01 Jul 2007

A Unique Ultracapacitor Direct Integration Scheme in Multilevel Motor Drives for Large Vehicle Propulsion

Shuai Lu

Keith Corzine
Missouri University of Science and Technology, corzinek@mst.edu

Mehdi Ferdowsi
Missouri University of Science and Technology, ferdowsi@mst.edu

Recommended Citation

S. Lu et al., "A Unique Ultracapacitor Direct Integration Scheme in Multilevel Motor Drives for Large Vehicle Propulsion," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 4, pp. 1506-1515, Institute of Electrical and Electronics Engineers (IEEE), Jul 2007.
The definitive version is available at https://doi.org/10.1109/TVT.2007.896970

A Unique Ultracapacitor Direct Integration Scheme in Multilevel Motor Drives for Large Vehicle Propulsion

Shuai Lu, *Student Member, IEEE*, Keith A. Corzine, *Senior Member, IEEE*, and Mehdi Ferdowsi, *Member, IEEE*

***Abstract*—This paper introduces a new set of methods to directly integrate ultracapacitor banks into cascaded multilevel inverters that are used for large vehicle propulsion. The idea is to replace the regular dc-link capacitors with ultracapacitors in order to combine the energy storage unit and motor drive. This approach eliminates the need for an interfacing dc–dc converter and considerably improves the efficiency of regenerative braking energy restoration in large vehicles using multilevel converters. Utilizing the proposed modulation control set, the two cascaded inverters can have their dc voltage levels maintained at any ratio (even a noninteger ratio) or dynamically varied over a wide range without disrupting the normal operation of the electric motor. As an advantage, ultracapacitor voltage or state of charge can be freely controlled for braking and/or acceleration power management. A regenerative energy management scheme is also proposed based on the vehicle's speed range considerations. Detailed simulation and experimental results verified the proposed methods.**

***Index Terms*—Cascaded multilevel inverter, electric vehicle, energy storage, hybrid converter, hybrid vehicle, regenerative braking, ultracapacitor, vehicle power management.**

I. Introduction

THE USE of electric motor drives in vehicles provides increased fuel economy, better vehicle performance, and control flexibility. For low-power sedan-sized (hybrid) electric vehicles, the conventional two-level six-switch inverter will still dominate due to strict cost considerations. Compared to two-level inverters, multilevel inverters excel in nearly all the performance indexes. Therefore, they are particularly suited for high-power rating large vehicular motor drives (> 250 kW) [7], [17]–[20], where the added power switch cost is less of a concern. Multilevel converters achieve much lower output harmonic distortion with less switching stress and reduce or eliminate the need for passive filtering devices. In addition, they offer significant reduction in motor drive electromagnetic interference emission, switching loss, common mode voltage causing the bearing leakage current, etc. [5]–[11].

The hierarchy of large vehicles starts from buses (mostly around or larger than 250 kW). The next higher power levels are the heavy duty trucks (mining and military vehicles), which are in the megawatt range. The traction drive has power level of a few megawatts. For the larger vehicles such as naval electric ships or commercial cruise liners, the power level is in tens of megawatts. Among these large vehicles, the series powertrain topology is dominantly used and the propulsion motor and inverter are rated for the full vehicle power. Therefore, applications of multilevel converters in large vehicles are receiving considerable research interest [7], [17]–[20].

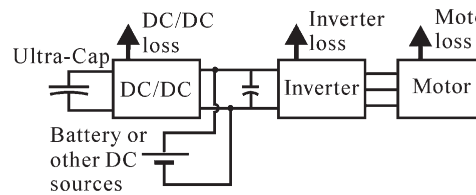

Fig. 1. Conventional ultracapacitor interface.

Battery banks are used as the main energy storage unit in most electric vehicles for fuel economy improvement. For large vehicles with the series powertrain topology, the battery banks function as the energy buffer for the onboard ac generator/rectifier system. Despite their large energy density, they suffer from a limited specific power and high losses during peak power transfer, particularly in regenerative braking and acceleration cycles. In comparison, ultracapacitors have much larger specific power and higher charge/discharge efficiency, despite their lower energy density. So as complementary energy storage, ultracapacitors offer load leveling, which greatly reduces the battery peak power demand and charging–discharging frequency. Therefore, their life spans are extended and the overall size and weight of the energy storage unit are reduced.

Conventionally, ultracapacitors were integrated into the energy storage unit through a dc–dc converter interface [1]–[4], as depicted in Fig. 1. The dc–dc converter maintains constant voltage to the inverter dc link, whereas the ultracapacitor voltage has wide variation ranges to fully utilize its energy capacity. Due to large inrush current during braking and acceleration, the dc–dc converter suffers from stability and efficiency issues [1]. Most of all, the dc–dc converter that was rated for the peak power current flow has high cost and weight (particularly the inductor).

In this paper, a new configuration and a control set are introduced for the multilevel converter with cascaded cells (MCCC) in large vehicle propulsion. The new multilevel configuration directly integrates the ultracapacitors without a dc–dc converter. As depicted in Fig. 2, the proposed topology consists of two

Manuscript received March 31, 2006; revised August 3, 2006 and September 20, 2006. This paper was presented at the 2006 IEEE Industry Applications Society Conference, Tampa, FL, October 8–12. The review of this paper was coordinated by Dr. B. Fahimi.

S. Lu is with MTS Sysytem Corporation, Eden Prairie, MN 55344 USA (e-mail: SL4xf@umr.edu).

K. A. Corzine and M. Ferdowsi are with the Department of Electrical and Computer Engineering, University of Missouri-Rolla, Rolla, MO 65409-0040 USA (e-mail: Keith@Corzine.net; ferdowsi@umr.edu).

Digital Object Identifier 10.1109/TVT.2007.896970

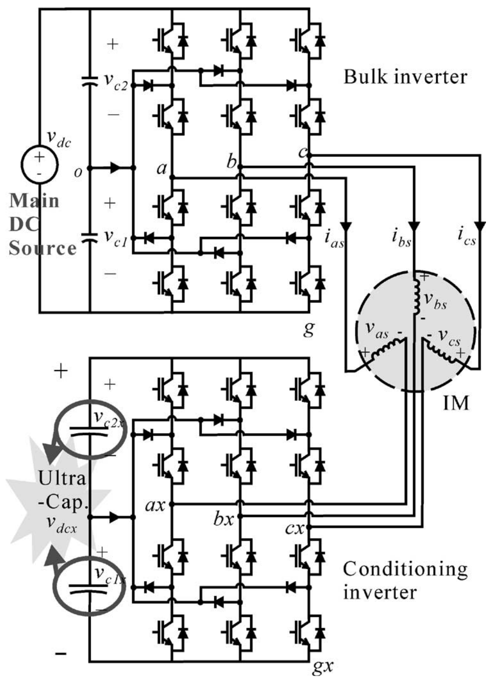

Fig. 2. Proposed large vehicle propulsion multilevel inverter with directly integrated ultracapacitor storage.

three-level diode-clamped inverters. The top inverter, which is referred to as the "bulk inverter," is fed by the main dc supply. The bottom inverter, which is referred to as the "conditioning inverter," is directly fed by ultracapacitors. The proposed converter control set can regulate the ultracapacitor voltage implicitly. Therefore, in the multilevel converter motor drives, a dc–dc converter is no longer needed for the ultracapacitor sources.

