High-Frequency Link Inverter for Fuel Cells Based on Multiple-Carrier PWM

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Abstract—Fuel-cell inverter applications typically have a relatively low voltage input, and require a battery bus for energy buffering. Circuit topology issues are examined based on these needs. The need for high step-up ratios, current control, low ripple, and battery storage leads to a current-sourced link converter as perhaps the best choice of conversion topology. High-frequency ac link conversion offers a possible way to reduce the number of power stages, in the form of a cycloconverter, known from previous work. It is shown that the control complexity in this converter can be addressed by adapting pulse-width modulation (PWM) techniques. Here, a multicarrier PWM approach is introduced as a convenient way to implement a high-frequency link inverter. The approach is a direct extension of conventional PWM, and supports square-wave cycloconversion methods that have appeared in prior literature. Simulation and experimental results are developed for a low-voltage ac link inverter, leading to a 48-V fuel cell input design.

Index Terms—Cycloconverter, fuel cell, fuel cell power conditioning, high frequency link, pulse width modulated inverters, pulse width modulated power converters, pulse width modulation (PWM).

I. INTRODUCTION

HIGH-FREQUENCY (HF) ac link inverter topologies, with or without soft switching, have important practical advantages compared to more conventional dc link inverters in terms of isolation, size of magnetics, and other properties. It is possible to obtain these basic advantages directly in a conventional PWM inverter with transformer-coupled output, but only if the transformer can handle the low modulating frequency. HF link topologies have not been common for medium power (1 to 20 kW), largely because of the number of power stages and control complexity. During a search for low-cost medium-power inverter topologies to process fuel cell power, our group recognized that HF links could reduce the part count and the number of power processing stages. The complexity drawback has been overcome with a multiple-carrier PWM technique, described in this paper. The paper extends the treatment in [1], to include a discussion of fundamental fuel cell interface issues and topology choices.

The contributions of the paper fall into two arenas. First, a critical evaluation of fuel cell power conversion circuit topologies is presented. Fuel cells have dynamic limitations that require energy storage devices, such as batteries, to be embedded in the converter. They have relatively soft voltage characteristics and require current control for best operation. Here these issues lead to a boost dc–dc input stage followed by an HF link processing stage. While various HF link approaches are well known, the multiple-carrier PWM control method introduced in this paper has substantial promise for simplifying the operation. The multiple-carrier PWM approach is discussed in depth.

Consider a low-cost application such as a 12-V or 48-V dc input inverter intended to deliver conventional ac voltage at mains frequency. A fuel cell system inverter is an example. In such a system, the voltage step-up ratio is high. Safety considerations are likely to demand galvanic isolation. Both the high ratio and the isolation imply that a transformer must be used. A conventional topology cascades a dc–dc forward converter with a PWM inverter. This configuration actually has three stages of power conversion: dc–ac in the forward converter primary, ac–dc in the rectification for the dc bus, then dc–ac in the inverter. The cascaded conversion would appear to have redundancy—especially since the topology adds a dc bus that must be filtered. It would be expected that a more direct approach should be possible.

To avoid redundancy while keeping the desirable HF link, many alternative circuit topologies have been proposed [2]–[7]. Among them is a “cycloconverter type” [8]–[14]. In this case, the dc source is chopped to a square wave. Then controls similar to those in ac–ac cycloconverters generate the desired output. The power conversion is more direct (two stages) than with a conventional dc bus structure. The dc bus is gone, along with its intermediate filtering. Moreover, this topology supports bidirectional power flow and is suitable for power conditioning systems that double as active filters [11].

Cycloconverters traditionally have been considered only for high power applications because of the complex nonlinear phase controls used in the cycloconversion process. The square-wave cycloconverter control method introduced in [8], [9] is termed “PWM control” by the authors and results in a PWM cycloconverter. It attempts to avoid some of the complexities of cycloconverter control. However, there is no discussion in [8], [9] relating the cycloconverter approach to conventional PWM, and several interesting properties of the control method (discussed below) were not exploited. In a subsequent paper [11], a control method for a square-wave cycloconverter described as a modified phase-angle control achieved natural commutation. Phase-angle control for natural commutation is also proposed in [13].

