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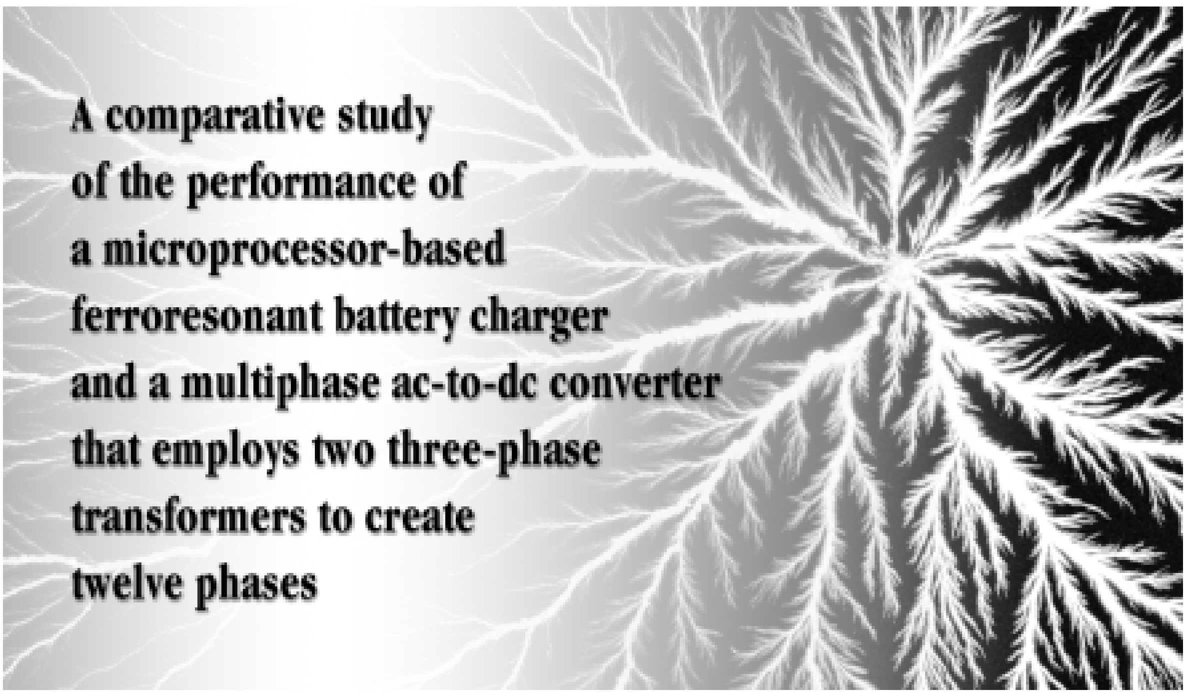
# Battery Chargers for Electric Vehicles






Electric vehicles (EV) are propelled by an electric motor that is supplied with power from a rechargeable battery. Performance characteristics required for many EV specifications far exceed the capabilities of conventional battery systems. However, as battery technology improves, the charging of these batteries becomes very complicated due to the high voltages and currents involved in the system and the sophisticated charging algorithms. This causes more disturbances in the existing ac power system, thereby increasing the needs for efficient, low-distortion chargers.

This article presents a comparative study of the performance of two types of battery chargers being developed for electric vehicles. The first charger is a microprocessor-based ferroresonant battery charger, referred to as the *ferroresonant charger*. The power delivery section of this charger is a ferroresonant transformer, which exploits the saturation of magnetic materials through its capacitor winding to produce a well-regulated output that resembles a square wave. The control section periodically places a resistive load across the battery under charge that allows this change in resistance to be detected. A microprocessor controls the timing and executes the gating of the needed switches in the circuit and then gathers and analyzes data from the battery charge monitor circuit. The monitor circuit measures the voltage drop across the battery, which is proportional to the battery internal resistance when the load is introduced.

The second charger is a multiphase ac-to-dc converter that employs two three-phase transformers to create twelve phases and is called the *twelve-phase charger*. One transformer primary is in the delta configuration, and the other transformer primary is in the wye configuration. The center-tapped secondaries create the twelve phases. Thyristors are used to control the output voltage of the charger through digital control of the firing angle. A microprocessor controls the charging profile of the battery. A motor-generator set is used to simulate the load to the charger for test conditions.

