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Shuai Lu

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

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

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

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

Electrical and Computer Engineering Department
University of Missouri - Rolla
Rolla, MO, USA
SL4xf@umr.edu; Keith@corzine.net; Ferdowsi@umr.edu

***Abstract*--This paper introduces a new set of methods to directly integrate ultracapacitor banks into cascaded multilevel inverters 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 electric and hybrid vehicles. Utilizing the proposed modulation control set, the two cascaded inverters can have their dc voltage levels maintained at any ratio (even a non-integer 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. An optimal regenerative energy management scheme is proposed based on the vehicle's speed range considerations. Detailed simulations verified the proposed methods.**

Keywords-cascaded multilevel inverter; energy storage; hybrid vehicle; hybrid converter; vehicle power management; regenerative braking; ultracapacitor

I. INTRODUCTION

Battery banks are used as the main energy storage unit in most hybrid electric vehicles (HEVs) (or EVs) for fuel economy improvement. Despite their large energy density; they suffer from a limited power density and high energy losses during peak electric power demand, particularly in regenerative braking and acceleration cycles. As an alternative source, fuel cells have similar drawbacks. 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/fuel cells peak power demand and charging-discharging frequency. Therefore their life spans are extended and the overall size and weight of the energy storage unit is reduced.

Conventionally, ultracapacitors were integrated into the energy storage unit through a dc-dc converter interface [1-4] as depicted in Figure 1. The dc/dc converter maintains constant voltage to the motor drive dc-link while the ultracapacitor terminal voltage has wide variation ranges to fully utilize its energy capacity. However, due to large inrush current during braking and acceleration, the dc-dc converter suffers from stability and efficiency issues [1]. Most of all, the

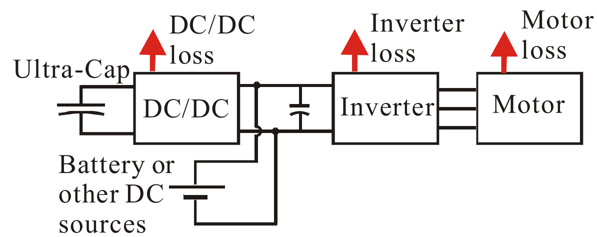

Figure 1. The conventional ultracapacitor interface

dc/dc converter rated for the peak power current flow has high cost and weight (particularly the inductor).

In this paper, a multilevel converter with cascaded cells (MCCC) is proposed for the electric drive in large HEVs or EVs (such as buses). While having the MCCC advantages, the proposed topology directly integrates the ultracapacitors into the inverter dc link. As depicted in Figure 2, the proposed converter consists of two three-level diode-clamped inverters. The top inverter, referred to as the bulk inverter, is fed by batteries (or fuel cell banks) and the bottom inverter, referred to as the conditioning inverter, is fed by the ultracapacitors.

With the integrated control methods introduced herein, the wide and dynamic dc-link voltage variation in the conditioning inverter by braking energy storage/release will not disrupt the motor drive output. With no dc-source in conditioning inverter, the ultracapacitor voltage is regulated at arbitrary level by the MCCC control. Therefore, the ultracapacitors power transfer and management can be done without using a dc/dc converter.

The added power switch cost using the MCCC in large HEVs is somewhat justified by its full array of advantages in nearly all the performance indices compared to the two-level six-switch inverter used in smaller drive systems [5-7]. Recently, the development in the integrated multilevel converter modules further improves its reliability and reduces the cost for its wider industrial applications.