This paper explores the possibility of a reduced-stage power conversion for a low-voltage fuel cell application. The topology
issues are discussed and naturally lead to a high-frequency cycloconverter circuit arrangement consistent with [11] and [13]. As it turns out, cycloconverter control techniques do not necessarily complicate the operation of a converter. A multicarrier PWM technique is introduced here as a way to make the control of a PWM cycloconverter essentially the same as that of a conventional PWM inverter. The proposed system design has advantages that are well matched to the special requirements of fuel cell conversion systems. Experimental work demonstrates the feasibility of the multicarrier approach.

II. TOWARD A SIMPLIFIED CONVERSION SYSTEM

A. Fuel-Cell Electrical Characteristics

A static current-voltage relationship for a prototype fuel cell is shown in Fig. 1. This particular curve is taken from a proton exchange membrane (PEM) fuel cell model; there is no loss of generality for the broad discussion in this paper. PEM fuel cells use hydrogen as the fuel source and have an open circuit voltage of 1.15 V per cell at 80°C and one atmosphere of pressure. Under load, the voltage drops abruptly and is typically 0.6 V per cell or even less. It is important that the working voltage be high enough to remain to the left of the “knee” in the curve, which occurs at about 9 A in Fig. 1. A fuel cell stack with 64 cells in series, based on Fig. 1, would have open-circuit voltage of 74 V and operating voltage of about 40 V. To support the operation of the fuel cell stack, there will be a parasitic load for pumps, fans, and other equipment, typically on the order of 1/6 of rated load. In Fig. 1, this balance of plant load implies an actual working voltage range of 0.5 to 0.8 V per cell. The power processing system must be able to handle this range and withstand the open-circuit voltage during startup conditions. In practice, a fuel cell stack with 64 cells would generate a working range of 32 to 52 V.

Fig. 1 provides only the static characteristic for the fuel cell. There are significant dynamic issues that must be addressed in any system. The dominate issues relate to fuel flow and transient response. Fig. 1 shows the behavior with 100% rated fuel flow in a flow-through type of system, but it does not reflect efficiency considerations. For example, if the cell in Fig. 1 operates at 2 A (about 25% of rated load) with 100% fuel flow, only a small fraction of the fuel will actually participate in the electrochemical reaction. In a vented flow-through stack, the remainder will be sent, unused, out the exhaust. Since direct recovery of hydrogen from the exhaust is difficult, wasted fuel represents very low efficiency. Other operating methods might use constant fuel pressure, in which case diffusion rates and oxygen supply limit the performance. In a practical system, the fuel flow (or pressure) must be adjusted to match the reactant delivery rate to the usage rate. A typical target is fuel utilization of at least 85% to avoid excessive waste.

Fig. 2 shows three of the family of curves that result when fuel flow is taken into account. In a flow-through PEM system, for a given electrical load, the fuel flow should be adjusted to give the proper match. This causes two problems. First, flow rates cannot be adjusted rapidly, and the internal chemistry must reach equilibrium before the cell can support increased load. Second, if the electrical load increases too rapidly, it could drive the curve over the knee, exceeding maximum power transfer and overheating the fuel cell stack with extra losses. The dynamics of fuel flow and diffusion of reactants are such that time constants associated with Fig. 2 range from several seconds for PEM technology to several minutes for some other fuel cell technologies—not useful for following fast-changing electrical loads.

In any application with an uncontrolled electrical load, an energy buffer such as a separate battery will be needed to permit instantaneous response to electrical load shifts while the fuel cell stack catches up. However, based on Fig. 2, it will not be feasible to simply add batteries in parallel with the stack. A battery V–I curve is similar to a fuel cell and the operating point cannot be managed with a direct parallel connection, especially as fuel flow rates change. In practice, this requires that a dual-port converter will be required to allow both a fuel cell and a battery to be used independently. A battery will also require bidirectional energy flow to maintain charge over long intervals.

