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A Universal Power Converter for Emergency Charging of Electric Vehicle Batteries

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Abstract **- An on-board electric vehicle battery charger capable of accepting AC or DC inputs in the range of 12 to 260 volts is described. The charger provides near-unity power factor and high efficiency for routine charging from AC sources, but can also be used to tap other sources of power in the event of an emergency.**

I. INTRODUCTION

The successful return of the electric car as a common mode of transportation will depend to a large degree on the industry's ability to remove the stigmas that many attach to the electric vehicle (EV). The public's perception of a slow-moving vehicle with low acceleration, for example, is no longer justified considering the recent advances the have been made in developing electric race cars[1]. Nevertheless, consumers are not likely to be swayed towards purchasing an electric car unless its price, performance and convenience can compete with that of the conventional gasoline-powered automobile. The only real remaining obstacle to widespread acceptance of the electric vehicle is that of limited range. This is due directly to the nonavailability of a lightweight, high-capacity, cost-effective and quickly-chargeable battery. Also related to this issue is the fact that consumers are wary of being stranded in a car that cannot be conveniently refueled or repaired, should a breakdown occur.

Infrastructure planning [2] and fast-charger development [3] are presently underway to mitigate this problem, but in the interim, EV manufacturers will have no choice other than to continue supplying vehicles which are based on existing technologies. The vast majority of these vehicles, in addition to those already on the highway, use lead-acid battery packs with voltages under 200 volts. Most use conventional battery chargers which are both inefficient and produce non-sinusoidal line currents on the 120/240 volt AC lines.

The concept described in this paper does not solve the problem of limited range, but it does provide an alternative for achieving range extension and consumer confidence that he will not be left helpless somewhere on the highway.

The basic thrust of this initial work is to make use of a high-frequency, lightweight, on-board universal power converter. In addition to performing efficient routine charging at the user's home or business, the converter is capable of conveniently tapping power from almost any available source. This will allow the EV owner to obtain emergency or extended-range power from sources which include low-current 110 volt receptacles, 220 VAC recreational vehicle (RV) receptacles, gasoline-driven generators, photovoltaic arrays of any voltage, and DC power packs of other electric vehicles. This converter even makes it possible to safely charge the EV's high-voltage system from another automobile's 12 volt ignition battery with "jumper" cables.

The prototype charger described in this paper has been designed to provide near-unity power factor when powered from the utility grid. This not only addresses concerns about power quality, but also allows reasonable levels of power to be drawn from electrical outlets without tripping circuit breakers. The converter is universal in the sense that it accepts input voltages in the range of 12 to 260 volts AC or DC. Efficient EV chargers have been developed previously [4]-[5], but these have not included provisions for emergency charging. The described converter represents a proof-of-concept stage and starting point for further research in this area.

II. CHARGER REQUIREMENTS

The following characteristics are considered necessary for any on-board emergency charger:

- lightweight
- flexible
- galvanically isolated with safeguards
- reliable
- foolproof and easy to use
- meets all electromagnetic emission regulations

The following additional characteristics are very desirable:

- near-unity AC power factor
- high efficiency
- low cost

If the on-board power converter is to be used for normal day-to-day charging, the converter's efficiency should be optimized for 120/240 volt AC operation. If the converter is to be used primarily for range extension and emergency charging, then flexibility and reduced weight might take higher priority.

III. A HARDWARE PROTOTYPE

A. Basic Operation

A prototype converter has been constructed to evaluate the concept of the universal emergency charger. A simplified diagram of the converter's power circuit is shown in Fig. 1. For routine charging from residential 120/240 volt AC lines,

