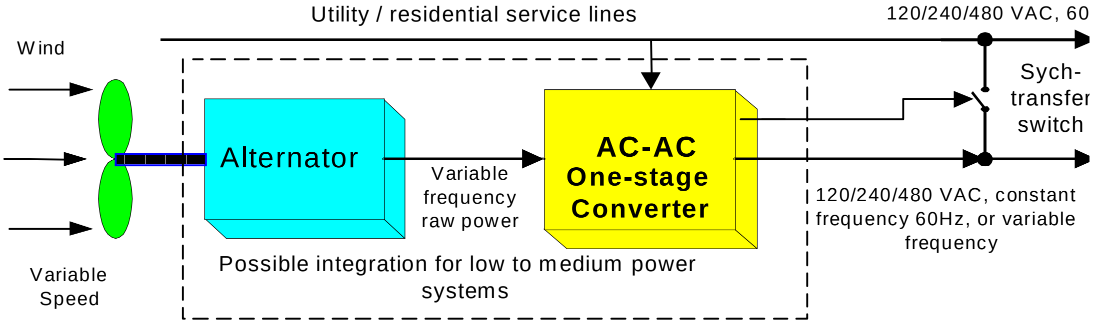
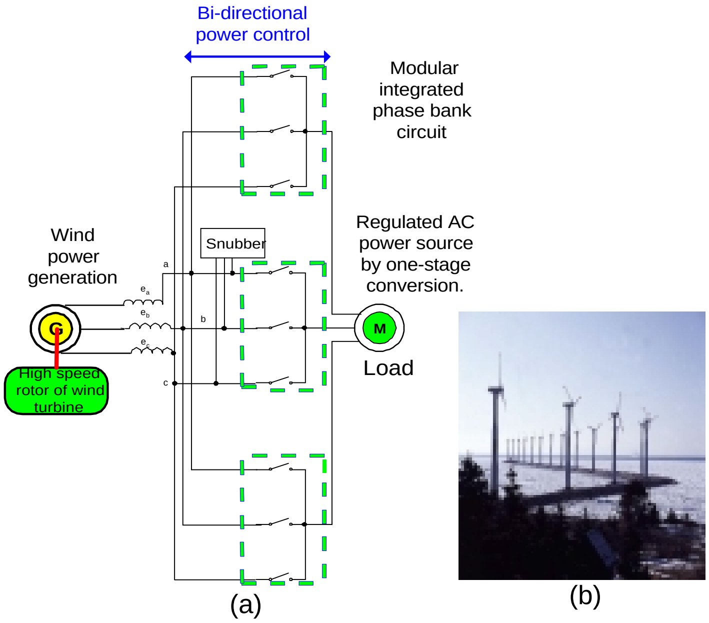


Figure 1. Simplified system block diagram employing integrated AC-AC converter

The proposed VF-VF technology and the new system will enable the variable speed operation of the wind turbines to keep the ratio of the rate of rotation of the wind-turbine rotor to the inflow wind speed constant [2, 3]. The aerodynamics would be optimized to obtain a maximum power coefficient [2]. The energy capture could be improved by an additional 10 to 30 percent according to previous studies. The new integrated VF-VF power converters will replace the conventional application-specific converters with a bulky DC-link (or two-stage converters with two-stage conversion, AC-DC-AC).

Integrated PWM AC-AC converters

A simplified power circuit diagram of the AC-AC converter systems with VF input, for potential wind power application is illustrated in Figure 2.



(a) Integrated 3-phase AC-AC converter using IAPM for wind power generation /regulation
(b) Potential application for medium size wind power turbine (VF-CF or VF-VF).