Convention dictates that fuel cells are intolerant to ripple current. Upon first examination, the physical structure of a fuel cell is similar to that of an electrolytic capacitor, and fuel cells in general have significant internal capacitance. However, since the electrochemistry is not perfectly efficient, internal losses limit the ability to withstand the extra losses caused by ripple current. In addition, ripple current at relatively low frequencies will perturb the operating point and could drive instantaneous operation beyond the knee of the characteristic curve. Thus a typical fuel cell is relatively intolerant to current ripple at low frequencies of 120 Hz or less but is more forgiving of higher frequency ripple at several kilohertz or more.

B. Inverter Topology Issues

Two generalized approaches can be taken in this inverter challenge, as developed in [16] and [17]: convert the energy from the fuel cell into ac form, as in Fig. 3 and step this up to the desired output, or use a dc–dc converter cascaded with an inverter, as in Fig. 4. Fig. 3 will require a bulky mains-frequency transformer, and will yield a heavy system with little opportunity for cost reduction. However, it offers the advantage of galvanic isolation. Fig. 4 involves a cascade of power conversion steps, each of which adds loss. Eliminating the line frequency transformer reduces the size and weight but also eliminates galvanic isolation.
The discussion that follows begins with the general arrangement in Fig. 4 to meet the system requirements.

The source impedance characteristics shown in Fig. 1 and 2, and the desire to operate the fuel cell at a specific “fuel utilization” level suggest current control as the appropriate interface with the fuel cell. The input current can be set at any moment to the ideal value for the available fuel flow and the maximum current ripple is determined by design. The current commanded from the fuel cell as well as the fuel flow rates can be adjusted to track the average output power requirements of the inverter as the average electrical load changes. Batteries can be provided as a supplement to respond to fast load variation. With this scheme, the dynamics of the fuel cell are decoupled from the transient dynamics of the electrical load. The arrangement could be as simple as a boost converter cascaded with an inverter bridge. But what about the batteries? In principle, they can be connected at the high-voltage dc bus. While a high-voltage battery is a simple approach, it raises its own problems. Batteries in the range needed (more than 300 V) are difficult to manage. It is especially difficult to maintain a tight charge balance [18], and it is unlikely that this could become a practical solution.

In practice, there are at least three reasons why the converter in Fig. 4 would not be implemented with a simple nonisolated boost converter. First, the step-up ratio (48 V to more than 300 V) is too high for efficient conversion without a transformer. Second, it is likely that other design, safety, and regulatory concerns will lead to requirements for galvanic isolation between the fuel cell and the inverter output. Third, the most likely power level (10 kW and higher) leads more effectively to bridge-type forward converter circuits.

As an alternative to a high-voltage battery, the fuel cell and batteries could act as two separate parallel inputs to the forward converter, as shown in Fig. 5. An advantage of the approach is the direct redundancy of the fuel cell and batteries. Another advantage is high operating efficiency: the batteries do not have to act as an intermediate energy source if power can flow directly from the fuel cell to the load. However, this concept presents at least three system level challenges that prevent it from becoming a low-cost solution. First, four significant magnetic elements are needed: two input-side inductors, the forward-converter transformer, and an output-side filter inductor (inside the “ac load” block). Second, the battery conversion port must be bidirectional. A significant concern is the control scheme. The system must decouple the fuel cells dynamically from the inverter—the input current on the fuel cell port must be controlled to a specified value no matter what the rest of the system is doing. This is expected to be difficult in the context of a single converter.

Fig. 6 shows an alternative in which the batteries define a low-voltage bus on the input side of the forward converter. Now a simple nonisolated boost converter can implement a low step-up ratio from the fuel cell to the batteries and enforce an arbitrarily low ripple current imposed on the fuel cell. A 64-cell stack with behavior like that in Fig. 2 could interface to a 48-V nominal lead-acid battery bus, or easily to a 60-V nominal battery. A key feature of this topology is convenient decoupling of control: the boost converter controls the fuel cell current, independently of the inverter. Another benefit is that bidirectional conversion is avoided. Battery maintenance is straightforward; the commanded fuel cell current is simply set higher than the inverter demand such that the extra current provides battery charging. This topology, in effect, places the fuel cell and battery into a
series port connection in place of the parallel port scheme in Fig. 5. A disadvantage is that the series arrangement adds an additional conversion stage in the power path and thus introduces a certain conversion redundancy.