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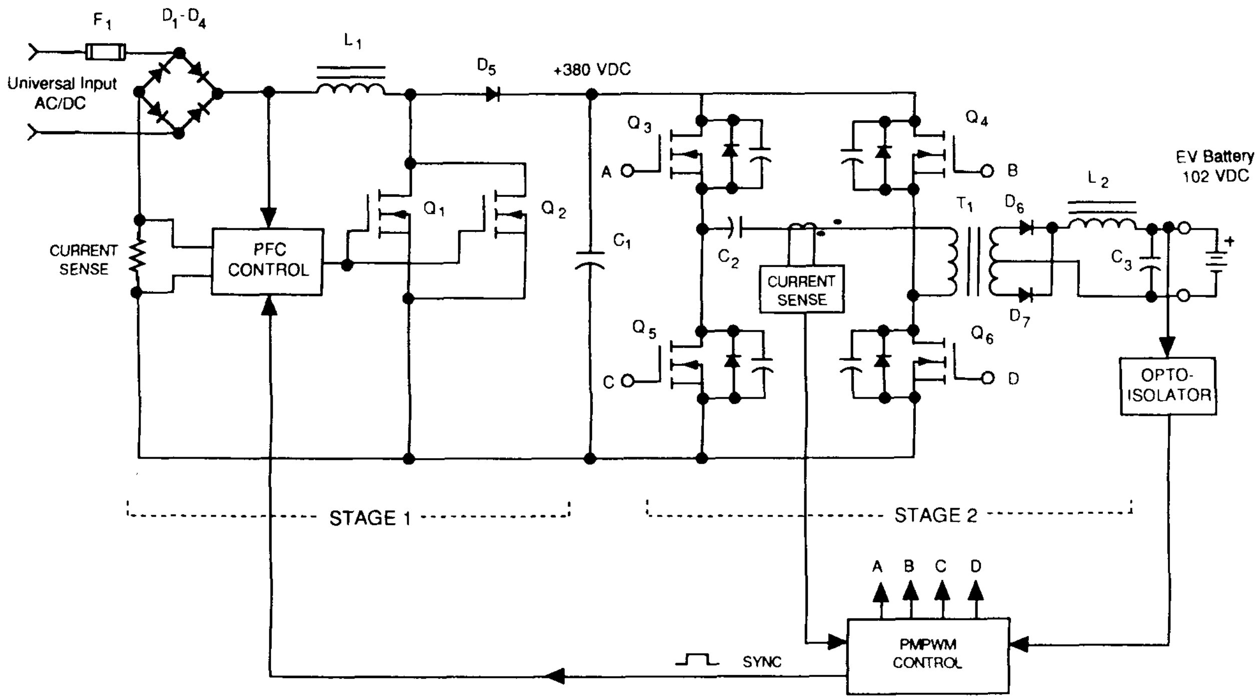

Fig. 1. Conceptual diagram of the prototype universal power converter.

the charger acts as two cascaded, synchronized converters operating at 100kHz. The first stage employs active power-factor correction to provide a nearly-sinusoidal input current. The second (full bridge) section controls power flow to the EV battery. Phase-modulated pulse width modulation (PMPWM) is used to obtain zero voltage switching (ZVS) of the MOSFETs, thereby increasing efficiency.

For input voltages in the range of 105 to 260 volts, the two power stages operate as independent sub-systems to supply full rated power to the battery. Once the EV battery voltage reaches the equivalent of 2.5 volts/cell, charging can either be terminated or reduced to a maintenance (trickle) level. When input voltages less than 105 volts are encountered, the PFC and PMPWM control circuits reduce the power flow so that device current ratings are not exceeded and practical duty cycles are possible. A HIGH/LOW charge switch is also provided as an integral part of the ON/OFF switch. In the HIGH position, maximum converter power is limited for safe operation from 20 amp circuits. The LOW position is used for 15 amp AC circuits and cigarette lighter plugs in automobiles. This type of switch requires the user to consider and select the proper HIGH or LOW setting prior to energizing the converter.

B. The PFC Section

Power factor correction (PFC) is achieved in the first stage using a conventional boost-type converter. A ML4821 average current mode PFC chip provides the basic control functions as shown in Fig. 2. A resistive shunt of 0.03 ohms is used for current sensing so that the circuit can accommodate both AC and DC power sources. Regardless of whether the input is AC or DC, the converter tracks the input waveform so that the charger appears as a resistive load. The controller operates in a conventional sense except that the gain of the current multiplier is adjusted by a factor K. That is, the output of the current multiplier is

$$I_{MO} = K \times I_{ref} \times (V_{EA} - 0.8) \qquad (1)$$

where I_{ref} = the reference current which is directly related to the instantaneous value of the input voltage

V_{EA} = the output voltage of the error amplifier

K = the gain adjustment factor which is controlled by the voltage on pin 8

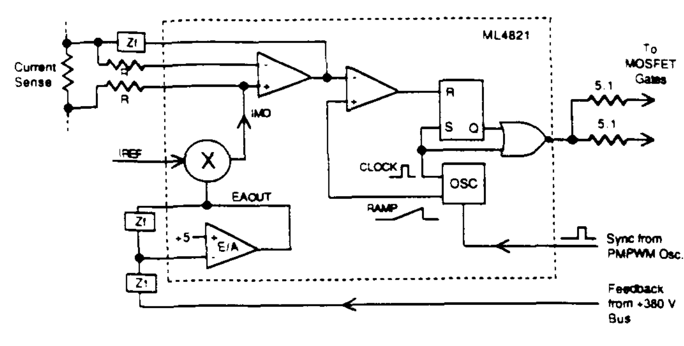

Fig. 2. The PFC Control Circuitry.

