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A New Topology for High Level Hybrid Cascaded Multilevel Inverter Motor Drive with Energy Storage and Power Distribution

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Abstract: *In this paper a new topology is proposed for energy storage and the power distribution using Ultra-capacitors in cascaded multilevel inverters. This consists of hybrid cascaded multilevel inverter (HCMI) topologies and corresponding control strategies are applied to motor drive, interfacing both dc sources and capacitor energy storage elements. For high power motor drive application this proposed topology has a capability to produce high voltage at fundamental switching frequency makes it possible to use switches with low voltage and current ratings. The major advantages of this proposed control method are reduced switching loss, improved efficiency with less number of dc sources, elimination of harmonics and the ability of the capacitor voltage to be successfully maintained at the desired value when the machine is in transient state. In this paper a 7-level cascaded multilevel inverter with motor drive is considered. Finally, the simulation results validate the concept of this topology.*

Keywords: *Hybrid cascaded multilevel converter, Energy storage, power distribution, Ultra-capacitors, motor drive.*

I. Introduction

Electrical energy storage is emerging as a key technology with applications in areas such as improved reliability and power quality in the utility sector and other non-stationary power applications, integration of renewable sources into distributed generation systems, improved energy efficiency and productivity in conventional power generation plants, and regenerative motor drive systems. Ultra-capacitors are different from the other type of capacitors mainly because their specific capacitance, [F/dm3] and energy density, [kJ/dm3] are several orders of magnitudes larger than that of electrolytic capacitors. The ultra-capacitor as an energy storage device dedicated for power conversion applications. In comparison to state of the art electrochemical batteries, the ultra-capacitors have higher power density, higher efficiency, longer lifetime and greater cycling capability. In comparison to the state of the art electrolytic capacitors, the ultra-capacitors have higher energy density. All these advantages make the ultra-capacitors good candidate for many power conversion applications.

Energy storage systems can be characterized by their specific requirements such as power levels, energy storage capacity, and response time (determined by storage times or discharge times).With the ultra-capacitor bank, it has the advantage of assisting the battery to provide energy boost during acceleration and to capture/gain regenerative energy during deceleration or braking. Energy storage can also function as a backup for supply failures. Conventionally, the power electronics/applications interface for ultra-capacitors is realized using a bidirectional dc-dc converter (buck/boost) to control power flow into and out of the ultra-capacitor, as shown in Fig.1.

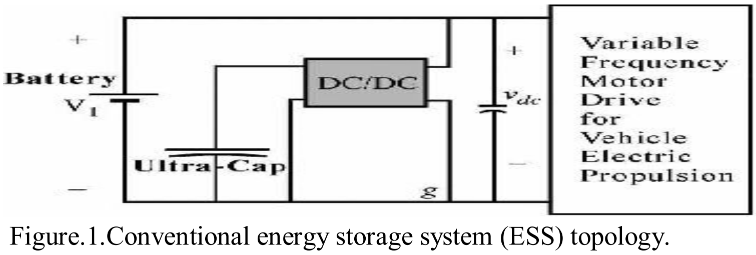

Figure.1.Conventional energy storage system (ESS) topology.

The dc-dc converter ensures that a constant dc-link voltage is obtained, regardless of variations of ultra-capacitor voltage. In low to medium power motor drive applications, dc-dc converters have several advantages such as high efficiency, fast transients, ease of control of power distribution between the dc energy source and the ultra-capacitor and higher power density. However, for high power applications, the efficiency of the dc-dc converter degrades very significantly and the associated high currents also increase electrical and thermal stress on the components and devices.

The cascaded multilevel inverter was invented for use in medium to high power applications. The traditional cascaded multilevel inverter interfaces DC energy sources. The advantages of cascaded multilevel inverters are:

- Requires less number of components per level.
- Modularized structure without clamping components.
- Simple voltage balancing modulation.

In the topology proposed in [3], the capacitor bank can only compensate for voltage harmonics in the bulk/main converter output and does not provide active power compensation. The topology in [5] can provide limited real power compensation, but no reactive power compensation. Therefore, there is the need to develop a topology and control methodology that can provide both active and reactive power compensation to optimize the performance of the motor drive system.

II. Proposed Topology

This paper proposes hybrid cascaded multilevel inverter topologies and corresponding control strategies applied to motor drive, interfacing both dc sources and capacitor energy storage elements.

Hence;

In the proposed topology, the capacitor is controlled to provide reactive power to cancel lower order harmonics through a conditioning converter.