## Ferroresonant Charger

This battery charger is designed to deliver a maximum current of 30 A at 150 V dc to a lead-acid battery pack. The charger is made up of two main parts, the ferroresonant transformer and the control circuitry. The control circuit consists of the microprocessor, the power electronics isolation and switches, and the voltage monitoring circuit. The charger utilizes gassing point detection to determine when to end the application of a charge on a set of batteries [1].

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Typically, the device applies voltage to the batteries under charge for 1 hour. The charge is then interrupted by the microprocessor turning off a triac between the secondary of the ferroresonant transformer and the bridge rectifier (Figure 1). After the transformer is disconnected from the battery pack, the microprocessor turns on a MOSFET switch that introduces a resistive load across the terminals of the battery pack [2]. The response of the battery to this resistive load is evaluated by the monitoring circuitry, and a voltage proportional to the voltage drop at the battery terminals is sent to the A/D of the microprocessor. The microprocessor calculates a running average of these voltage signals and looks for a noticeable change in the signal that indicates the onset of gassing in the battery pack under charge. After the MOSFET is on for 700 ms, it is turned off, and the triac is gated to return the charge voltage to the battery pack. After 5 minutes of charging, the process repeats.

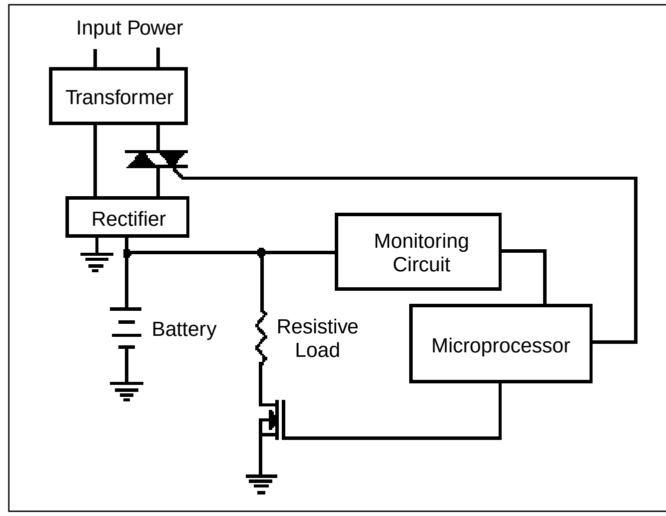


*Figure 1. Charger circuit [2]*

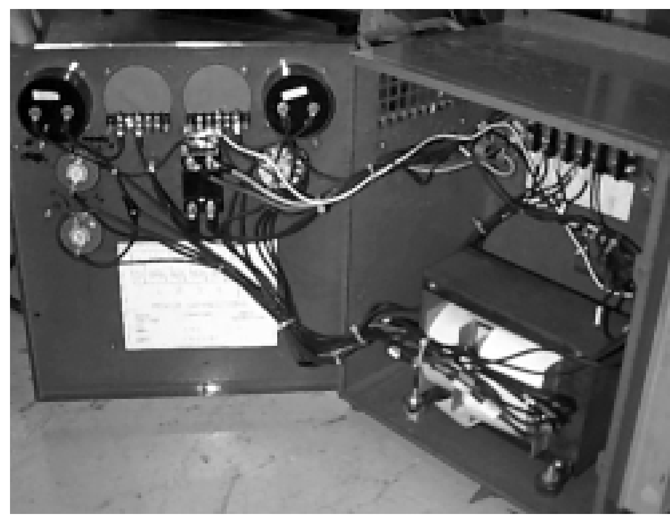
## Transformer Performance

The ferroresonant transformer is a form of voltage regulator [3]. Figure 2 shows a common form of a ferroresonant transformer voltage regulator. The primary and secondary sections of the ferroresonant transformer are physically separated by the magnetic shunts. The primary section is made up of only the primary winding, while the secondary section contains the output winding and the resonating winding, which is connected to the resonating capacitor. The primary operates in the linear portion of the B-H curve, while the secondary operates in the saturated mode. The capacitor determines the resonance characteristics. When the flux density of the transformer secondary winding reactance reaches a maximum, the impedance becomes a small saturated inductance. This low impedance forces the capacitor to discharge and recharge to the opposite polarity. Ferroresonant transformers have several inherent advantages: the output waveform is very close in shape to a square wave; this is excellent for applications that require rectification.