More specifically, with no real-power dc source in the conditioning inverter, the ultracapacitor voltage is regulated at an arbitrary level by the new MCCC control set. Also with the new controls, the wide and dynamic dc-link voltage variation in the conditioning inverter by braking energy storage/release will not disrupt the motor drive output. Therefore, the ultracapacitor power transfer and management can be done without using a dc–dc converter.

The proposed large vehicle MCCC inverter control and the motor drive using direct torque control with space vector modulation (DTC-SVM) are briefly described in Section II. The detailed discussion of the proposed methods, which enables the ultracapacitor direct integration implicitly with MCCC control, is given in Sections III–V. The regenerative energy control scheme is designed based on the energy storage "natural split" concept and introduced in Section VI. Detail simulations applying the proposed control set in vehicle energy management are presented in Section VII. The results of laboratory validation are presented in Section VIII.

II. Multilevel Converter-Fed Motor Drive for Large Vehicles

A. Multilevel Converter Topology

Fig. 2 shows the multilevel converter that is proposed for large vehicles. Compared to other multilevel topologies, this specific configuration offers higher modularity and fault tolerance capability. The two cascaded inverters (classic three-level diode-clamped inverters) are separate modules cascaded through a split neutral motor. Note that for power ratings larger than 15 kW, induction motors with a split neutral are widely available off-the-shelf (conventionally for a "Y-start Δ-operating" scheme).

With the increasing integration level and overall reliability of multilevel converter module, the prospects of multilevel technology in wider vehicular applications are evident. Particularly, the three-level diode-clamped converter module is now a mature product line from ABB, Siemens, etc. This fact makes the proposed multilevel topology stand out as a very practical solution in vehicular propulsion, as it needs no complicated assembly as in other multilevel topologies. It is virtually "plug and play" with off-the-shelf modules.

The two modules are physically separated and can operate separately. This provides the inherent fault tolerance features without complex controls. When one inverter module fails, it can be simply disconnected and the motor input terminals on its side are shorted to operate the healthy three-level inverter individually. Less voltage output levels (resolution) are available in the fault tolerant mode.

When two inverters use different dc-link voltages (at a 2 : 1 or 3 : 1 ratio), the equivalent voltage output has a higher number of voltage levels with given switch count [8]–[11]. This configuration is also referred to as a "hybrid converter," since there is a "natural split" of power generation between the two inverters, where the one with larger dc voltage produces higher power with lower frequency (bulk inverter on top); and the other inverter (conditioning inverter in bottom) produces lower power at the pulsewidth modulation (PWM) frequency.

B. Motor Drive Control Method Selection

In vehicle system level control, the torque seen by the wheels is split in real time between the internal combustion engine (ICE) and the electric motor. The split ratio changes dynamically to use the motor to produce fluctuating power peaks and leave the baseline power to the ICE. This requires instantaneous torque response from the motor. Stator-flux-oriented drive offers the needed torque control. It witnesses considerable recent research efforts mostly because it is less prone to motor parameter variation and requires no speed feedback for flux orientation [12], compared to the rotor-flux-oriented control.

As a popular variant of the stator-flux-oriented control, DTC-SVM [12], [13] has been chosen as the motor drive in this paper. Its block diagram is given in Fig. 3. The stationary frame q–d voltage references (reference voltage vector v_{ref}) are computed by the DTC-SVM in real time and then synthesized by the modulation control set that is introduced hereafter.

C. Overview of the Proposed Modulation Control Set

Given the reference voltage v_{ref}, it is up to the multilevel modulator to synthesize it and create the appropriate gate signals for each inverter cell. In this vehicle application, the

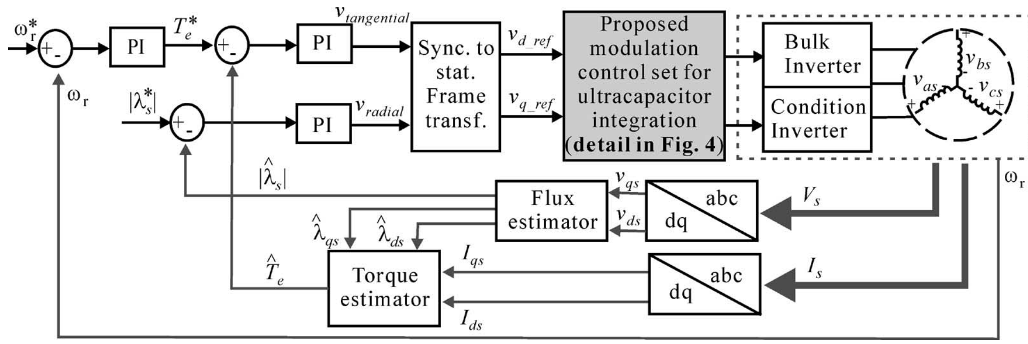

Fig. 3. Hybrid multilevel inverter-fed DTC-SVM motor drive with the proposed modulation control set.

tasks for the modulator are far more complicated than space vector algebra alone. To achieve flexible power management of ultracapacitors without using dc–dc converter, several unique control methods are integrated as a seamless modulation control block as highlighted in Fig. 3. These methods include the following: 1) hybrid modulation; 2) ultracapacitor voltage regulation; 3) noninteger dc voltage ratio modulation; and 4) regenerative braking/acceleration energy flow management and ultracapacitor sizing considerations.

1) Hybrid Modulation (to be Described in Section III): This method instantly tracks the v_{ref} that is produced by DTC-SVM and switches the bulk inverter at the fundamental frequency, while the conditioning inverter switches at the PWM frequency to produce multilevel voltage output. This modulation lays the foundation for the rest of the control methods. First, this modulation decouples the controls of the two inverters; therefore, the power flow into ultracapacitors can be handily controlled. Second, it reduces the modulation complexity with dynamically changing dc-link voltage ratio between the two inverters.

2) Ultracapacitor Voltage Regulation (to be Described in Section IV): The conditioning inverter has no stable dc source. Therefore, the ultracapacitor voltage needs to be regulated at a certain level. This is done by controlling the power flow into the conditioning inverter. The specific voltage level depends on the vehicle energy management decisions.

3) Noninteger DC Voltage Ratio Modulation (to be Described in Section V): This guarantees that the wide variations of the ultracapacitor voltage v_{dcx} and the changing dc-link voltage ratio between bulk and conditioning inverters will not deform the inverter output to the motor as commanded by DTC-SVM.