Reduction of redundancy is embodied in a high-frequency link arrangement, shown in Fig. 7. In this circuit, the forward converter is replaced with a simple square-wave inverter that produces a HF link at the transformer. The internal rectifiers and dc bus filtering have been eliminated. The output inverter is replaced with an ac–ac converter that processes the HF link and delivers the ac mains frequency output. This circuit provides all the advantages of Fig. 6 with a simpler structure and less losses. As in Fig. 6, current control on the boost converter provides the ideal interface to the current source characteristics of the fuel cell. This structure extends well to any arbitrary fuel cell stack. For example, fuel cells with nominal 24-V output can interface effectively with 24-V or 36-V batteries in the circuit structure of Fig. 7. In any case, the appropriate choice of battery bus voltage would be the lowest value that supports the input boost converter. The forward converter control could be as simple as a direct square-wave switch process or integral volt-second control for soft-start operation, load voltage regulation, and battery bus regulation as demonstrated in [17]. Using conventional techniques, the output control seems complicated since the stage is a cycloconverter. However, the control of this stage can be implemented with PWM methods, discussed as follows.

The fuel cell power processing system proposed in our work uses the general design of Fig. 7 as its basis. An important design advantage is the decoupling of the fuel cell operation and control from the output control. The boost converter will be used in an input-current control mode, while the battery buffer maintains the low-side dc bus. Variable voltage characteristics like that of Fig. 1 will have no effect on the output operation. When integral volt-second control is applied to the forward converter bridge, battery voltage regulation also becomes unimportant over the operating range of interest. Because of this control strategy, the output converter can be designed independently from the input boost converter. The discussion below carries through this aspect of the design.

C. Operation of a PWM Cycloconverter

The concepts in Section II-B. present a progression of solutions to known design difficulties. To incorporate these benefits and eliminate the redundant conversion step shown in Fig. 6, we propose the PWM cycloconverter shown in Fig. 7. It will be shown in Section III. that the conventional PWM inverter can be unified through a multiple-carrier PWM framework. The control concept introduced in [8] and [9] is extended to demonstrate that multiple-carrier PWM methods lead to HF link inverters that are nearly as simple to control as conventional PWM inverters. These cycloconverter-type inverters produce exactly the same waveforms as conventional PWM while supporting HF links. They also make bidirectional energy delivery [10] easy.
Specific choices can also support natural commutation, thus reproducing results in [11], [13] directly from familiar PWM processes. Many useful expansions of traditional PWM can be added by using the multiple-carrier PWM framework. These include

a) a simplified gate drive waveforms which supports convenient gate transformer coupling, for both pulse-controlled and fully gate-controlled switches;
b) natural commutation with the proper choice of PWM process;
c) either primary-side or secondary-side of the bridge control;
d) a doubled effective switching frequency at the output with respect to the HF link and to the inverter switches.

The multicarrier PWM technique allows the topology in Fig. 7 to be a low-cost inverter design for fuel cell applications.

### III. MULTICARRIER-SEQUENCE GENERATION

Conventional PWM sequences are generated by comparing a triangle or ramp carrier with a modulating function. In multiple-carrier PWM, the modulating process is performed in more than one manner, and the results are combined to produce a useful unified sequence. A block diagram of the generation process is shown in Fig. 8. First, a base carrier (a triangle or ramp) is phase-shifted, then divided into independent time segments by means of a decommutator [19] operating in synchronism with the carrier clock. A decommutator is common in time-division multiplexing (TDM) communication systems and has a similar function here: to segment the base carrier into time slices that can be used as separate carriers. The decommutation rate $f_{decom}$ is set to the same frequency as the carrier in case of a ramp waveform, or to twice the frequency of the carrier in the case of a triangle waveform. Each separate decommutator output is compared to the modulating function or with a phase-shifted image. The comparator outputs are combined arithmetically to generate a gate control sequence. With proper choices of phasing in Fig. 8, gate sequences will result that, when switched against a square-wave source, produce PWM output. This is a generalization of an “unfolding” process [20]; in this case the sequences can be two-level or three-level as compared to previous three-level HF link unfolding.