The proposed large HEV (or EV) oriented MCCC inverter control and 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 in Sections III-V. The regenerative energy control scheme is designed based on the energy storage

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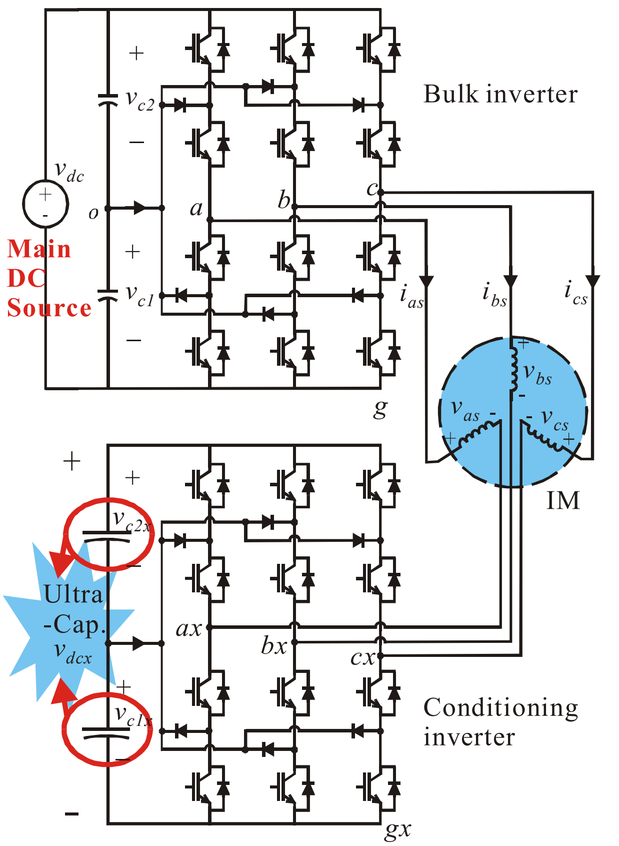

Figure 2. The proposed large vehicle propulsion multilevel inverter with directlyintegrated ultracapacitor storage

"natural split" concept and introduced in Section VI. Detail simulations applying the proposed control set in vehicle energy management are presented in Sections VII. Section VIII draws conclusions and presents an overall evaluation of the proposed scheme.

II. MULTILEVEL CONVERTER FED MOTOR DRIVE FOR LARGE HEVs/EVs

A. Hybrid Converter Power Section

Fig. 2 shows the multilevel converter proposed for large vehicles. Compared to other multilevel topologies, this specific configuration offers higher modularity and fault tolerance capability [8, 9]. First, the two cascaded inverter cells (the classic three-level diode-clamped inverter) are separate modules and can operate individually in case of failure in one. Secondly, in large power ratings (>15-kW), induction motors with split neutral are widely available off-the-shelf (conventionally for "Y-start, Δ-operating" scheme).

When two inverter cells use different dc-link voltages (at 2:1 or 3:1 ratio), the equivalent voltage output has higher numbers of voltage levels with given switch count [8-11]. This configuration is also called a "hybrid converter", since there is "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 PWM frequency.

B. Motor Drive Control Method Selection

In HEV system level control, the torque seen by the wheels is split in real time between the internal combustion engine (ICE) and 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 parameters 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, direct torque control with space vector modulation (DTC-SVM) [12, 13], has been chosen as the motor drive in this work. Its block diagram is given in Fig. 3. The stationary frame *d-q* voltage references (reference voltage vector v_{ref}) are computed by the DTC-SVM in real time and then synthesized by the modulation control set 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