4) Regenerative Braking/Acceleration Energy Flow Management and Ultracapacitor Sizing Considerations: The aforementioned control set eliminates the need for dc–dc converter as an ultracapacitor interface. The energy can be directed in/out of the ultracapacitor with flexibility. The efficient way of managing the regenerative energy has to be investigated as well as the ultracapacitor rating and its effective variation range. These issues are to be detailed in Section VI. The four control methods constitute the highlighted block in Fig. 3. They are summarized in Fig. 4 with an overall conceptual block diagram. Each part of this modulator control set is discussed in detail in the following sections.

III. Hybrid Modulation

Hybrid modulation that was used in this paper is visualized in Fig. 5, which shows the voltage space vector plot when the dc voltage ratio between the bulk and conditioning inverters is 3 : 1. The MCCC gives an equivalent nine-level converter. The nine layers of the hexagon pattern voltage vectors can be organized hierarchically. In Fig. 5, the heavily dotted vectors represent all switching states of the three-level bulk inverter (which are named “bulk vectors”). The subhexagon vector pattern centering each bulk vector represents all the switching states of the conditioning inverter. Therefore, a reference voltage vector v_{ref} can be decomposed into the nearest bulk vector and a “relative reference” within the subhexagon centering the bulk vector. The conditioning inverter uses three nearest vectors to synthesize the “relative reference” with PWM. The resulting voltage outputs in both inverters are shown in Fig. 6. The hybrid modulation decouples the multilevel SVM into the bulk inverter staircase modulation and the three-level SVM in conditioning inverter. The power distribution between the two inverters can be handily controlled by the bulk inverter modulation.

As v_{ref} follows a circular locus in one fundamental cycle, it uses certain sequence of the bulk vectors depending on the modulation index. For instance, the sequence indicated by the blue line is used at high m index. When v_{ref} falls into the overlapped region of two neighboring subhexagons, it could use either bulk vector, the decision of which determines the duration time on each bulk vector in the sequence. By modifying the bulk vector duration time, the bulk inverter output staircase edges are shifted. This practice directly controls the power distribution between the two inverters. Therefore, it is utilized to control the voltage (or status of charge) of the ultracapacitors in the conditioning inverter. This is further discussed in Section IV.

IV. Ultracapacitor Voltage Regulation

Several methods have been proposed for the single dc source operation in the MCCC, which maintain conditioning inverter capacitor voltage v_{dcx} without utilizing any independent voltage source [8], [11]. In essence, all these methods directly or indirectly adjust the real power flow difference between the bulk inverter output and the load demand. For example, if v_{dcx} is lower than the required level, more power should be supplied by the bulk inverter than the load power demand. The extra

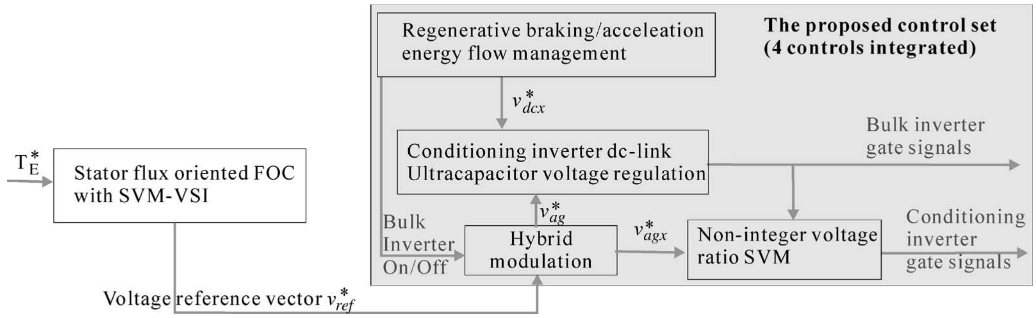

Fig. 4. Overall block diagram of the proposed modulation control set.

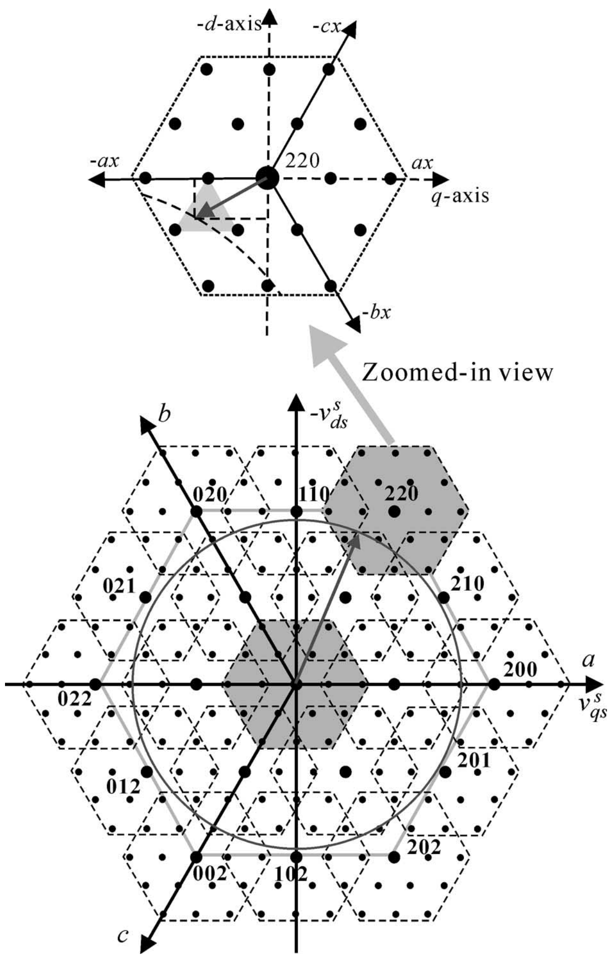

Fig. 5. Hybrid modulation visualization.

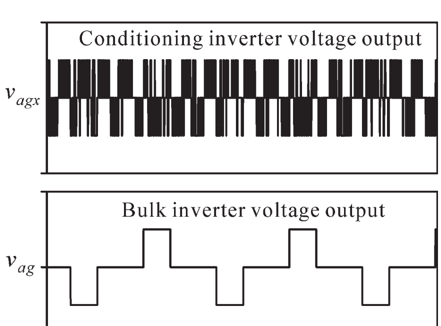

Fig. 6. Hybrid modulation voltage output.

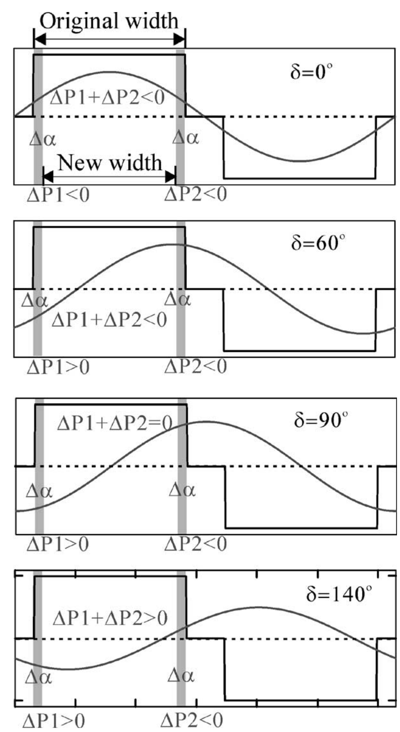

Fig. 7. Power adjustment by staircase width for various power factors.

power will end up charging the conditioning inverter capacitor and increase its voltage.