A sample of the converter's input voltage is modified by a passive network prior to being applied to pin 8. It is this control signal that reduces the power level of the input converter when low voltages sources are connected to the input.

Details of how input power is connected are shown in Fig. 3. Resistor R limits inrush current when the converter is connected to a power source. This not only reduces stress on the components and prevents saturation of the boost inductor, but prevents sparking when the user connects the power. A time delay is not necessary on the switch since the main reservoir capacitor C_1 will be fully charged by the time the user activates the "select-and-energize" switch. A single power cord with foolproof adaptors is provided for connecting the converter to various power sources.

C. Low Voltage Operation

Operating the universal converter from a low voltage DC source (such as 12 volts) poses several problems. First, significant input currents would be required to maintain charging at full rated power. This would mean that the ratings of all the power components would have to be scaled up in order to withstand currents that would seldom be encountered. In addition, the required duty cycle of the input PFC section would not be practical. Second, all voltage drops due to semiconductors or resistive elements in the primary circuit would become significant and reduce the efficiency of the converter. Third, the control ICs require at least 16 to 18 volts to commence operation.

The first problem is averted by the automatic reduction in control system gain with decreasing input voltages. At very low voltages, converter input current is further limited by the cycle-by-cycle current limiting function of the ML4821. Maximum permissible input power is as shown in Fig. 4. While the practicality of charging an EV battery at the 220 watt level may seem questionable, the real gain is one that is psychological in nature. If a stranded motorist believes he has options, there will be less chance of a panic. Trickle charging the battery through, for example, a cigarette lighter plug for 15 minutes will allow sufficient time for the batteries to temporarily rejuvenate themselves due to redistribution of the battery electrolyte. This small bit of battery "life" may be just enough to allow the motorist to make it over a steep hill or to a nearby service station or telephone.

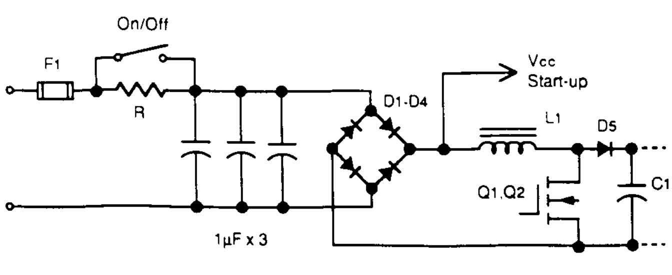

Fig. 3. Details of Input Power Connection.

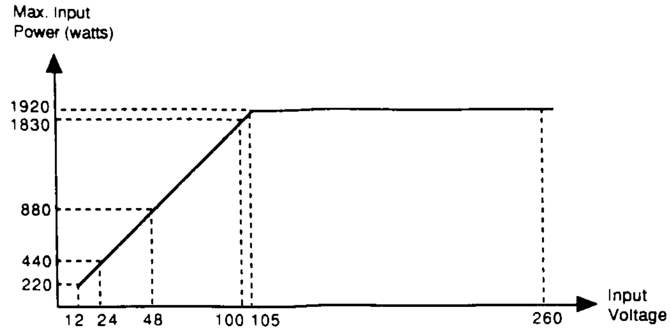

Fig. 4. Maximum Permissible Input Power vs Input Voltage.

The second and third problems are addressed with the auxiliary input circuit shown in Fig. 5. Instead of applying current through the main bridge rectifier, low-voltage DC is connected through a single power diode D_8 . This reduces the rectifier voltage drop to that of one diode. When power is applied, capacitors C_2 and C_3 are charged in parallel. When multi-function ON/OFF switch is activated, switches S_1 and S_2 are thrown, placing the capacitors in series to obtain twice the input voltage. These capacitors are chosen to provide just enough energy to operate the boost converter for a few cycles. Once normal operation is started, power for V_{cc} is supplied by a low-current parasitic winding on L_1. Start-up is normally accomplished by the precharge current through the 82K resistor.