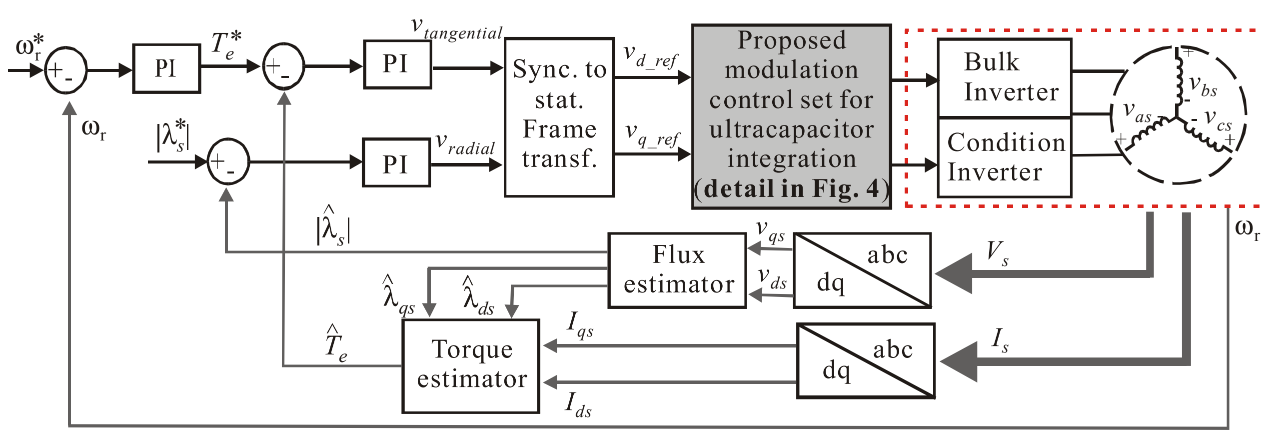

Figure 3. The hybrid multilevel inverter fed DTC-SVM motor drive with the proposed modulation control set

signals for each inverter cell. In this HEV application, the 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:

1) *Hybrid modulation* (to be described in Section III):

This method instantly tracks the v_{ref} 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 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) *Non-integer 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 command by DTC-SVM.

4) *Regenerative braking/acceleration optimal energy flow management and ultracapacitor sizing considerations:*

The control set above eliminates the need for dc/dc converter as ultracapacitor interface. The energy can be directed in/out of the ultracapacitor with flexibility. The optimal and efficient way of managing the regenerative energy has to be investigated as well as the ultracapacitor optimal rating and its effective variation range. These issues are to be detailed in Sections VI. The four control methods constitute the highlighted block in the Fig 3. They are summarized in Fig. 4 with an overall conceptual block diagram. Each part of this modulator control set is discussed in the following sections in detail.

III. HYBRID MODULATION

Hybrid modulation used in the paper is visualized in Figure 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 Figure 5, the heavily dotted vectors represent all switching states of the three-level bulk inverter (named “bulk vectors”). The sub-hexagon 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 sub-hexagon 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 Figure 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 sub-hexagons, 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 the next section.