Figure 2. Integrated VF input one-stage converter systems for wind power applications

The mathematical relations between the voltages and currents in the input and output and the switching functions of the power converter are given in the following equations:

$$\begin{bmatrix} V_{uv} \\ V_{vw} \\ V_{wu} \end{bmatrix} = \begin{bmatrix} S_{ua}-S_{va} & S_{ub}-S_{vb} & S_{uc}-S_{vc} \\ S_{va}-S_{wa} & S_{vb}-S_{wb} & S_{vc}-S_{wc} \\ S_{wa}-S_{ua} & S_{wb}-S_{ub} & S_{wc}-S_{uc} \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{ua} & S_{va} & S_{wa} \\ S_{ub} & S_{vb} & S_{wb} \\ S_{uc} & S_{vc} & S_{wc} \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} \quad (2)$$

Where the input source voltages are described by:

$$V_{an} = V_{im} \cos(\omega_i t - \psi_i) \quad (3)$$

$$V_{bn} = V_{im} \cos\left(\omega_i t - \psi_i - 120^o\right) \quad (4)$$

$$V_{cn} = V_{im} \cos\left(\omega_i t - \psi_i + 120^o\right) \quad (5)$$

The symbol S_{jk} is the bilateral switch in each phase of the power converter circuit in which $j \in \{u, v, w\}$ represents the phase on the load side, and $k \in \{a, b, c\}$ represents the phase on the input side. A number of pulse width modulation (PWM) control algorithms that defines the switching matrix in equations (1) - (5) have been reported in references and author's previous work.

The AC-AC power converters with VF input are highly compact and low-weight, and can offer many advantages over the conventional two-stage converters. The advantages include:

- Higher total input power factor (per unit or leading) and improved energy conversion efficiency at all rotating speeds and load conditions of the electrical machines, thus resulting in possible maximum energy conversion efficiency.
- Eliminate temperature and weather sensitive power components, such as electrolytic DC-link capacitors, which enables a longer system lifetime and higher designed operating temperature.

- Fully integrated regenerative capability.
- Large percentage reduction of the volume and weight. Eliminate large reactive power components, such as DC-link electrolytic capacitors and inductor. Eliminate the mechanic gearbox. This effectively reduces system cost, size and turbine head weight and increase reliability.

3. Integrated AC Power Module and Device Optimal Utilization

Integrated AC power modules

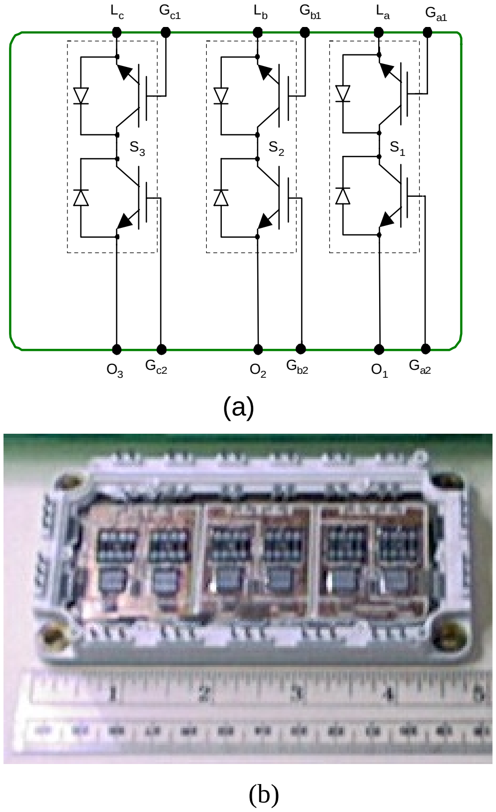
High-power bilateral semiconductor switches with self turn-off capability are required to build the AC-AC converters. Up to the present time, such high-power AC switches are not available. In the past, discrete two-quadrant power semiconductor devices were commonly evaluated and used by the power conversion community. However, considering a 3-phase to 3-phase converter, using 18 two-quadrant switches results in excessive parasitic inductance. The large number of components and complicated wire connections would be major disadvantages for the circuit commutation at high alternating current in the PWM operation.

To overcome these problems, a new concept for a 3-in-1 integrated bi-directional power module (IAPM), for AC-AC power converters, has been conceived. IGBT devices at the chip level are integrated into individual AC switches as shown in Figure 3. A simplified schematic showing the grouping and partitioning of the circuit is outlined in Fig. 3 (a). Cutting-edge Trench-gate IGBTs with vertically optimized device structure are used for the basic switching elements. This type of Trench-gate IGBTs will have a 20% reduction in both conduction loss and switching loss in comparison with the existing IGBT devices.