Compared to the previous methods, the method used in this paper requires much less real-time computation. It adjusts the real power flow by controlling the fundamental magnitude of the bulk inverter. As introduced in Section III, the adjustment is done by shifting the bulk inverter staircase edges. To do so, the bulk vector in d–q plane needs to be first transformed into time domain for each phase.

Then, the staircase edge shifting method is effective for the full range of power factors as in Fig. 7, which illustrated this control in power adjustment. Herein, the main inverter a-phase voltage and current are plotted for a power factor angle δ of 0°, 60°, 90°, and 140°. The $\Delta\alpha$ is positive, which reduces the staircase width, and the resulting total power output are always reduced at positive impedance angles. Therefore, the total capacitor charge is reduced. With the same analysis, negative $\Delta\alpha$ results in output power increase from the main inverter. For the negative load power, which has a negative power factor angle, the $\Delta\alpha$ adjustment has the reverse effects

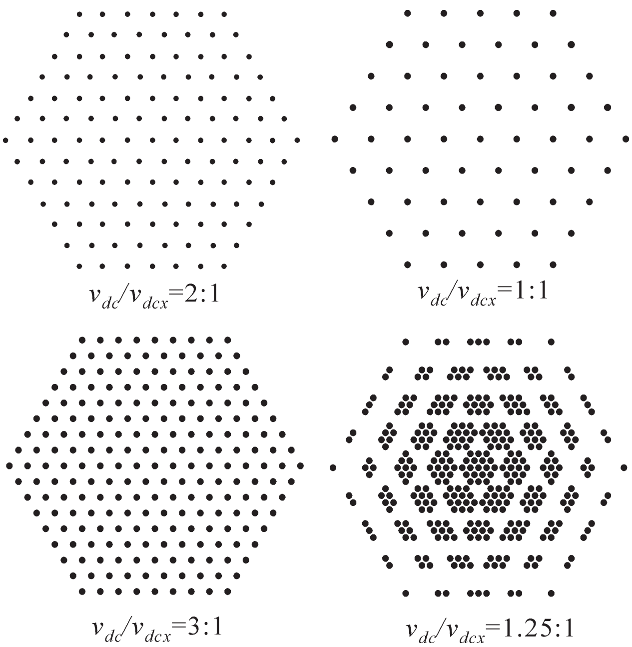

Fig. 8. Vector plot of different voltage ratios.

on capacitor charge, as shown for the $\delta = 140^\circ$ case, where the width reduction introduces positive power increment.

The control implementation flowchart is straightforward and will not be detailed in this paper. Herein, the focus of the capacitor voltage regulation is in its practical implications in vehicle operations. With the ultracapacitors in the dc link of the conditioning inverter, commanding its voltage v_{dcx} is to control its state of charge. This gives the vehicle system level controller the flexibility to freely assign its system-on-a-chip that is based on the driving conditions. In addition, at regenerative braking or fast acceleration phases, it can distribute the total active power production and regeneration between the two inverters.

V. Noninteger DC Ratio MCCC Modulation

As the ultracapacitors are directly across the conditioning inverter dc link, the peak energy transfers during the regenerative braking and acceleration cause wide variation in v_{dcx} and results in a noninteger dc-link voltage ratio between the two cascaded inverters (other than 2 : 1, 3 : 1, etc.).

Conventionally, only integer voltage ratios are used in MCCC, since it creates uniform distribution of the voltage vectors, which form meshes of equilateral triangles for space vector modulator. As in Fig. 8, the voltage ratio of 3 : 1, 2 : 1, and 1 : 1 result in nine, seven, and five layers of voltage vectors in the hexagon pattern, respectively. Note that the noninteger voltage ratio such as 1.25 : 1 results in nonuniform vector patterns, which are not usable for the regular SVM.

As a solution, a new modulation method handling noninteger (even dynamically changing) dc ratio between the cascaded inverters that is introduced in [16] by the authors is used herein. This method dynamically traces the changing ultracapacitor voltage and produce undeformed phase voltage output (fast average). As a result, the ultracapacitor status of charge can be arbitrarily controlled.

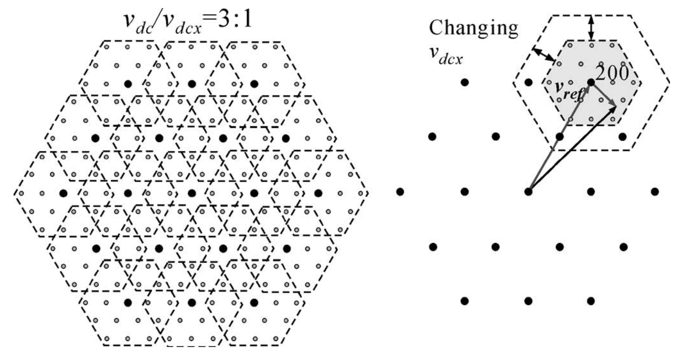

Fig. 9. Noninteger voltage ratio modulation illustration.

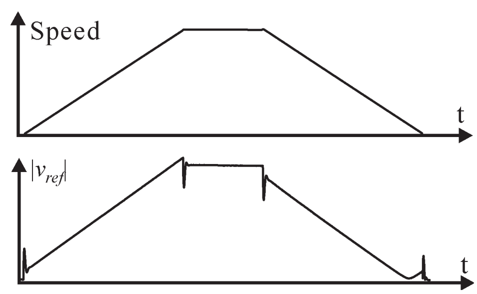

Fig. 10. Typical motor drive voltage versus speed.

The noninteger voltage ratio modulation is illustrated in Fig. 9. Out of the nonuniform voltage vector patterns, this certain bulk vector (switching state 200) that is close to the v_{ref} is used as a pivot for the highlighted subhexagon, which consists of all the switching states of the conditioning inverter. Then, v_{ref} is synthesized with the bulk inverter vector 200, together with the three nearest vectors enclosing v_{ref} in the subhexagon. Moreover, the size of subhexagon is directly related to the ultracapacitor voltage v_{dcx}, so v_{ref} can be visualized as being synthesized by three vectors of an equilateral triangle with varying size. By sampling v_{dcx} in each PWM cycle and using the reference voltage real value instead of the modulation index (m index), the duty cycles for the conditioning inverter can be dynamically adjusted to maintain the correct fast-average value of the voltage output. This justifies the elimination of the dc–dc converter.

VI. Regenerative Braking and Acceleration Energy Management

This section introduces a concept called *energy storage device natural split using hybrid multilevel converter*. The concept offers an insightful look at the proposed regenerative energy management scheme and the proper placement and sizing of the ultracapacitors.