IV. ULTRACAPACITOR VOLTAGE REGULATION

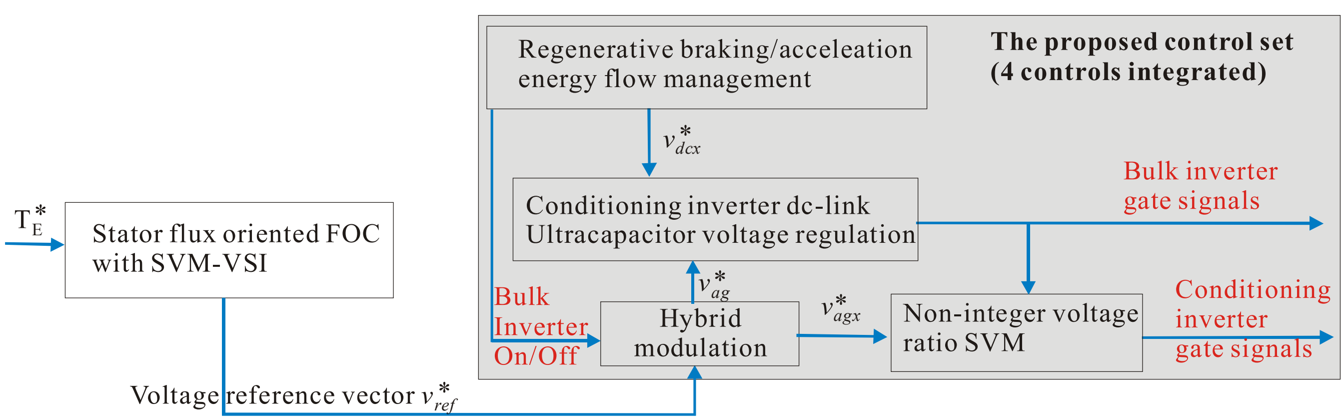

Figure 4. Overall block diagram of the proposed modulation control set

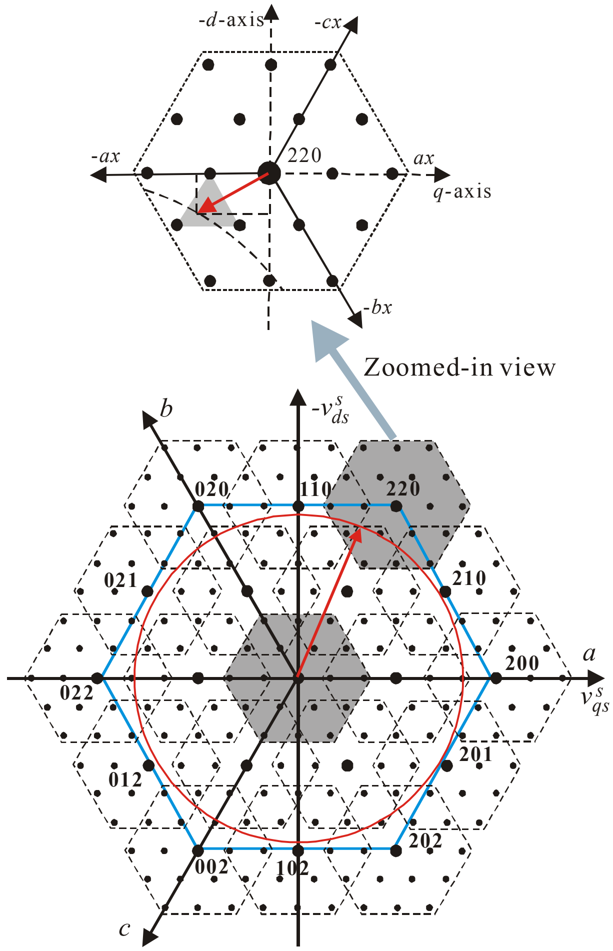

Figure 5. Hybrid modulation visualization.

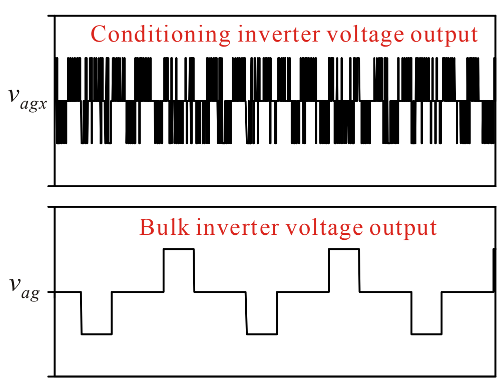

Figure 6. Hybrid modulation voltage output

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 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 the previous section, 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 Δα 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 same analysis, negative Δα results in output power increase from main inverter. For the negative load power, which has a negative power factor angle, the Δα adjustment has the reverse effects on capacitor charge, as shown for the δ=140° case, where the width reduction introduces positive power increment.

The control implementation flow chart is straightforward and will not be detailed in the paper. Herein, the focus of the capacitor voltage regulation is in its practical implications in HEV (or EV). 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 HEV system level controller the flexibility to freely assign its SOC based on the driving conditions. Also at regenerative braking or fast acceleration phases, it can distribute the total active power production and regeneration between the two inverters.