The AC switches are then configured and designed into IAPM modules by a direct bonding copper (DBC), according to an optimized configuration for the three-phase applications. A physically fabricated IAPM, it's DBC and internal circuit layout is shown in Figure 3 (b).
A complete diagram of a three-phase integrated AC-AC converter system for wind power applications is shown in Figure 2 (a). Each phase circuit consists of three built-in AC-switches. This forms a novel 3-to-1 integrated high-power phase-bank. The key parameters of the IAPM is given in Appendix.

Device Rating Optimal Utilization of IAPM

In a design of a bidirectional switch, the current ratings of the diode and IGBT should be equal. In this paper, we will further address several important design optimization issues, including the optimal power rating determination of the bidirectional switches, best silicon utilization and design economy, as well as other system design issues.



(a) Simplified schematic of integrated power module
(b) DBC and internal circuit layout
Figure 3. Integrated AC Power Module layout

Consider a per phase power circuit, shown in Figure 2(a) and the per phase switch configuration in Figure 3(a). A load current, i_u, is evenly shared over a considerable time period by three AC switches, s_1, s_2, and s_3. The relation between an average current carried by a bilateral switch, $I_{Save} = I_{Tave} = I_{Dave}$, and the phase load current, i_0, can be approximated by $I_{Tave} = I_{Dave} = \frac{1}{3} I_{0p}$, where I_{0p} is the peak value of the phase load current in the worst case. It can be shown that the relationship between the device and the load rms current is given by: $I_{T\mathrm{rms}} = \sqrt{\frac{2}{3}} I_{0\mathrm{rms}} = 0.816 \cdot I_{0\mathrm{rms}}$. Where $I_{0\mathrm{rms}}$ is the load rms current.

The above analysis indicates that the theoretical average current and rms current carried by an individual bilateral power switch are far less than a per-phase load current. The silicon power devices of IAPM should run at a lower temperature at equivalent load and cooling conditions in comparison with those in conventional inverter systems. A careful design of device rating and proper thermal management of the power converters could result in an improved device current utilization factor. The objective of this optimal design is to achieve maximum utilization of the device’s current rating for a predefined load current rating. For the existing silicon based power devices, the constraint of the optimization is to limit the device junction temperature to under 125°C with a safe margin. For new types of power devices in the future, such as Silicon Carbide (SiC), the upper operating junction temperature can be over 250°C. Various optimal designs can be obtained based on different device characteristics, load profiles, and cooling mechanisms. This is a very important design optimization for obtaining a cost-effective system design.

On the other hand, the AC-AC converter eliminates the large voltage overhead in a conventional two-stage converter or AC drive due to the requirement of handling energy regenerated on DC link. Therefore, the voltage utilization factor of the devices in AC-AC converter is 15-20% higher than that of a conventional inverter system [8].

4. Control System Based On Integrated DSP

A single-board DSP controller based on a TMS320C32 is employed to control the AC-AC converter and the variable frequency and variable voltage control of the AC motor load [8-10]. On board, TMS320C32 is a low-cost, 32-bit floating-point DSP, operating at 50 MHz. The matrix control equations in equation (1) to (5) are translated into the modulation algorithms in the time domain that perform PWM modulation in both the input and the output sides [8]. Different algorithms can be programmed in the firmware modules and then compiled and downloaded for execution. The modulation and the control algorithms can be conveniently selected and executed for performance comparison and evaluation.