To generate HF links, the gate control sequence must avoid low-frequency content yet retain information about the modulating function. This can be done by generating two separate PWM sequences with a single modulating function $m(t)$, then subtracting the sequences to eliminate low-frequency modulation. The result is a three-level signal. An alternative is to modulate one sequence with a function $m(t)$, the other with $-m(t)$, and then add them. The result is a two-level signal. Since the sequences are constrained by the decommutator into separate time windows, both the three-level and two-level combinations still retain information about the underlying $m(t)$ function, even though low-frequency content is removed. In an inverter application, the combination signal is now ready to serve as the HF link waveform. Alternatively, an uncontrolled (but synchronized) square wave can be used for the HF link, in which case the combination signal serves for the gate drives of the output-stage switches.

Under the framework of Fig. 8, families of multicarrier PWM sequences can be constructed. Table I lists nine two-carrier conditions, the resulting sequences, and the ultimate equivalent PWM approach that would have generated the same output.
waveform. The four shaded entries in Table I are depicted in Fig. 9 as examples. Also in Fig. 9, the control sequence is “mixed” with a square wave to show the recovery of a two-level PWM signal at the converter output. All the sequences given in Table I are intended for HF link applications: the modulation and combination processes are selected to cancel out \( m(t) \), either with a phase shift or by subtraction.

The gate sequence waveforms in Fig. 9 demonstrate several interesting aspects of multiple-carrier PWM. The two-level gate sequences in Fig. 9(a) and (b), for instance, maintain a duty ratio of nearly 50% all the way through the modulation cycle. The information is encoded as phase modulation in these cases. Phase modulation has been discussed for ac link inverter applications in the past [5], [21]. The 50% duty ratio supports convenient transformer coupling for the gate drives. Since the pulse width has virtually no dynamic range, there are no limitations for narrow or wide pulses. It is important to notice that the gate drive sequence in Fig. 9(a) is always phase-lagging relative to the HF link square-wave, while that in Fig. 9(b) it is always phase-leading. Thus, unidirectional devices can be used in the output stage. If sequence (a) is used when load current is positive while (b) is used for negative load current, a complete nat-

Fig. 9. Typical two-carrier PWM sequence generation process. (a), (b), (c), and (d) correspond to rows 2, 5, 6, and 9 of Table I, respectively.
urally-commutated PWM cycloconverter (as in [11] and [13]) results. The sequences in Fig. 9(a), (b), and (d) all produce a PWM output with an effective switching frequency double that of the switching devices—an advantage for reducing switching losses. The three-level gate-drive sequences in Fig. 9(c) and (d) support HF link gate drives, with simple rectification at the gate terminals to recover the correct signals.

IV. HF LINK INVERTER CIRCUIT CONFIGURATION AND SWITCH TIMING

Fig. 10 shows a cycloconverter-type HF link converter which comprises an open-loop inverter to generate a square wave, the HF link transformer, the output converter stack, and possible additional passive filtering for the output. This figure represents the outlined portion of Fig. 7. To apply Fig. 7 in a low-cost fuel cell processing application, two-carrier PWM can be used as a convenient way to support natural commutation with this circuit. The primary-side inverter bridge is conventional [and uses metal oxide semiconductor field effect transistors (MOS-FETs) or insulated gate bipolar transistors (IGBTs)], while the output bridge consists of eight unidirectional switches organized in four pairs. With natural commutation, only the leading edge of the gate pulses is needed, and the only feedback is the sign of the output currents. The thyristor implementation shown in Fig. 10 supports link frequencies up to a few kilohertz. For high-frequency operation, IGBTs would also be used in pairs in the output bridge. Reverse-blocking IGBTs [15] are of interest to lower part count in this design. When a three-phase application is to be supported, the output bridge would have six pairs of devices.