A. Power "Natural Split" and Energy Flow Management

In the variable frequency drive, the synchronous motor speed is directly related to phase voltage magnitude (except for the resistive voltage drop), as shown in Fig. 10. Therefore, high motor speed corresponds to larger modulation index (m index)

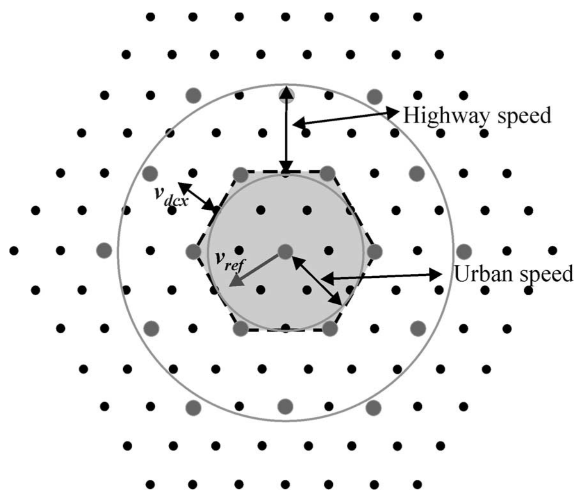

Fig. 11. Low/high speed operating range analysis.

or $|v_{\mathrm{ref}}|$ as indicated in the "highway speed range" in Fig. 11, where MCCC voltage vectors at 2 : 1 dc ratio are plotted. When the motor speed and m index are low, v_{ref} is totally within the highlighted inner subhexagon, i.e., the conditioning inverter is able to synthesize v_{ref} with the bulk inverter being disabled (bulk inverter is at switching states 000 or 222, and equivalent to shorted neutral point).

During braking or acceleration, disabling bulk inverter will direct the peak power to the conditioning inverter and charges or discharges its ultracapacitors. This practice offers the maximal efficiency. In Fig. 11, the initial ultracapacitor v_{dcx} is one-half of v_{dc}, and the inner subhexagon can inclose v_{ref} at urban speed. As braking starts, $|v_{\mathrm{ref}}|$ decreases, whereas v_{dcx} and the subhexagon size increase with inflow of the regenerated energy. Therefore, for the whole process of braking from urban speed, v_{ref} can be inclosed by the inner subhexagon and the conditioning inverter alone can produce v_{ref} and direct all the regenerative energy into the ultracapacitors.

The opposite process exists for acceleration to urban speed with only ultracapacitors. Figuratively speaking, the inner subhexagon shrinks while the vehicle speeds and $|v_{\mathrm{ref}}|$ increases. Given a large enough initial inner subhexagon, v_{ref} can be inclosed even after it reaches the urban speed. Obviously, the initial v_{dcx} must be higher than $(1/2)v_{dc}$. In both cases, with the noninteger dc ratio modulation, the normal phase voltage output is not disrupted by the dynamic v_{dcx} variation.

When the vehicle is at steady speeds, the bulk inverter is enabled and the net power is only from the its dc sources. The ultracapacitor voltage is regulated at a certain level (any noninteger ratio) and the conditioning inverter acts as an active filter to use PWM to "condition" the bulk inverter staircase voltage into multilevel voltage to the motor. The hybrid modulation is used herein. This steady-state mode offers the opportunity to charge the ultracapacitors to the desired value. One distinct feature of the proposed scheme is that the charging can be done implicitly by commanding a higher v_{dcx}; the ultracapacitor voltage regulation discussed previously will adjust the power distribution and direct net power into the conditioning inverter.

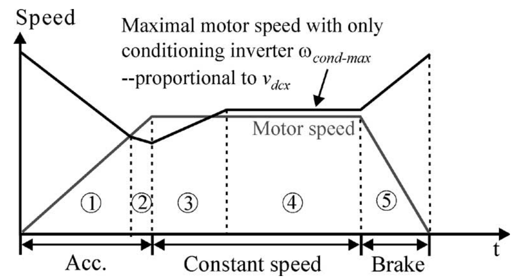

Fig. 12. Ultracapacitor voltage and maximal speed with conditioning inverter alone.

Typical vehicle driving profiles [14] show much more frequent power peaks during stopping and accelerations in the urban driving than in the highway. Therefore, the majority of the regenerative energy is at the urban speeds, which is usually less than half of the highway speed (rated motor speed).

From the previous discussion, it can be seen that there is a distinct "split" of the two types of power demands between the two inverters. The stable power of less magnitude is from the bulk inverter, whereas the peak power surges in braking and acceleration are mostly from conditioning inverter. This power demand "natural split" justifies the proposed energy storage device placement, in which bulk inverter uses only the battery source and conditioning inverter has only ultracapacitors.

In addition, based on the previous analysis, the overall energy management scheme is devised and illustrated in Fig. 12. This scheme considers the case when the initial ultracapacitor charge could not support the whole acceleration cycle. Herein, a vehicle cycle is further divided into five regions. The blue line represents the maximal achievable $|v_{\mathrm{ref}}|$ or motor speed with conditioning inverter only. It varies with the inner subhexagon size or v_{dcx}. In region 1, the bulk inverter is disabled and the ultracapacitors are the only source for acceleration. At a certain point, the conditioning inverter with the reduced v_{dcx} will no longer synthesize the v_{ref} correctly. Then, the rest of the acceleration (region 2) uses both inverters. With the hybrid modulation and v_{dcx} regulation, the ultracapacitor is further discharged to share part of the acceleration energy. Then, in region 3, which is the constant speed cruise, the ultracapacitor is gradually charged by simply ramping up the v_{dcx} command. When the v_{dcx} reaches the desired value, it is stabilized for the rest of the cruising phase, which is region 4. Finally in region 5, the braking can be done with only conditioning inverter and the regenerated energy are completely stored in ultracapacitors.

B. Ultracapacitor Rating and Its Variation Range

The ultracapacitor cost is a major factor in the large vehicle electric drive system design. To tradeoff between the cost and storage capacity, a fact to note is that braking and acceleration occur subsequently. Due to loss, the regenerated energy in braking is less than the energy needed for accelerating to the same speed. Therefore, the braking energy stored in ultracapacitors can be totally released before next braking. Since it is less efficient to direct the regenerated energy to battery, an economical ultracapacitor sizing might be just enough to absorb

TABLE I
INDUCTION MACHINE PARAMETERS

$J = 0.1\ \mathrm{kg \cdot m^2}$	$r_s = 0.25\ \Omega$	$r'_r = 0.36\ \Omega$
$L_{ls} = 2$ mH	$M = 69.3$ mH	$L'_{lr} = 2$ mH

the energy from one regular full braking or supply the energy to a full acceleration from/to urban driving speeds. It might be economically unfeasible to rate the ultracapacitor for less frequent driving profiles such as the complete energy absorption of multiple braking cycles and a full braking from highway speed or other unusual cases like the extended time of steep downhill driving.

To fully exploit the given ultracapacitor capacity, two parameters need to be determined. The first one is the proper voltage ratio between two inverters that is maintained during constant speed driving. The second one is the maximal ultracapacitor voltage rating and its variation range.