The data presented result from two test cases: with the secondary winding open-circuited, and with a resistive load of 18 ohms across the secondary winding. The V-I, or overload, characteristics of the ferroresonant transformer were measured for three different cases to determine the effect of varying the resonating capacitor value. The V-I curves were generated by loading the transformer while operating with three different resonating capacitor values: 45, 53, and 65 microFarads [2]. The load placed on the secondary of the ferroresonant transformer was a large capacitor (16,000 micro-Farads) in parallel with a resistive load. The resistive load was varied between 2.5 and 20.1 ohms. The purpose of this load was to attempt to simulate the impedance of a battery since the capacitor holds a dc voltage similar to the battery voltage and the resistor sinks a current analogous to a charge current.

The transformer output power for the three cases was measured as the load resistance varied. Results show that the transformer delivers a maximum of 4.6 kW as designed. It was emphasized that, until the resistor value fell below 2.8 ohms, the output of the transformer was very similar in all three cases.

Another measurement of interest is how well the ferroresonant transformer holds its output voltage with variations in the input voltage. This test was performed for two different loads. Given an input voltage of 230 V ac, the rectified output of the transformer delivered 152.4 V at 16.6 A. The voltage then was varied until the output voltage differed by 1% from 152.4 V. The maximum output of the variac was 265 V ac (input to the transformer); the output was 153.6 V at 16.6 A, which was still within 1%, so the upper voltage was not established. The input voltage that resulted in the output dropping by 1% was 174.4 V ac. Increasing the load so that the output at 230 V ac was 150.4 V at 21.3 A resulted in an upper and lower voltage of 258.6 and 199.3 V ac, respectively.


*Ferroresonant battery charger*

Both tests indicate that the ferroresonant transformer holds its output voltage very well with large changes in the input voltage. In the first test, a 25% drop in the input voltage caused only a 1% drop in the output voltage, and, with a larger load in the second test, a 13% drop in the input voltage caused a 1% drop in the output voltage. It can be seen that at larger loads a change in input voltage causes a larger change in the output voltage relative to the same change in input voltage at lower loads.

## Battery Charging Tests

Testing the charger made it possible to evaluate its performance while loaded with a set of high-voltage EV batteries. The battery pack that was charged by the ferroresonant charger was made up of eleven 12-V battery modules. The batteries are rated at 45 amphours at the 1 hour rate, and their maximum charge voltage suggested by the manufacturer is 14.1 V/module. The maximum suggested charge current is 30 A.

The main tests included looking at the efficiency of the charger, the current total harmonic distortion (THD) generated by the charger, and evaluation of the charger control and moni-