5. Initial Performance Evaluation for High and Low Frequency Alternator Systems

Operation at industrial utility frequencies

Figure 4 illustrates the voltage and current waves of IAPM bilateral switches during a commutation. Trace 1 shows an IAPM device voltage waveform during a turn-off with a load current near its peak value. The corresponding load phase current waveform is shown in Trace 2. The transient turn-off voltage and current are well controlled by the commutation circuit, with no voltage spike overshoot and no interruption in the load current. With the integrated power module and new phase bank design, and highly integrated system design [9,10], the new AC power switching devices operate satisfactorily at a switching frequency of 8 kHz. The voltage waveform of the commutation is clean with little overshoot. The dv/dt of the turn off voltage is controlled at about 250 V/μs, which is far less than the counterpart of a modern industrial inverter. The reduction of the dv/dt induces stress on the motor windings and switching devices. Figure 5 shows the output voltage and the load current of an integrated PWM AC-AC converter [8] in a test on a 15 Hp induction motor load. This emulates a direct AC motor load from an either wind power or micro-turbine fed AC-AC conversion system. The motor currents are sinusoidal. The output voltage of the prototype converter is measured as 455 V rms at a nominal output frequency when the input voltage is 480V. A high voltage transfer ratio of 1:0.95 is achieved in this design. However, there is a trade-off between the high voltage transfer ratio and the high quality control of the input current. It is expected that in this over-modulation scheme the input current quality may be degraded somehow at full load and full voltage output due to the switching frequency of the input side modulation is reduced to minimum. Optimization at system level should be conducted depending on an individual system requirement.

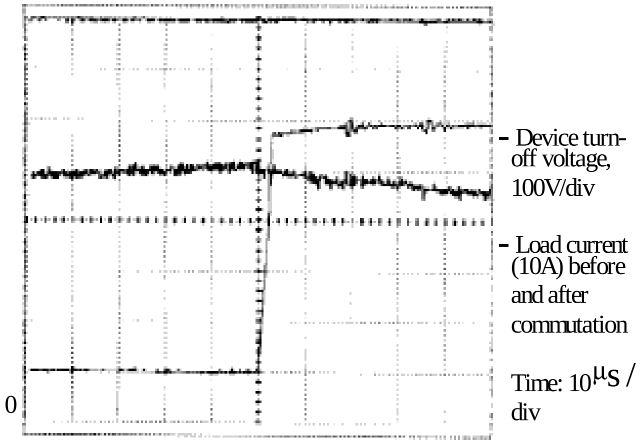
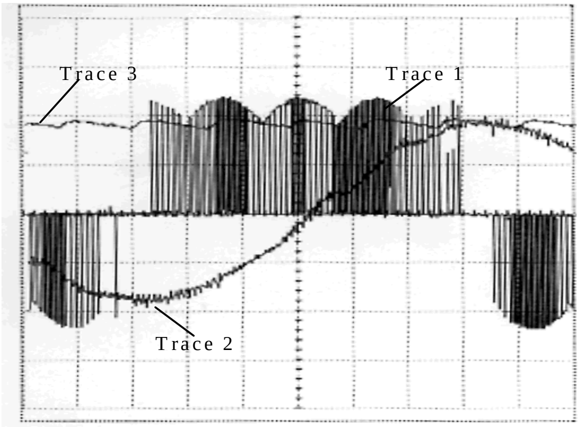


Fig. 4. Voltage and current waves of IAPM bilateral switches during commutation



Trace 1: Converter line-line output voltage, 250V/div
Trace 2: Motor Current, 10A/div
Trace 3: Input voltage for gate supplies
Time: 1ms/div

Fig.5. Voltage and current of AC-AC converter fed induction motor drive at 455V output (f_1=40 Hz, f_s = 8 kHz)

High frequency capabilities supporting high power density design

Many modern micro-turbines and their build-in alternators operate at high rotating speed above several thousand RPM. The direct output frequency from the alternator can be designed to be higher than our utility frequency, say 60 Hz. If the direct output frequency is designed in a range of 5 – 10 times of the our utility frequency, this would result in a frequency variation range of 300 – 600 Hz. The major advantage for operating at higher frequency range is that the size and weight of the alternator and corresponding power filters can be significantly reduced. The system’s power density can be increased. However, this put a new performance challenge to the one-stage power converter for this system. Up to date, the authors are only aware of the reports of AC-AC converters with constant frequency input at 50 or 60 Hz [6-10].

Initial simulation and experimental evaluation of the high frequency capability of our proposed PWM AC-AC converter are conducted at various input frequencies and reported below.

Figure 6 shows a digital simulation of the AC-AC converter operating at 400 Hz input and 400 Hz output. The time records the input voltage and input current is shown in Figure 6 (a) and the frequency spectrum of the input current is shown in Figure 6 (b). There is no harmonic components, such as 3rd, 5th and 7th harmonics, that are visible.