In the modified proposed topology, the capacitor energy storage can be controlled not only to provide reactive power compensation to improve on power quality, but also to provide real power during acceleration, and absorb regenerative power during deceleration or braking period.

The multilevel inverter topologies and their respective control strategies each have some inherent advantages that make them suitable for different motor drive applications.

This proposed topology consists of one common converter neutral end (o) and three output ends (a, b, and c) shown in Fig.2. Each phase consists of two H-bridges connected in series. Compared to the conventional cascaded H-bridge multilevel inverter, only one dc energy source is used in each phase, while the other energy source is replaced by a capacitor. The value of voltage across the capacitor is half of the dc source value. The H-bridge with dc source is termed as main converter and with capacitor is termed as conditional converter. This structure is favorable for high power drive applications since it provides the capacity to produce high voltage with low switching frequency. It also improves the reliability by reducing the number of dc sources.

In the proposed topology, the capacitor is controlled to provide reactive power to cancel lower order harmonics through a conditioning converter. The main converter supplied by a DC source can therefore be controlled to provide real power with reduced switching loss and improved efficiency. Analysis approach for the interaction between modulation index and displacement power factor has been developed to establish the capacitor charging and discharging conditions for induction machine load. A major advantage of the proposed control method is the ability of the capacitor voltage to be successfully maintained at the desired value when the machine is in transient state, which is a key contribution.

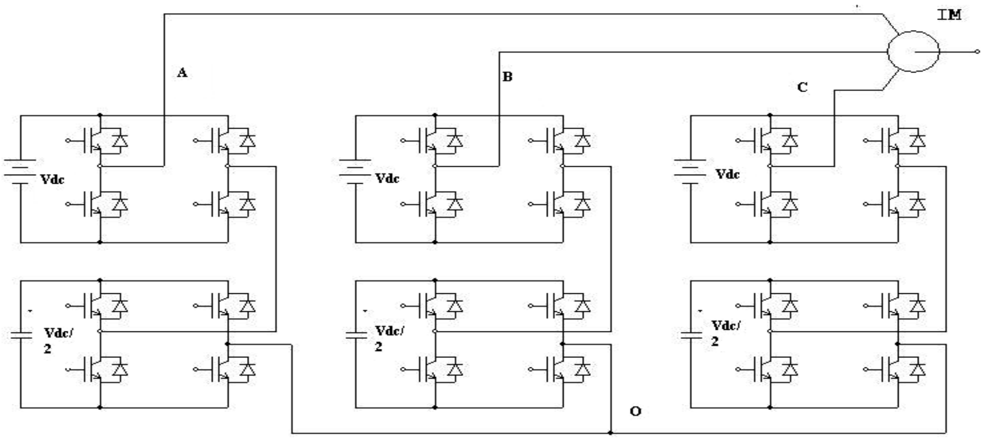

Figure.2: Circuit diagram for Proposed Topology (HCMI).

The relationship between the output voltage and the switching function S is shown in table1. The redundant switching states (RSS) are utilized for capacitor voltage regulation.

Table.1: Output voltage vs. switching function.

$v_{\substack{ao\\bo\\co}}$	$-\frac{3v_{dc}}{2}$	$-v_{dc}$	$-\frac{v_{dc}}{2}$		0	$\frac{v_{dc}}{2}$		v_{dc}	$\frac{3v_{dc}}{2}$
$S_{\substack{a1\\b1\\c1}}$	-1	-1	-1	0	0	0	1	1	1
$S_{\substack{a2\\b2\\c2}}$	-1	0	1	-1	0	1	-1	0	1

The output voltage and the switching angles of the proposed topology are shown in Fig.3 and Fig.4.

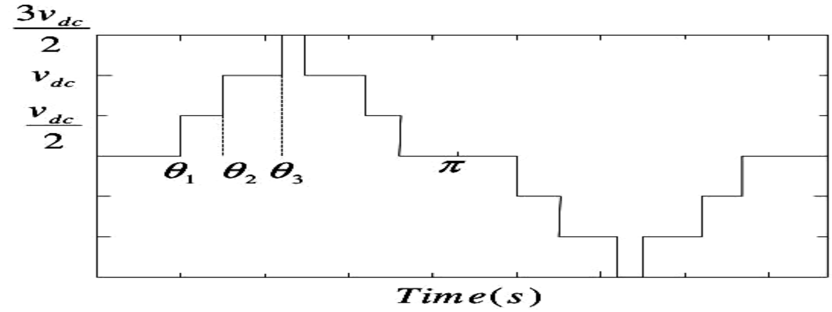

Figure.3: Voltage output of HCMI.