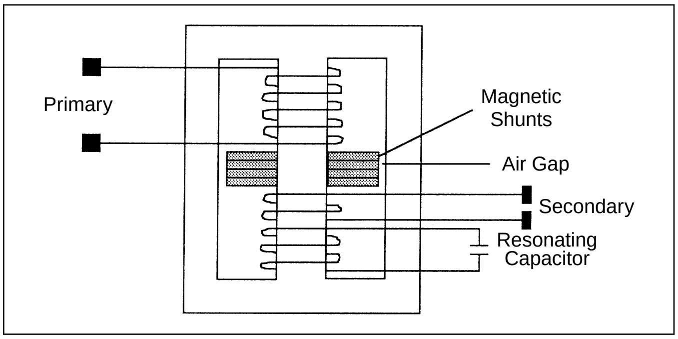



*Figure 2. A common form of the ferroresonant transformer voltage regulator [4]*

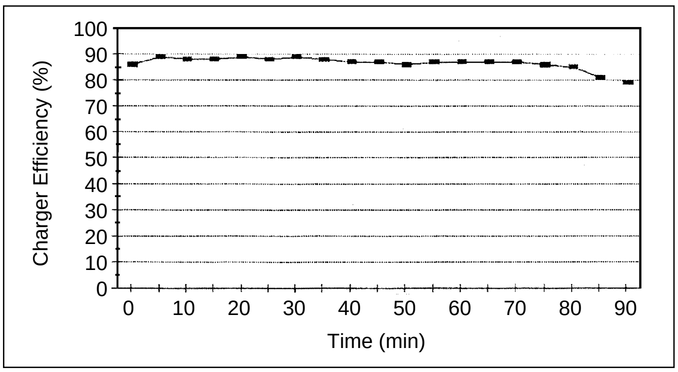



*Figure 3. Battery charger efficiency*

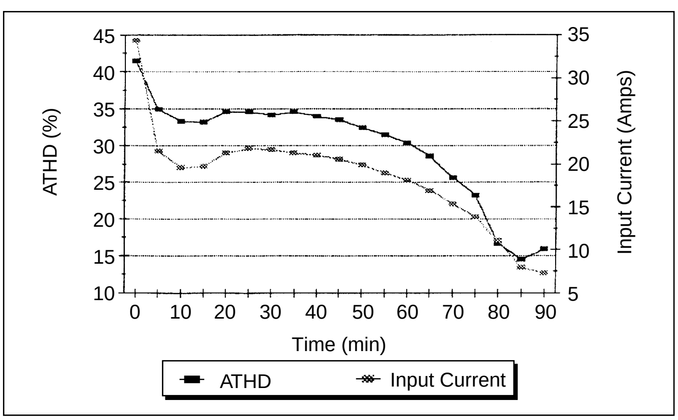



*Figure 4. Measured input current harmonic distortion*

toring circuitry. Figure 3 shows the measured charger efficiency during a charge on the battery pack. The average charger efficiency during this test was 86.5%. The losses are device losses and transformer losses. These losses are directly proportional to the output current of the charger, since the voltage drop across the devices is basically constant during conduction.

Figure 4 illustrates the total harmonic distortion measurement on the charger input current (ATHD) during the same charge depicted in Figure 3. The charger produces less than 35% current THD at approximately 22.5 A output. Current THD measurements exceeding 20% are generally considered too high. However, the results are better than several battery chargers in use today. By way of comparison, the current THD produced by the on-board battery charger of an electric Ford Escort station wagon was measured at 59.6% THD at an output current 15.7 A.

## Twelve-Phase Charger

A twelve-phase ac-to-dc converter is used as a battery charger. Two three-phase transformers generate the twelve phases; one transformer primary is connected in delta and the other transformer primary is in the wye configuration. The center-tapped secondaries furnish the twelve phases. Twelve thyristors are used to regulate the output voltage by controlling the firing angle of each phase. The conduction angle can be controlled by an eight-bit digital input from a microprocessor.

The power supply was built and tested [5], and modifications have been done to charge batteries rated at high voltages and currents. Thyristors are used to regulate the output voltage by controlling the firing angle of the thyristors with a digital controller. The controller is optically coupled to the thyristors' gate drivers, which trigger each thyristor by applying a current pulse to its gate terminal.

The digital controller controls the conduction angle of the twelve thyristors. The conduction angle can be programmed by an eight-bit input. The device operates best between a conduction angle of 0° and 105°; thereby, the output voltage varies between a minimum of 0 V and a maximum of 167.86 V for a nominal 120 $V_{rms}$ system in this range.

The high-density complementary metal-oxide semiconductor (HCMOS), an advanced eight-bit microcontroller unit (MCU) with on-chip peripheral capabilities, is used for this application. On-chip memory includes 2K bytes of electrically erasable programmable read-only memory (EEPROM), and 256 bytes of random-access memory (RAM). It has an eight-channel analog-to-digital (A/D) converter with eight bits of resolution. The voltage to be monitored is applied to the A/D converter. The current to be monitored is passed through a Hall-effect current sensor that is calibrated to read 0.3 V/amp. A low-pass filter is used to smooth the ripple of the output voltage of the current sensor. Figure 5 shows the interfacing of the twelve-phase system and the MCU.