D. The Output Power Stage

Power flow to the EV battery is controlled using PMPWM. This method achieves ZVS by keeping all pulse widths fixed in duration, with their relative phases varied to control the power delivery cycle. Control signals are derived from a ML4818 integrated circuit (IC). Referring to Fig. 1, operation is as follows:

Mode 1: Assuming that MOSFETs Q_3 and Q_6 have been conducting, the power cycle ends with Q_6 turning off.

Mode 2: The parasitic output capacitances of Q_4 and Q_6 charge towards the +380 volt bus, driven by the transformer's leakage inductance current. This action continues until the body diode of Q_4 turns on.

Mode 3: Q_4 is turned on, with V_{DS4} being near zero volts.

Mode 4: Q_3 is turned off allowing the transformer current to charge and discharge the output capacitances of Q_3 and Q_5 towards zero volts. This continues until the body diode of Q_5 turns on.

Mode 5: Q_5 turns on, causing current to flow through Q_4 and the transformer in the opposite direction. Power is delivered to the EV battery for the amount of time determined by the control circuit.

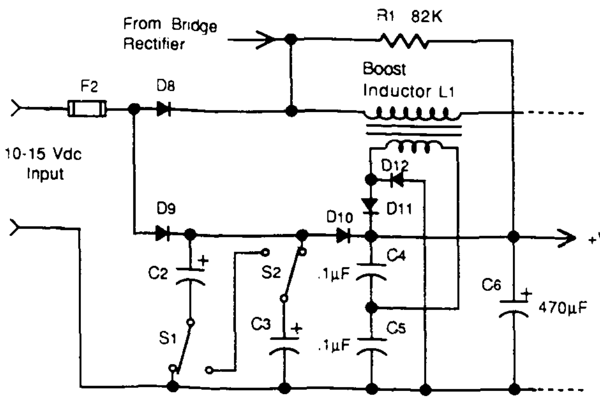

Fig. 5. Low-Voltage Start-up Circuit.

This sequence is repeated but for the opposite transistors to complete the entire cycle.

Cycle-by-cycle current limiting via a small current transformer protects the output devices, but also limits charging current when the battery pack is at a low state-of-charge. The current limit stage of the ML4818 continuously interrupts the normal duty cycle until the battery voltage is almost equal to the open-circuit voltage of the converter. The converter then operates like a constant voltage charger with battery current tapering off as the battery approaches 2.5 volts/cell.

For both safety and the reduction of voltage and current stresses on the components, the following 10-second power-up sequence is used.

1) C_1 is precharged prior to the converter being turned on.
2) When the V_{CC} storage capacitor voltage reaches 16 volts, the PFC output ramps up to full voltage.
3) As the 380 volt bus voltage is established, the PMPWM stage engages.
4) The PFC's oscillatory syncs with the PMPWM oscillator. This step synchronizes energy transfer through the converter and prevents "beat"frequency components from appearing in the signals of the two control loops.

The major power components are listed in TABLE 1.

IV. EXPERIMENTAL RESULTS

Preliminary tests have been performed on the experimental converter at power levels up to 800 watts. Fig. 6 shows the overall efficiency of the converter as a function of input voltage. It will be noticed that the converter operates at peak efficiency between 120 and 240 VAC. This is deliberate by design so that the converter will operate best from the most-likely sources of power. As expected, efficiency is poor when operating with low input voltages. However, it would probably be rare to ever use the charger in this region. Throughout most of the operating region, approximately 8% of the input power is lost in the active PFC section, with the remaining losses occurring in the PMPWM section. PFC losses, of course, increase at the extremes since the duty cycle of the converter is also at its extremes.

TABLE I
Power Circuit Components

Q1,Q2	APT5020 MOSFETs (500V, 28 Amp)
Q3-Q6	APT5025 MOSFETs (500V, 23 Amp)
D1-D4	Bridge Rectifier (600V, 35 Amp)
D5-D7	MUR6030 (600V, 30 Amp)
L1	175uH, Micrometals T-300-8 toroid, 55 T, #14 wire
T1	Magnetics P45530 E-core, 0.02" gap, 20T, parallel #18 wire, 8T,8T, #14 wire
C1	1200uF, 450V
C2	4uF, 400V Polypropylene

The input power factor for a 120VAC line at 500 watts is calculated as 0.98 using the first 17 harmonic components and the equation

$$PF = I_{rms}(1)/I_{rms}(n) \qquad (2)$$

where $I_{rms}(1)$ = the RMS value of the fundamental current component

I_{rms} = an estimate of the RMS value of the line current - - found by taking the root-sum-square of the first n current components.