For the first problem, v_{dcx} should be commanded to make the resulting $\omega_{\text{cond}-\max}$ slightly larger than the motor actual speed (Fig. 12). Then, the conditioning inverter alone can sustain the entire braking and direct all the regenerated energy into the ultracapacitors. For urban driving, the steady-state dc ratio is most likely kept between 3 : 1 and 2 : 1.

Another consideration is v_{dcx} boundaries, which determines the effective energy capacity. Its lower limit can be set at $(1/3)v_{dc}$ (3 : 1 voltage ratio). Its upper limit can be set at v_{dc}. This enables large energy storage potentials and discharging depth, which is up to $(1/3)^2 = 1/9$. Both upper and lower voltage limits are easily enforced in the software of the v_{dcx} regulating control in Section IV.

VII. SIMULATION ANALYSIS

The proposed control set integrating four methods was verified by detailed simulations. For direct ultracapacitor integration, the control set replaces the SVM block in the induction motor DTC-SVM drive as in Fig. 3. The simulated motor drive uses scaled down parameters. Table I shows the induction motor parameters. The commanded stator flux is $0.35\ \mathrm{V \cdot s}$.

The bulk inverter dc voltage is fixed at 420 V, and the conditioning inverter's ultracapacitor is 0.1 F (scaled down value) with its voltage regulated normally at 210 V.

Fig. 13 shows the regenerative braking process in urban speed driving. Traces 1 through 5 are the reference voltage magnitude, motor speed, ultracapacitor voltage, phase current, and line-to-line voltage, respectively. Before braking, the $|v_{\text{ref}}|$ corresponding to the motor speed lies slightly outside of the inner subhexagon, as in Fig. 11. The bulk and conditioning converter uses hybrid modulation, and the bulk inverter provides real power. Once braking starts, $|v_{\text{ref}}|$ jumps to a lower value due to the motor resistance voltage drop. This brings $|v_{\text{ref}}|$ within the subhexagon. As previously analyzed, the conditioning inverter can work alone for the rest of the braking process.

Also note the sudden change of the line-to-line voltage v_{ab} outline. It changes from four-level to three-level output after

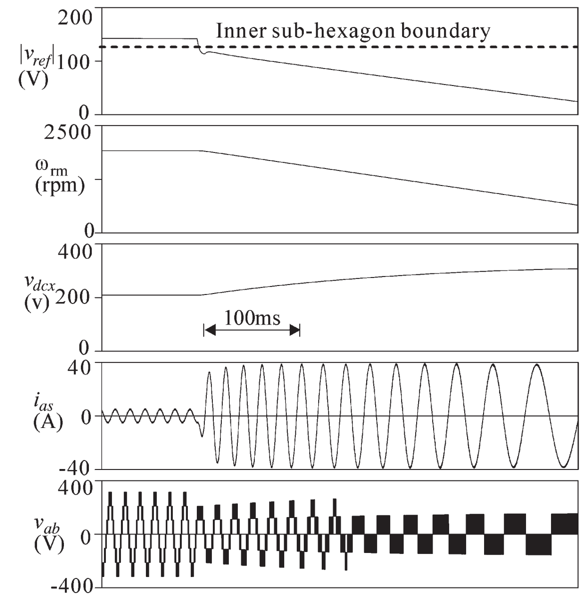

Fig. 13. Urban speed regenerative braking process.

the bulk inverter gets disabled, then eventually to two-level performance as $|v_{\text{ref}}|$ decreases. The braking energy builds up in the ultracapacitors, as observed in the v_{dcx} trace and the envelope of v_{ab}. With the proposed modulation method, the fast average of the phase voltage is not disrupted by the changing v_{dcx} and the sinusoidal current is not distorted.

Fig. 14 shows a full cycle of highway speed braking and acceleration. An example of energy management using the proposed control set is illustrated. The five traces on the left are the motor speed, reference voltage magnitude, phase current, torque, and ultracapacitor voltage, respectively. The full cycle is further divided into seven regions. Region 1 is the highway speed cruising where bulk inverter provides all the real power. Initially when braking starts, $|v_{\text{ref}}|$ is beyond the inner subhexagon and the bulk inverter cannot be disabled in region 2, so that hybrid modulation is still used and the ultracapacitor absorbs part of the regenerative energy while the rest goes into batteries in the bulk inverter. In region 3, the inner subhexagon incloses v_{ref} for the rest of braking, so that bulk inverter is disabled and all regenerated energy goes into ultracapacitors as in the previous urban driving example. After the standstill region 4, the vehicle accelerates, first with ultracapacitors power only (region 5). Obviously, the capacitor alone is not enough for a full acceleration; therefore, in region 6, bulk inverter is enabled again to supply part of the power, and the capacitor voltage regulating control further discharges the ultracapacitor and supplies the other part of the power needed until the acceleration ends. Then, in region 7, v_{dcx} is maintained at 192 V, forming a noninteger dc ratio with v_{dc}.

Note that it is a vehicle system level decision regarding how far the ultracapacitors are to be discharged. The control set offers the flexibility to regulate its state of charge dynamically over a wide range without dc–dc converter.

Additionally, it is insightful to look at the zoom-in view on the right side of Fig. 14. As motor speed and $|v_{\text{ref}}|$ increase with a decreasing v_{dcx}, the number of v_{ab} levels (steps) and its

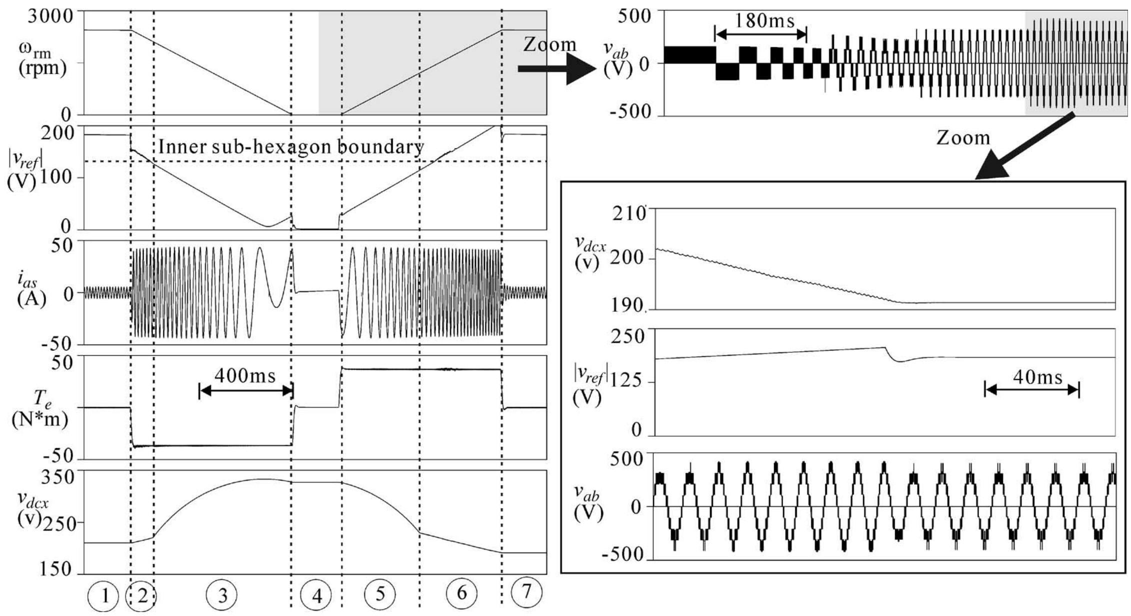

Fig. 14. Highway speed regenerative braking and acceleration process with an example of energy management.