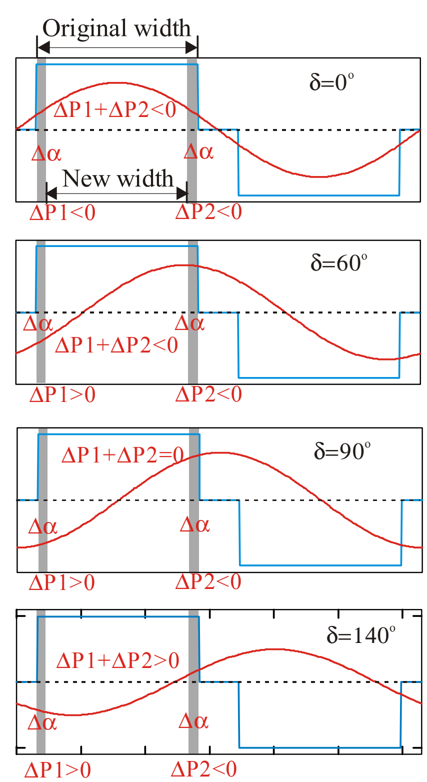

Figure 7. Power adjustment by staircase width for various power factors

V. NON-INTEGER 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 non-integer 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 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 non-integer voltage ratio such as 1.25:1 results in non-uniform vector patterns which are not usable for the regular SVM.

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

The non-integer voltage ratio modulation is illustrated in Figure 9. Out of the non-uniform voltage vector patterns, this certain bulk vector (switching state 200) close to the v_{ref} is used as a pivot for the highlighted sub-hexagon, 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 sub-hexagon. Moreover, the size of sub-hexagon 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 to the load. This justifies the elimination of the dc-dc converter.

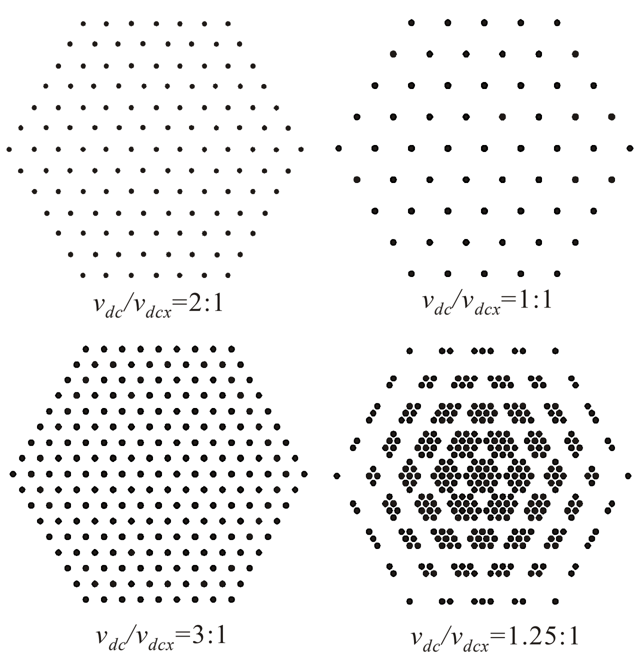

Figure 8. Vector plot of different voltage ratio

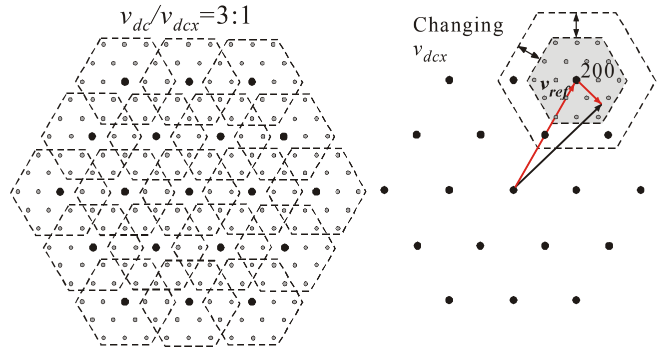

Figure 9. Non-integer voltage ratio modulation illustration

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 optimal 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 Figure 10. Therefore, high motor speed corresponds to larger modulation index (m-index) or $|v_{ref}|$ as indicated in the "highway speed range" in Figure 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 sub-hexagon, 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 Figure 11, the initial ultracapacitor v_{dcx} is 1/2 of v_{dc}, and the inner sub-hexagon can enclose v_{ref} at urban speed. As braking starts, $|v_{ref}|$ decreases; while v_{dcx} and the sub-hexagon size increase with inflow of the regenerated energy. Therefore, for the whole process of braking from urban speed, v_{ref} can be enclosed by the inner sub-hexagon 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 sub-hexagon shrinks while the vehicle speeds and $|v_{ref}|$ increases. Given a large enough initial inner sub-hexagon, v_{ref} can be enclosed even after it reaches the urban speed. Obviously, the initial v_{dcx} must be higher than ½ v_{dc}. In both cases, with the non-integer dc ratio modulation, the normal phase voltage output is not disrupted by the dynamic v_{dcx} variation.