### *Battery Simulator*

A motor-generator system is used to simulate the load to the charger. To start the system, the twelve-phase dc supply is connected to a dc motor-generator set, which acts as the battery simulator. First, the dc motor is used to bring the motor-generator to approximately synchronous speed. The field is then adjusted to bring the terminal voltage up to the same value as the utility voltage. Synchronizing lamps are used to synchronize the system. Once synchronized, the back emf of the dc motor simulates the battery voltage and the energy from the charger is transferred to the ac power grid.

The voltage and current are continuously monitored. If the voltage is greater than the full-charge open-circuit voltage $E_c$, the charger will not be turned on or a small trickle charge may be applied. If the battery voltage is less than $E_c$, the normal charging sequence begins. As the battery status changes, the current is kept constant by varying the conduction angle until the target voltage is reached, then the charger will automatically turn off or a trickle charge is maintained.

### *Test Results*

The field voltage is initially set at 100 V and increased to raise the battery voltage as its charge increases. This causes the current to decrease, but the conduction angle automatically increases to maintain the current constant at the set value. When the target voltage is reached, the conduction angle is reduced to maintain a trickle current flow or set to zero to turn off the charger. The forward voltage drop across each thyristor was measured to be approximately 1 V. The power supply for the digital controller and the microcontroller delivered 5.05 V and 0.567 A, or 2.86 W.