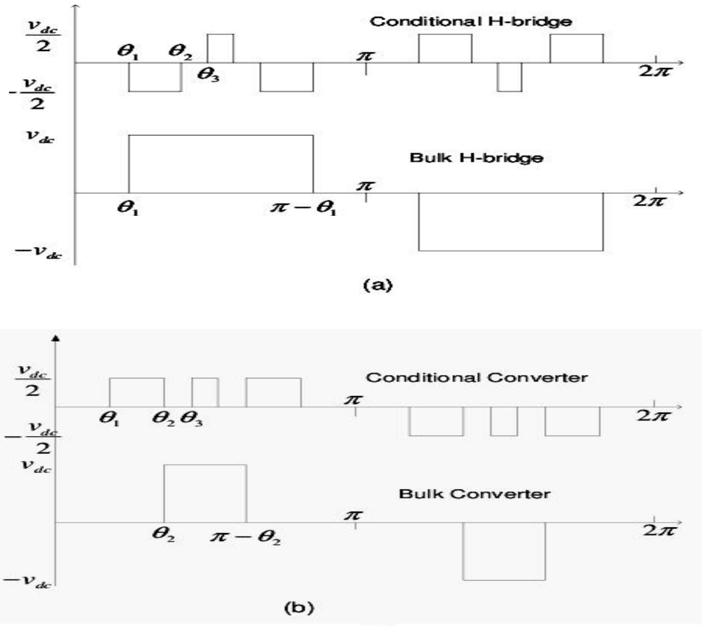

Figure.4: Switching scheme for HCMI. a) Capacitor charging cycle. b) Capacitor discharging cycle.

For a three-phase system, the triple harmonics are cancelled in the line-line voltage. The switching angles θ_1, θ_2, and θ_3 can be found by solving the following equations:

$$2V_{dc}/\pi\ [\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3)] = V_1$$
$$\mathrm{Cos}\ (5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) = 0$$
$$\mathrm{Cos}\ (7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) = 0$$

These three equations are derived from the Fourier series expansion of the 7-level equal step waveform. The second and third equations are used to eliminate the 5th and 7th harmonics. The first equation adjusts the magnitude of the desired fundamental waveform, where V1 is the peak of the fundamental voltage. The capacitor voltage is regulated by choosing the appropriate switching function when the output voltage is set to $-V_{dc} / 2$ or $V_{dc} / 2$.

This topology can also be modified such as not only to provide reactive power compensation to improve on power quality, but also to provide real power during acceleration and absorb regenerative power during deceleration or braking period by controlling capacitor energy storage.

Each phase of the modified proposed topology splits the supply of real power between a “main” converter supplied by a dc source, and two “auxiliary” converters supplied by energy storage elements. A hybrid modulation strategy combining sinusoidal pulse width modulation (SPWM) with phase-shift control is adopted for this topology. The motor drive control scheme is given as;

i. Power distribution control to split the supply of real power between the main and auxiliary converters.
ii. voltage balancing control of energy storage elements, firstly to ensure that each capacitor voltage is regulated to the desired value, secondly to ensure voltage balance between all the capacitors in each cascaded converter phase or cluster, thirdly to ensure voltage balance between t three clusters of single-phase cascaded converters, and lastly to obtain balanced ac output current by forcing the converter neutral point current to zero.

This modified proposed topology consists of three single-phase cascaded H-bridge pulse-width modulated converters per phase, connected in series. Similar to proposed topology, this modified proposed topology consists of a common or neutral point (o), and three output ends (a, b, and c). Fig.5 below shows the circuit topology of the modified HCMI.