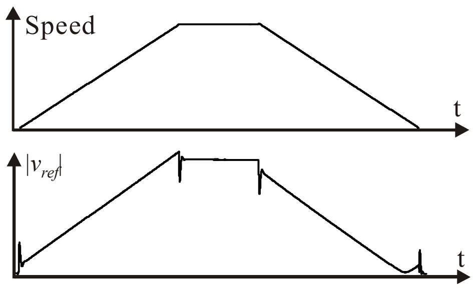

Figure 10. Typical motor drive voltage vs.speed

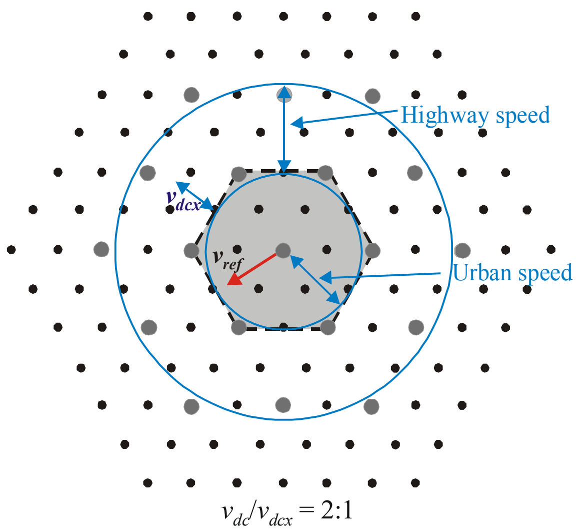

Figure 11. The low/high speed operating range analysis

When the vehicle is at steady speeds, the bulk inverter is enabled and the net power is only from the its dc sources (batteries or fuel cells). The ultracapacitors voltage is regulated at certain level (any non-integer 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.

Typical vehicle driving profiles [14] show much more frequent power peaks during stopping and accelerations in the urban driving than 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 distinct “split” of two types of power demands between the two inverters. The stable power of less magnitude is from the bulk inverter while the peak power surges in braking and acceleration are mostly from conditioning inverter. This power demands “natural split” justifies the proposed energy storage device placement, in which bulk inverter uses only the battery/fuel cells source and conditioning inverter has only ultracapacitors.

Also based on the previous analysis, the overall energy management scheme is devised and illustrated in Figure 12. This scheme considers the case when the initial ultracapacitor charge couldn't support the whole acceleration cycle. Herein, a vehicle cycle is further divided into 5 regions. The blue line represents the maximal achievable $|v_{ref}|$ or motor speed with conditioning inverter only. It varies with the inner sub-hexagon size or v_{dcx}. In region 1, the bulk inverter is disabled and the ultracapacitors are the only source for acceleration. At 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, 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 concern in HEV (EV) 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 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, 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 is the optimal voltage ratio between two inverters maintained during constant speed driving. The second is the maximal ultracapacitor voltage rating and its variation range.

For the first problem, v_{dcx} should be commanded to make

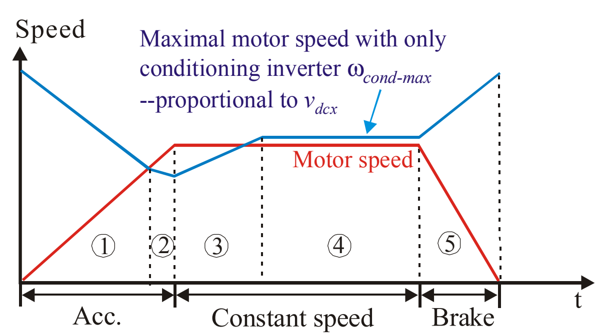

Figure 12. Ultracapacitors voltage and maximal speed with conditioning inverter alone

the resulting $\omega_{cond-max}$ slightly larger than the motor actual speed (Figure 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 software of the v_{dcx} regulating control in Section IV.