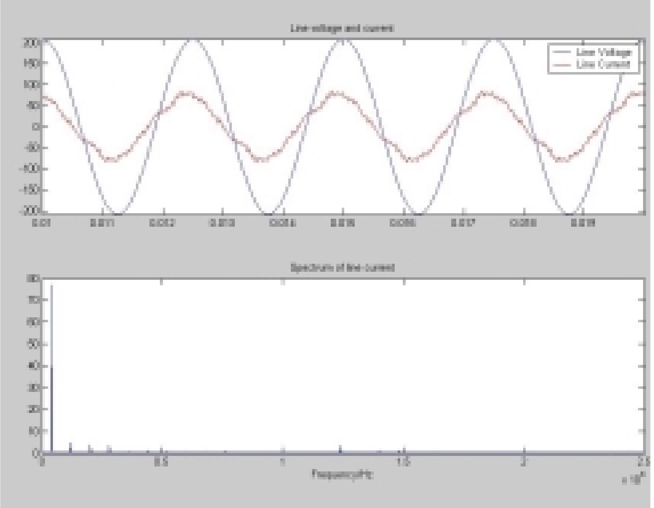
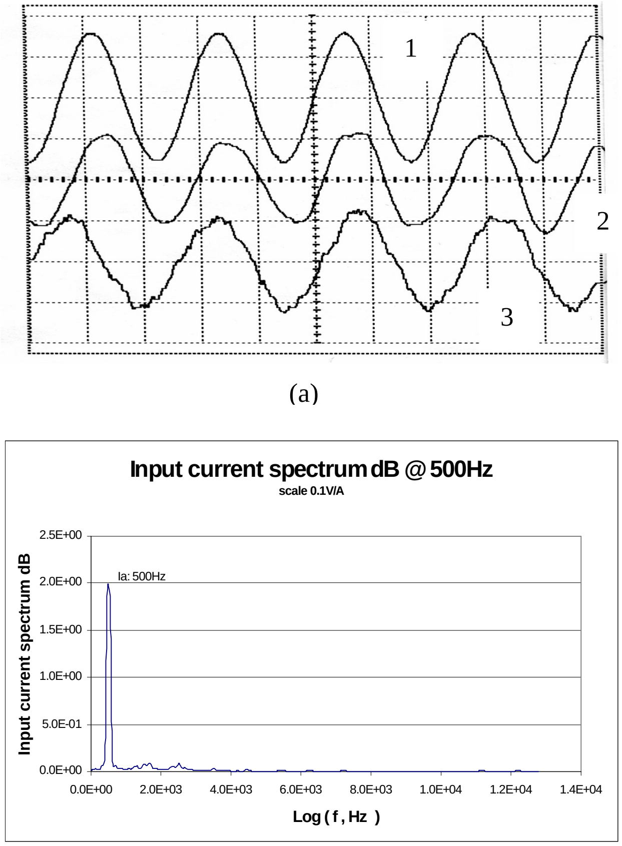


Figure 6. Digital simulation of AC-AC converter operating at 400 Hz input

Figure 7 illustrates our initial experimental results of the input current and voltage of the AC-AC converter with an induction motor load. The converter system is fed by an input power frequency 500Hz, over 8 times of the utility frequency. Trace 1 in Figure 7 shows the input voltage waveform with no voltage glitches and spikes during the device commutation. Trace 2 illustrates an approximation of sinusoidal input current. The input current is in phase with the input voltage. This results in an approximate per unit total power, thus improving the energy conversion efficiency. Trace 3 illustrates the output motor current operating at 400 Hz in an open loop V/Hz control mode with a good quality sinusoidal modulation. The converter output frequency covers 0 – 400 Hz range. The 400 Hz class system would result in reduced size and weight for electromagnetic components and electrical machine design, including both electrical motors and generators comparing with those designed for 50/60 Hz class system.