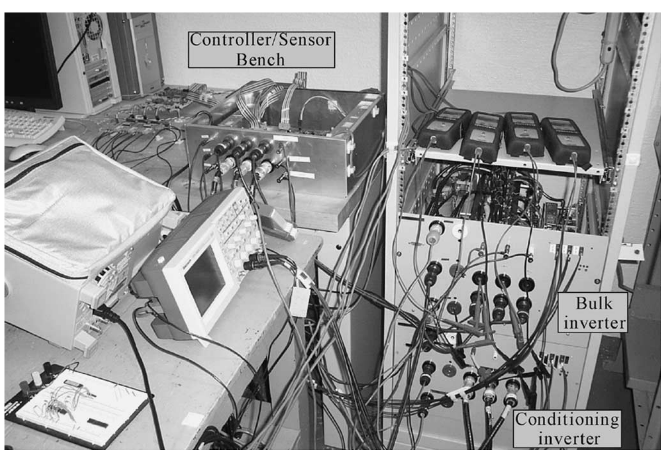

Fig. 15. Laboratory setup.

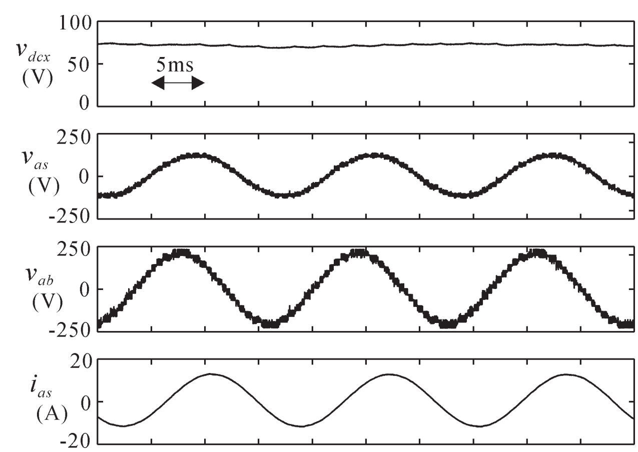

Fig. 16. Laboratory measurement at rated motor load.

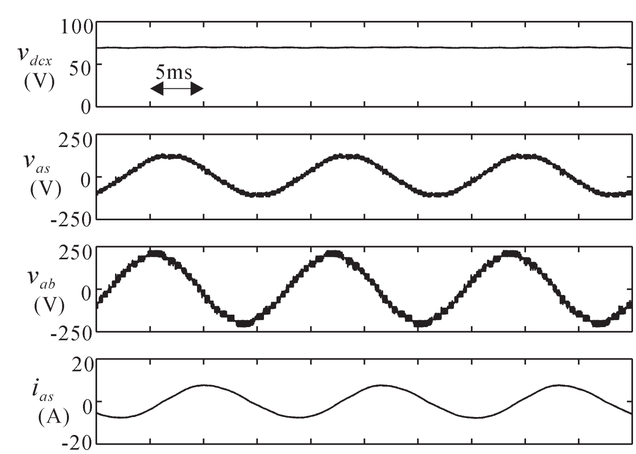

Fig. 17. Laboratory measurement at no load.

envelope change accordingly. Furthermore, the noninteger dc ratios between two inverters result in certain overlapped levels in multilevel line-to-line voltage v_{ab}; whereas in conventional MCCC with integer dc ratios, it has purely clear-cut steps. However, the fast-average value that is applied to the motor load remains sinusoidal despite the unusual v_{ab} shape. A more thorough analysis of MCCC with noninteger dc ratios is given in another paper [16] by the authors.

VIII. Experimental Results

The laboratory prototype is shown in Fig. 15. Two three-level diode-clamped inverters are cascaded through a 3.7-kW induction motor (same parameters as in Table I) that is coupled with a dynamometer station. The two inverters are controlled via fiber optics from the controller bench where a TI-TMS320C32 digital signal processor implements the control set shown in Fig. 4. The bulk inverter dc voltage is set at 210 V. As a scale down system test, the conditioning inverter dc link uses electrolytic capacitors instead of an ultracapacitor bank. Figs. 16 and 17 show the laboratory measurement of

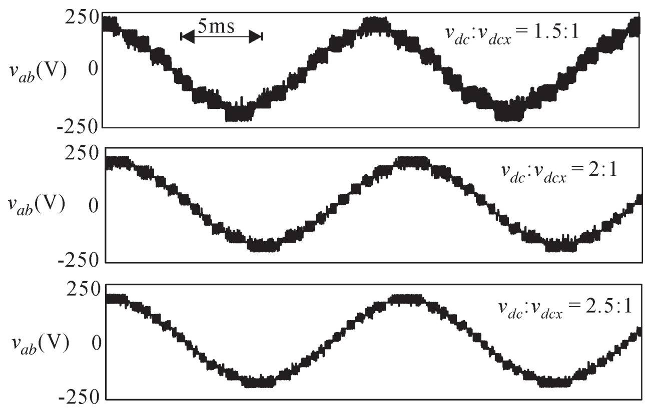

Fig. 18. Laboratory data of the arbitrary capacitor voltages that were regulated at different dc ratios.

the motor running at full load and no load at 1765 r/min. The four traces from the top are the conditioning inverter capacitor voltage, motor phase voltage, equivalent line-to-line voltage, and phase current, respectively. In either case, the proposed control well regulates the capacitor voltage at the commanded value. The exceptional performance of the multilevel PWM voltage output is obvious compared to the conventional two-level PWM inverters that are used in vehicular propulsion. In this test, the capacitor voltage is maintained at one-third of the bulk inverter dc voltage. Laboratory measurement that is shown in Fig. 18 demonstrates that the capacitor voltage can be controlled at arbitrary values (dc ratios) without disrupting the normal output to the motor, which is evident in the normal line-to-line voltages.

IX. Conclusion

A new method of integrating energy storage devices into the multilevel motor drive of large vehicles has been presented in this paper. The energy regenerated from braking will be stored in ultracapacitors that are embedded in the conditioning inverter of a cascaded multilevel motor drive; hence, there is no need for an interfacing dc–dc converter and the efficiency of the system is higher. Due to the inherent energy storage characteristics of ultracapacitors, the dc-link voltage ratio of the cascaded bulk and conditioning inverters is not an integer and varies by time. However, employing the proposed set of modulation methods, the motor drive output remains undisrupted while the ultracapacitor state of charge is freely controlled. Extensive simulation and experimental results prove the excellence of the proposed control set and power management scheme.