VII. SIMULATION ANALYSIS

The proposed control set integrating four methods were verified by detailed simulations. For direct ultracapacitor integration, the control set replaces the SVM block in the induction motor DTC-SVM drive as in Figure 3. The simulated motor drive uses scaled down parameters. The induction motor has the following parameters shown in Table I. The commanded stator flux is 0.35 V·s.

Table I. Induction Machine Parameters.

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

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

Figure 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 $|v_{ref}|$ corresponding to the motor speed layes slightly outside of the inner sub-hexagon as in Fig. 11. The bulk and conditioning converter uses hybrid modulation and the bulk inverter provides real power. Once braking starts, the $|v_{ref}|$ has a jump to a lower value due to the motor resistance voltage drop. This brings $|v_{ref}|$ 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 4-level, to 3 level output after the bulk inverter gets disabled, then eventually to 2 level performance as $|v_{ref}|$ 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.

Figure 14 shows a full cycle of highway speed braking and acceleration. An example of energy management using the proposed control set is illustrated. 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 7 regions. Region 1 is the highway speed cruising where bulk inverter provides all the real power. Initially when braking starts, $|v_{ref}|$ is beyond the inner sub-hexagon and the bulk inverter can't 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, inner-subhexagon encloses 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 supply the other part of the power needed until the acceleration ends. Then in region 7, v_{dcx} is maintained at 192V, forming a non-integer 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 wide rang without dc-dc converter.

Additionally, it is insightful to look at the zoom in view on the right side of the Figure 14. As motor speed and $|v_{ref}|$ increase with a decreasing v_{dcx}, the number of v_{ab} levels (steps) and its envelope change accordingly. Furthermore, the non-integer dc ratios between two inverters result in certain overlapped levels in multilevel line to line voltage v_{ab}; while in conventional MCCC with integer dc ratios, it has purely clear-cut steps. However, the fast average value applied to the motor load remains sinusoidal despite the unusual v_{ab} shape. More thorough analysis of MCCC with non-integer dc ratios is in another paper [16] by the authors.