In Fig. 10, the multicarrier PWM sequence, multiplied by a square wave, recovers an output waveform identical to that obtained with conventional PWM. The square wave can be applied to either the input or output bridge, while the multicarrier sequence is applied to the other. Fig. 11 shows a simulation switch timing diagram for the circuit of Fig. 10. The output traces at the bottom of the figure reproduce conventional PWM. Natural commutation in the HF link circuit is supported if the edges of functions Q1 and Q3 are used when the output current is positive, and the edges of Q5 and Q7 when it is negative.

When a short dead time is provided for the primary-side inverter, the general operation is unchanged, as discussed in [17].

V. PWM CYCLOCONVERTER EXPERIMENTAL WORK

Practical advantages of multiple-carrier PWM in the context of a naturally-commutated HF link inverter include ease of implementation and simplicity of gate drive circuits. More formal advantages are related to the PWM process: the output voltage waveform is a true PWM signal and established results about harmonics, filter design, ripple, and other design issues can be applied directly. There are many alternatives for generating multiple-carrier PWM signals, such as the use of synchronized push-pull PWM ICs, or digital approaches.

Fig. 12 shows a test circuit for a naturally-commutated square-wave cycloconverter (similar to the power circuit in [11]), that uses the two-carrier process in Fig. 8 for control. The circuit operates from an input 1-kHz square wave, generated from a low-voltage dc rail as shown on the left side of Fig. 10. Since the output bridge devices in this experiment are silicon controlled rectifiers (SCR), only the leading edge of the PWM pulse is needed. The decommutator is not necessary because pulse transformers are needed to transmit only the signal leading edge. Thus, both comparators in Fig. 8 can be used directly with the original ramp. The two multivibrators are triggered from the rising edge of the respective comparators to produce a 15 μs gate pulse train. The upper multivibrator creates a phase-delayed gate pulse train to be used when load current is positive, while the lower multivibrator creates a phase-advanced gate pulse train to be used when the load current is negative. Simple logic is used with a current comparator to separate the positive and negative current conditions. Notice that in contrast with [11], the gate pulses have been generated directly as in conventional sine-ramp PWM comparisons. Here a single ramp serves as both carriers.

A similar circuit as Fig. 12 can be realized with MOSFET or IGBT devices configured as bi-directional pairs in the output
bridge. In this case, the complete process in Fig. 8 would be needed to generate the complete 50% gate drive pulses. The 50% gate pulses still support pulse transformer coupling, retaining the simplicity of the gate drive isolation. The PWM cycloconverter process scales directly to higher switching speeds possible with these devices.

Fig. 13 shows experimental waveforms generated with the control circuit of Fig. 12. The top trace is the ramp, at 2 kHz. The second trace is a 60-Hz sinusoidal modulating function set for a 73% modulation depth. The two bottom traces are outputs of the two PWM comparators. They represent combinations of signals $P_1(t)$ and $P_2(t)$ in Fig. 9. For example, every other pulse in the trace labeled $DE$ corresponds to the rising edge of waveform $P_1(t)$ in Fig. 9(a), while the rest correspond to the falling edges of $P_2(t)$ in Fig. 9(a). Similarly, the trace labeled $AD$ corresponds to Fig. 9(b). These combined waveforms are adequate as SCR's are used in this experiment and only the leading edges of the pulses are of interest. We consider signal $P_1(t)$ as phase lagging with respect to a 1-kHz square wave synchronized with the ramp, while $P_2(t)$ can be treated as phase leading.

Fig. 14 shows again the ramp and modulating function overlapped. The bottom two traces are the delayed pulse train $Q_D$ and the advanced pulse train $Q_A$ generated by the multivibrators. Signal $Q_D$ corresponds to all edges of the gate drive sequence in Fig. 9(a) while $Q_A$ corresponds to the edges in Fig. 9(b). Notice that $Q_A$ pulses at the crossing points of the ramp and the sine wave. The signal $Q_D$ is less obvious; its crossing points correspond to the negative of the modulating function. For natural commutation, the delayed waveform is blanked when the current is negative, while the advanced waveform is blanked when the current is positive. The effect of the lagging current of the inductive load is readily observed.