References

[1] W. Lhomme, P. Delarue, P. Barrade, A. Bouscayrol, and A. Rufer, "Design and control of a supercapacitor storage system for traction applications," in *Proc. IEEE Ind. Appl. Soc. Conf.*, Oct. 2005, vol. 3, pp. 2013–2020.

[2] R. M. Schupbach, J. C. Balda, M. Zolot, and B. Kramer, "Design methodology of a combined battery–ultracapacitor energy storage unit for vehicle power management," in *Proc. IEEE Power Electron. Spec. Conf.*, Jun. 2003, pp. 88–93.

[3] E. Ozatay, B. Zile, J. Anstrom, and S. Brennan, "Power distribution control coordinating ultracapacitors and batteries for electric vehicles," in *Proc. Amer. Control Conf.*, Jun./Jul. 2004, vol. 5, pp. 4716–4721.

[4] J. R. Anstrom, B. Zile, K. Smith, H. Hofmann, and A. Batra, "Simulation and field-testing of hybrid ultra-capacitor/battery energy storage systems for electric and hybrid–electric transit vehicles," in *Proc. IEEE Appl. Power Electron. Conf.*, Mar. 2005, vol. 1, pp. 491–497.

[5] J. Rodríguez, J. S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls and applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 724–738, Aug. 2002.

[6] D. G. Holmes and T. A. Lipo, *Pulse Width Modulation for Power Converters—Principles and Practice*. Piscataway, NJ: IEEE Press, 2003.

[7] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel converters for large electric drives," *IEEE Trans. Ind. Appl.*, vol. 35, no. 1, pp. 36–44, Jan./Feb. 1999.

[8] S. Lu, K. A. Corzine, and T. H. Fikse, "Advanced control of cascaded multilevel drives based on P–Q theory," in *Proc. IEEE Int. Electr. Mach. and Drives Conf.*, May 2005, pp. 1415–1422.

[9] K. A. Corzine, S. D. Sudhoff, and C. A. Whitcomb, "Performance characteristics of a cascaded two-level converter," *IEEE Trans. Energy Convers.*, vol. 14, no. 3, pp. 433–439, Sep. 1999.

[10] M. D. Manjrekar, P. K. Steimer, and T. A. Lipo, "Hybrid multilevel power conversion system: A competitive solution for high-power applications," *IEEE Trans. Ind. Appl.*, vol. 36, no. 3, pp. 834–841, May/Jun. 2000.

[11] M. Veenstra and A. Rufer, "Control of a hybrid asymmetric multilevel inverter for competitive medium-voltage industrial drives," *IEEE Trans. Ind. Appl.*, vol. 41, no. 2, pp. 655–664, Mar./Apr. 2005.

[12] G. S. Buja and M. P. Kazmierkowski, "Direct torque control of PWM inverter-fed AC motors—A survey," *IEEE Trans. Ind. Electron.*, vol. 51, no. 4, pp. 744–757, Aug. 2004.

[13] T. G. Habetler, F. Profumo, M. Pastorelli, and L. M. Tolbert, "Direct torque control of induction motor using space vector modulation," *IEEE Trans. Ind. Appl.*, vol. 28, no. 5, pp. 1045–1053, Sep./Oct. 1992.

[14] M. Amrhein and P. T. Krein, "Dynamic simulation for analysis of hybrid electric vehicle system and subsystem interactions, including power electronics," *IEEE Trans. Veh. Technol.*, vol. 54, no. 3, pp. 825–836, May 2005.

[15] T. M. Jahns and V. Blasko, "Recent advances in power electronics technology for industrial and traction machine drives," *Proc. IEEE*, vol. 89, no. 6, pp. 963–975, Jun. 2001.

[16] S. Lu and K. A. Corzine, "Cascaded multilevel converters with non-integer or dynamically changing DC voltage ratios," in *Proc. IEEE Int. Power Electron. and Motion Control Conf.*, Aug. 2006, pp. 1–5.

[17] K. Carpentier, "The electric ship integration initiative—An overview," in *Proc. IEEE Electr. Ship Technol. Symp.*, Jul. 2005, pp. 1–7.

[18] P. Tenca, G. Stumberger, and T. A. Lipo, "Analysis and modeling of future electrical propulsion and launch systems at the University of Wisconsin-Madison," in *Proc. IEEE Electr. Ship Technol. Symp.*, Jul. 2005, pp. 12–19.

[19] N. P. Schibli, T. Nguyen, and A. C. Rufer, "A three-phase multilevel converter for high-power induction motors," *IEEE Trans. Power Electron.*, vol. 13, no. 5, pp. 978–986, Sep. 1998.

[20] S. Dieckerhoff, S. Bernet, and D. Krug, "Power loss-oriented evaluation of high voltage IGBTs and multilevel converters in transformerless traction applications," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1328–1336, Nov. 2005.

Shuai Lu (S'05) received the B.S.E.E. degree in electrical engineering from the Chongqing University, Chongqing, China, in 1997, the M.S.E.E. degree in electrical engineering from the University of Wisconsin, Milwaukee, in 2003, and the Ph.D. degree in electrical engineering from the University of Missouri, Rolla, in 2007.

He is currently a Senior Research and Development Engineer at the MTS Systems Corporation, Eden Prairie, MN. He is the author or coauthor of many technical papers, including seven IEEE Transactions papers. He is also the holder of two pending patents. His research interests are power electronics and motor drives, including multilevel converters, multiphase power conversion, electric motor analysis/design/control, and their applications to hybrid (electric) vehicle and renewable energy. His current focus is the ultra-high-power-density and high-performance electric drive systems for hybridizing racing cars and ground vehicle testing systems.

Keith A. Corzine (S'92–M'97–SM'06) received the B.S.E.E., M.S.E.E., and Ph.D. degrees from the University of Missouri, Rolla, in 1992, 1994, and 1997, respectively.

He was with the University of Wisconsin, Milwaukee, from 1997 to 2004. He is currently an Associate Professor in the Department of Electrical and Computer Engineering, University of Missouri. His research interests include power electronics, motor drives, naval ship propulsion systems, and electric machinery analysis.

Mehdi Ferdowsi (S'01–M'04) received the B.S. degree in electronics from the University of Tehran, Tehran, Iran, in 1996, the M.S. degree in electronics from Sharif University of Technology, Tehran, in 1999, and the Ph.D. degree in electrical engineering from the Illinois Institute of Technology, Chicago, in 2004.

In August 2004, he joined the Department of Electrical and Computer Engineering, University of Missouri, Rolla, where he is currently an Assistant Professor. He has authored more than 20 journal and conference papers. His major research interests include digital control of switched mode power converters, battery charge equalization, electric and hybrid vehicles, and multilevel converters.

Dr. Ferdowsi is the recipient of the Joseph J. Suozzi INTELEC 2003 Fellowship Award from the IEEE Power Electronics Society.