VIII. CONCLUSIONS

A new method of integrating energy storage devices into

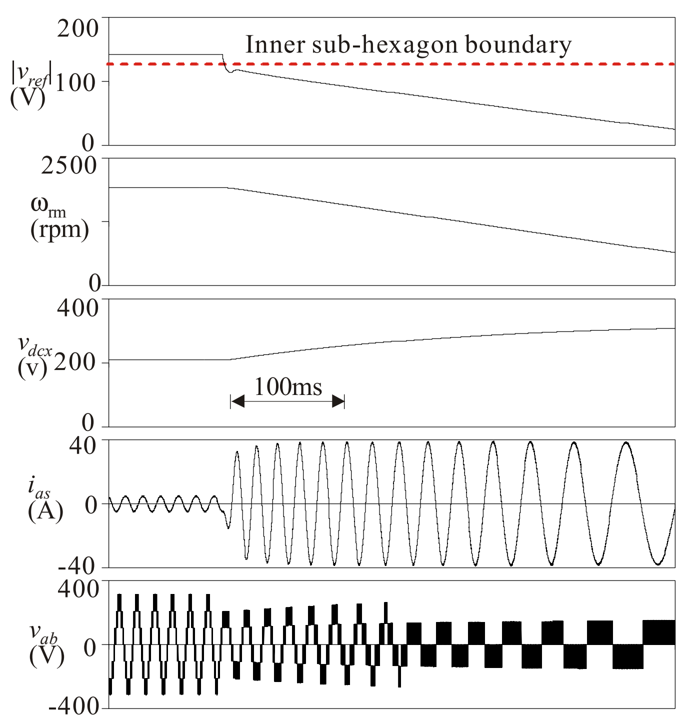

Figure 13. Urban speed regenerative braking process

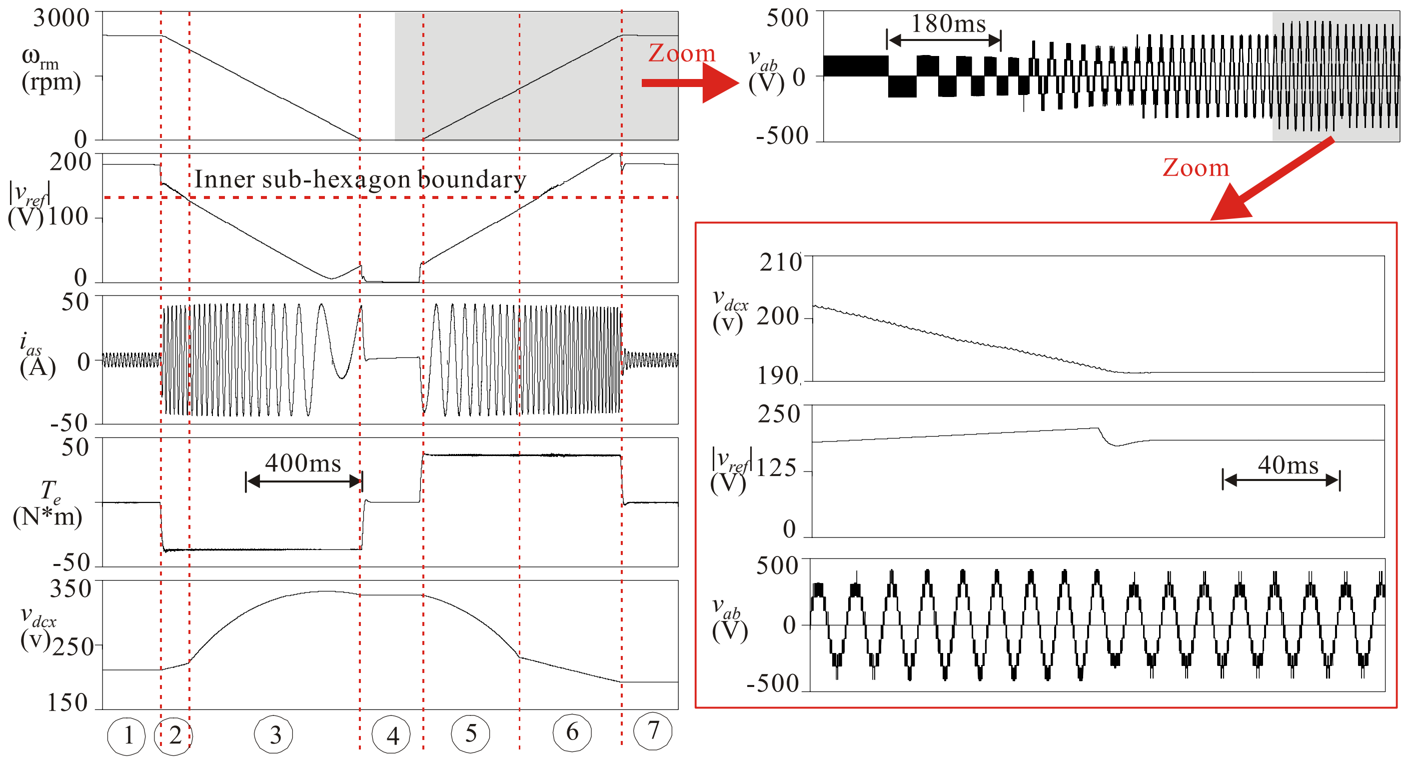

Figure 14. Highway speed regenerative braking and acceleration process with an example of energy management

the motor drive of electric and hybrid vehicles has been presented in this paper. The energy regenerated from braking will be stored in ultracapacitors 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 results in urban and highway driving modes prove the excellence of the proposed control set and power management scheme.

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