Fig. 15 shows waveforms from the converter operation with the 2 kHz ramp for reference. The 1-kHz square wave synchronized to the ramp was produced by a push-pull forward converter. The turns ratio of the HF transformer provided 120-V peak to peak link voltage from a 30-V source. The bottom two traces are the cycloconverter output voltage and output current. The output voltage is identical to that produced by conventional two-level PWM behavior. The filtering effect of the series connected 35 mH and 6.2-Ω load was chosen to allow significant ripple to make the switch action and PWM behavior clear.

Notice that the SCRs are switching at 1-kHz each. The polarity of the square wave link voltage automatically enforces natural commutation between the SCR pairs (Q1,Q2) and (Q3,Q4) for positive load current and (Q5,Q6) and (Q7,Q8) for negative load current. The combined behavior of alternate switching gives rise to an effective 2-kHz switching frequency at the output, even though each device switches at half this rate. This important property of the PWM cycloconverter process can be used to extend the effective operating range of any given switching device.

Cycloconverter commutation during the load current zero-crossing is an important control issue, well understood from conventional ac cycloconverter results. Ideally, the current polarity detection scheme in Fig. 12 would use the “fundamental current zero” technique described in [22]. While this scheme results in ideal commutation with no cross-over distortion, it is known to be difficult to implement in practice. Instead, Fig. 12 uses a modification to the “first current zero” approach discussed in [22]. Blanking both the $Q_A$ and $Q_D$ signals at the current zero-cross forces discontinuous current operation to allow sufficient reverse recovery time for the SCR devices. The resulting zero-cross distortion is shown in the output voltage and current in Fig. 16.

From an overall perspective, the system operation can be understood in terms of direct PWM. A conventional PWM inverter provides either of two output levels. PWM switch action is combined with a fixed dc potential to supply these levels. In a cycloconverter-type system, the input is already two-level, and it is possible to identify a switch sequence that will deliver the same PWM output as in the conventional case. It has been shown that such a switch sequence can be generated based on conventional PWM techniques. It is also important that a switch sequence
can be configured to provide certain desirable properties such as 50% duty ratio, effective frequency doubling, or natural commutation.

In the fuel-cell application, the use of two-carrier PWM supports the streamlined topology of Fig. 7. Total system losses are lower than in a forward-converter/PWM inverter cascade, both because one diode stage has been eliminated and because of the frequency doubling effect. The arrangement of Fig. 7 is promising for the development of low-cost inverters with isolated low-voltage dc input.

VI. CONCLUSION

Fuel cells are well-suited to current-sourced converters because of their control requirements and low tolerance for mains-frequency ripple. Fuel cell conversion systems require an energy buffer, such as a battery, because of slow dynamics of their operating point adjustment. While simple topologies based on high-voltage dc buses are possible, the battery management problems inherent in a high-voltage bus make it compelling to locate batteries at a low-voltage port. With conventional methods, the end result is a multistage power converter. It was shown that the number of stages can be reduced, leading to a HF-link conversion approach. The reduction came from recognizing redundancy in the power processing. Without a dc link bus, rectifiers and filter components along with their associated losses were eliminated. Applying the techniques of PWM cycloconversion resulted in a PWM output exactly identical to conventional PWM techniques.

Multicarrier PWM is introduced as a way to unify PWM cycloconversion and conventional PWM control. The results of multicarrier PWM also can be used to provide gating signals suitable for isolated gate drives, and for other implementation aspects of HF link inverters. The output results can be set up to match those of conventional two-level PWM, with an effective ripple frequency double that of the switching.

A promising topology was proposed for low-cost inverters with isolated low-voltage dc input, suitable for fuel cell applications. The combination of a current-controlled input, controlled to adjust the average power demand from a fuel cell,
battery buffer, and PWM cycloconverter provides a reduced parts-count solution compared to conventional boost-forward-inverter cascade topologies. As shown in this paper, when multicarrier PWM is used for control, cycloconverter-type HF link inverters can be realized without additional complexity as compared to conventional cascaded inverters. Thus the reduced converter can be controlled with PWM methods that support convenient operation. The combined converter isolates the fuel cell from its load both electrically and dynamically while reducing parts count and, therefore, reduces costs relative to previous solutions.

ACKNOWLEDGMENT
The authors wish to thank E. Landsman for valuable comments and references.

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