The actual input voltage and current waveforms are shown in Fig. 7. While this is much better than a conventional

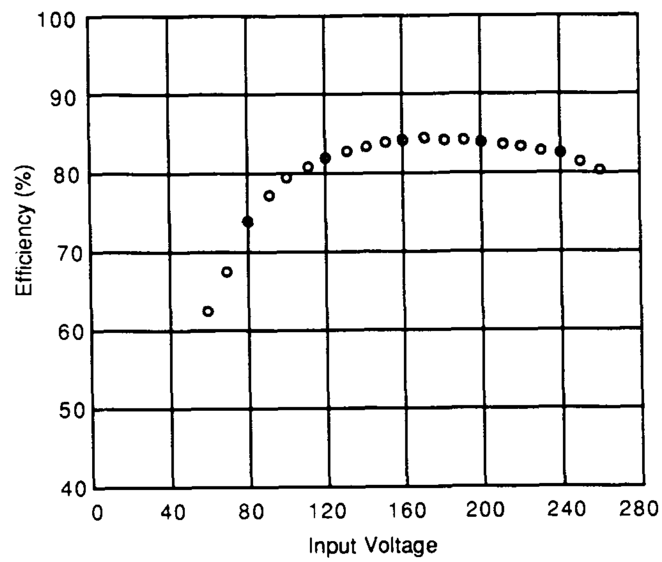

Fig. 6. Converter Efficiency vs. Input Voltage.

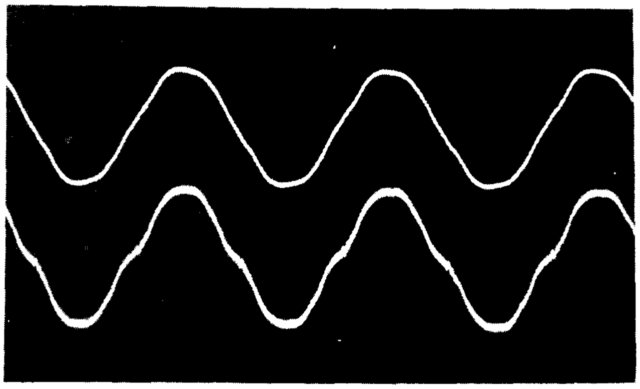

Fig. 7. Input voltage and current waveforms for 120VAC @500 watts. Top trace: Input voltage, 200 volts/div. Lower trace: Input current, 5Amp/div.

rectifier-type battery charger, it is expected that the waveshape can be improved with circuit refinements and input filtering.

Fig. 8 shows efficiency vs input power level. It is seen that operation from a 240 volt supply has a slight advantage as input current is decreased. In both Figs. 6 and 8, data for dc sources are not shown, but they are typically a few percent higher than the AC data. This is perhaps because the converter operates as a straight boost-type dc-to-dc converter. With AC inputs, the active PFC must cope with both zero crossings and peak voltages where duty cycles (and losses) are at their extremes.

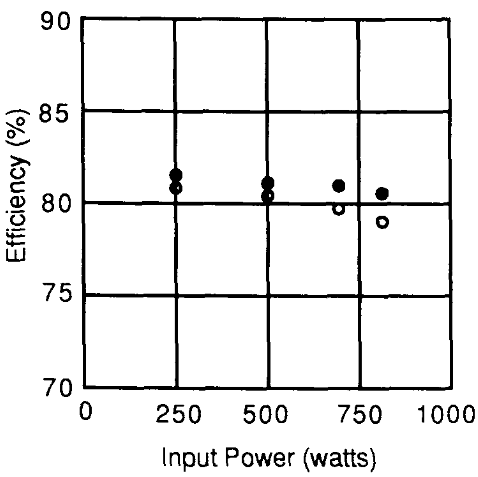

Fig. 8. Overall Efficiency vs. Input Power.

V. CONCLUSIONS AND FUTURE WORK

This paper describes a flexible EV power converter that can serve both as the regular charger and as an away-from-home charger in the event of an emergency. It also allows short range extensions without the worry of acquiring special equipment or making special arrangements. Active PFC is used to present a well-behaved load to either AC or DC sources. The converter's efficiency and input power factor are much better than those of conventional battery chargers. However, they can still be improved substantially.

Having tested a prototype, we are now refining some of the control circuitry and repackaging the converter as a 1.7kW unit for field testing. It is expected that the efficiency can be improved by combining the PFC and PWM functions to form a new topology with fewer semiconductor voltage drops. Better efficiency at low voltages and better power factor are expected with minor modifications of the control strategies.

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