In comparison, the input current and the current spectrum of a conventional variable frequency inverter with a diode-rectifier front-end are illustrated in Fig. 8. This type of the waveform contains rich harmonics, including the 5th and 7th order of harmonics with substantially large amplitude in comparison with the fundamental current component.

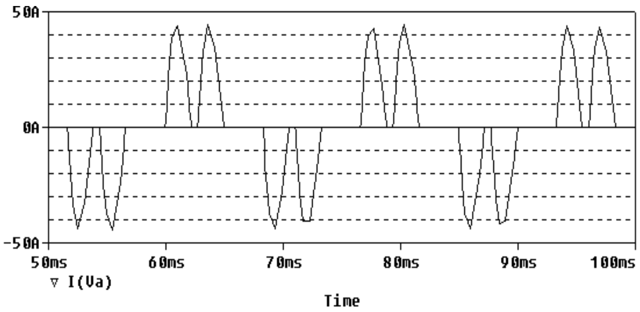


(a)

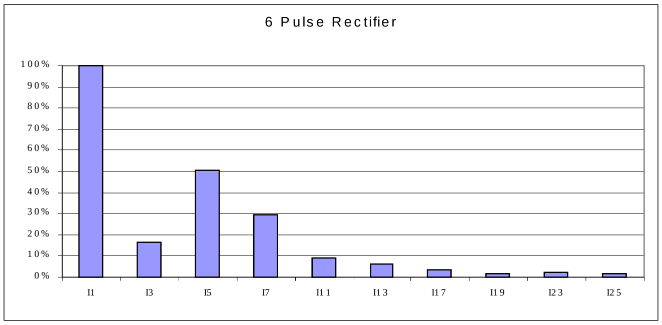
(b)

Trace 1: Input line voltage
Trace 2: Converter input line current, 20A/div
Trace 3: Output motor current, 20 A/div
Time: 1 ms/div
(a) Converter input and output waveform
(b) Input current spectrum

Figure 7. Input current and voltage of AC-AC (VF-CF) converter operating at 500 Hz input and induction motor load (400 Hz output)



(a)



(b)

Figure 8. Illustration of input current harmonics of conventional two-stage converter

The waveform distortion of the input current deteriorates the total input power factor and produces the harmonic pollution as expected. From the initial evaluation and comparison, the integrated PWM AC-AC converter offers superior performance in higher total input factor and reduced harmonics on the input side over the conventional rectifier-inverter configuration.

In addition to alternative energy conversion and future wind-power systems, the potential applications of this new PWM direct power converters include popular general-purpose industrial and military power conversion systems and AC drive products [8].

6. Conclusions

A new system scheme for future variable-speed wind turbine and micro-turbine has been reported. This scheme is enabled by newly developed capability of VF to VF one stage conversion at high input frequencies. Initial theoretical analysis and optimal utilization of IAPM's silicon for the direct power converters have been outlined. Preliminary evaluation shows that the propose converter can handle satisfactorily for different ranges of frequency inputs, including 60/50 Hz input system and 400/500 Hz class system. Both simulation and experimental results confirm the feasibility of the proposed PWM AC-AC converter.

Comparative study also shows the AC-AC converter has superior performance in terms of higher total input power factor and low harmonics over the conventional rectifier-inverter configuration. The new system can potentially improve the efficiency and power density of future variable-speed wind turbines and micro-turbines.

Appendix

Key device parameters of IAPM

DC Blocking Voltage, V_{ce}	1200V
$I_c = I_{DF}$	150A, $T_c = 25°C$ 100A, $T_c = 80°C$
Pulsed collector current $t_p = 1$ ms	300A, $T_c = 25°C$ 200A, $T_c = 80°C$
Reverse Recovery Time (t_{rr}) & Reverse Recovery Charge (Q_{rr}) ($I_f = 100$ A, $V_r = -600$ V, $V_{GE} = 0$ V, $d I_f / dt = -800$ A/µs, $T_j = 125°C$)	$t_{rr} = 0.3$ µs (typical) $Q_{rr} = 11$ µC (typical)
Fall Time ($V_{CC} = 600$ V, $V_{GE} = -15$ V, $I_C = 100$ A, $R_G = 6.8\Omega$)	70 ns

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