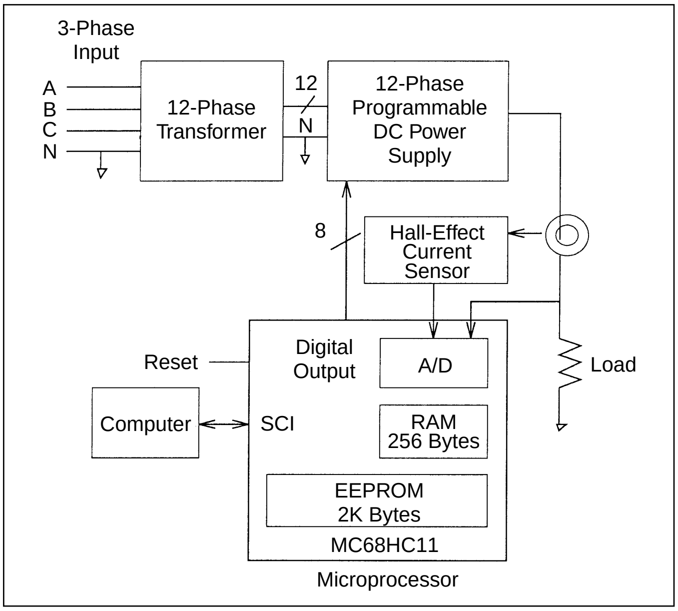



*Figure 5. Microprocessor control system*

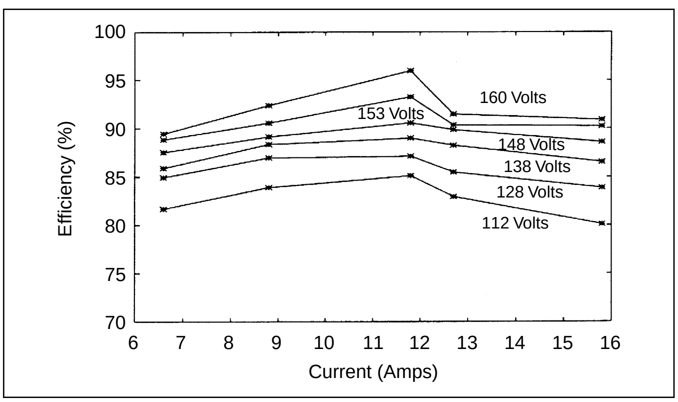



*Figure 6. Variation of current with efficiency*

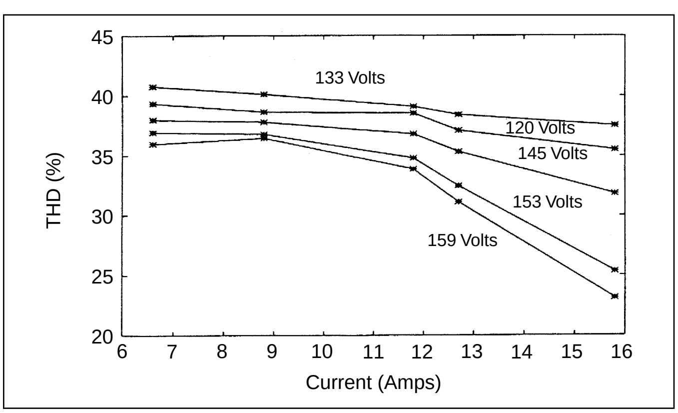
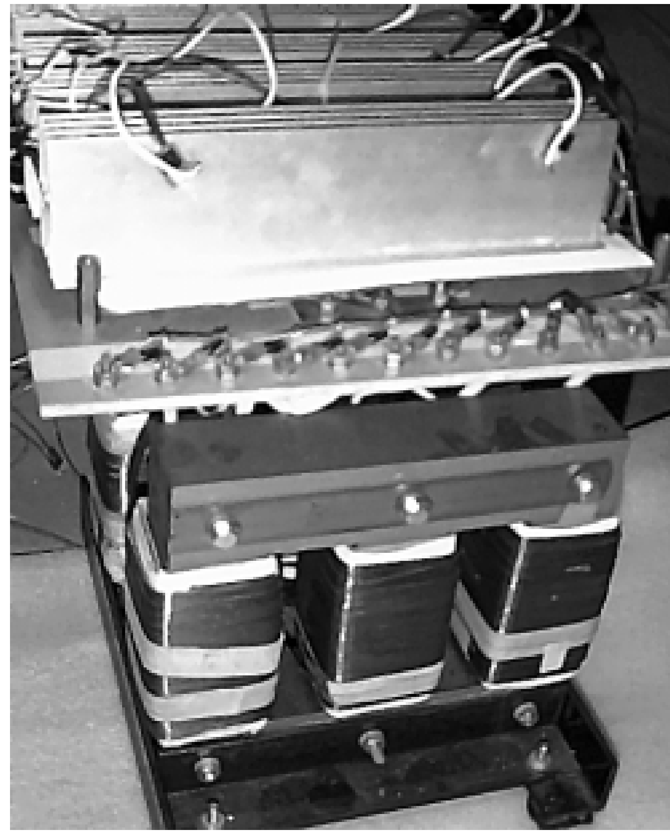



*Figure 7. Current versus total harmonic distortion*

Figure 6 illustrates the variation of current with efficiency for different voltage levels. It may be seen that the efficiency increases as the current is raised from 6.6 A to 11.8 A and then decreases as the current is increased. A harmonic analyzer was used to measure the voltage and current harmonic contents on the primary side of the twelve-phase transformer. Figure 7 depicts the total harmonic distortion (THD) at different currents for voltages ranging from 110 to 160 V. The harmonic distortion is minimum for a current of 15.8 A.



*Twelve-phase battery charger*

## Conclusions

Test results of the ferroresonant charger show that the use of a ferroresonant transformer in a battery charging application yields many benefits due to the transformer characteristics. The efficiency of the battery charger was measured at an average of 86.5% through a charge cycle, with a range of 79-89%. The total harmonic distortion of the input current was 34% at a charging current of 22 A. More battery characterization tests are needed to fine-tune the charger monitor circuit and software. Since the device is microprocessor-based, tuning can be done through software, saving time and effort.

The twelve-phase charger can be programmed very easily due to the unique method of controlling the conduction angle of thyristors. The charger could be used for any battery less than 160 V and 16 A or 2.56 kW. The THD of the primary is greatly reduced at the higher operating range required for batteries. The maximum efficiency is 96% at a maximum voltage of 160 V. The only limiting factor is the transformer, which, if modified, would yield better efficiencies.

## Acknowledgments

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## References

[1] F.D. Heavey and R. Engleman, "Method and apparatus for charging batteries," U.S. Patent 4 956 597, 1990.

[2] C.R. Mersman, M.M. Morcos, and N.G. Dillman, "Performance of ferroresonant transformer in microprocessor-based battery charger for electric vehicles," in *Proc. 7th European Power Electronics Conf.*, Trondheim, Norway, 1997, pp. 162-167.

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