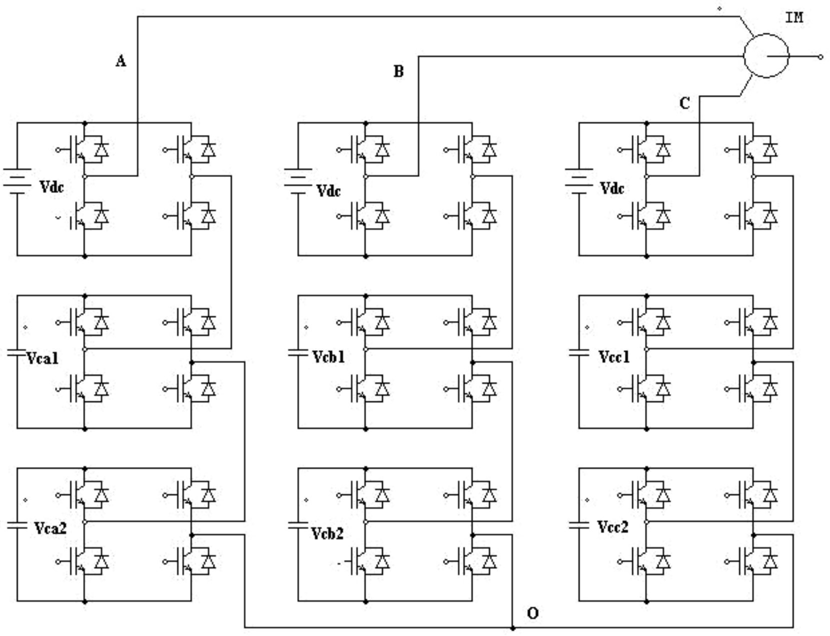

Figure.5: Modified proposed topology (HCMI).

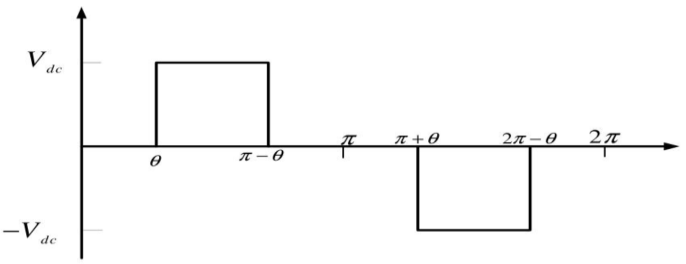

Figure.6: Voltage output for main converter.

The output voltage of each phase is shown in Fig.6 above. The output voltage is the sum of the individual voltage outputs of each of the three H-bridges. The higher voltage or main converter is powered by a dc source while the other two H-bridges are supplied by a capacitor. Similar to topology I, topology II is a good candidate for high power motor drive applications since it has the capacity to produced high voltage while switching at fundamental frequency. Switching at fundamental frequency makes it possible to use power electronics switches with low voltage and current ratings. In this proposed topology, the cascaded multilevel converter is not only used for reactive power compensation to improve on power quality, but also as an energy storage system to provide real power during acceleration and absorb regenerative power during deceleration or braking.

III. Operational Modes

The operation of modified proposed topology depends on the power requirement for regenerative motor drive system such as EVs and HEVs in any drive cycle is characterized by line peak power demands during acceleration and braking periods.

The different operational modes of the modified proposed topology are explained as:

i) Constant Speed Mode:

The constant speed mode for the modified proposed topology gives the average line power during this period is provided by the dc energy source, which at the same time, also charges the ultra-capacitors. In this case, the lower level converters powered by the ultra-capacitors only provide harmonic compensation to the main converter and do not supply any real average power. Electromagnetic torque requirement for this segment is also minimal. The charging and discharging periods and states are shown in below Fig.7.

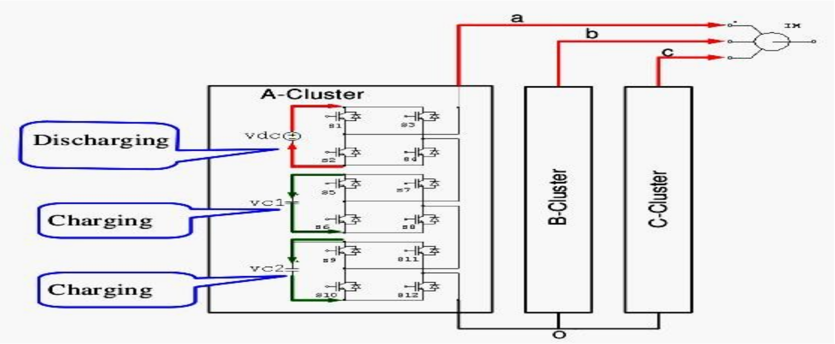

Figure.7: Real power flow during constant speed mode.

ii) Acceleration Mode:

The acceleration mode of the modified proposed topology is most of the peak power demand for this period is supplied by the ultra-capacitor. The advantages are two fold: firstly, it reduces stress on the battery thereby extending the battery lifespan. Secondly, it greatly reduces the battery size. In this segment, the dc voltage of the ultra-capacitor is not controlled to a particular reference, but is allowed to vary between a maximum value of 75V and a minimum value of 37.5V, so that the ultra-capacitor can function as energy storage. The energy provided by the ultra-capacitor is given as;

$$W= 1/2C\ (Vcmax^2-Vcmin^2)$$

A very effective power distribution scheme will be designed to share the distribution of real power between the battery and the ultra-capacitor. The charging and discharging periods and states are shown in below Fig.8.

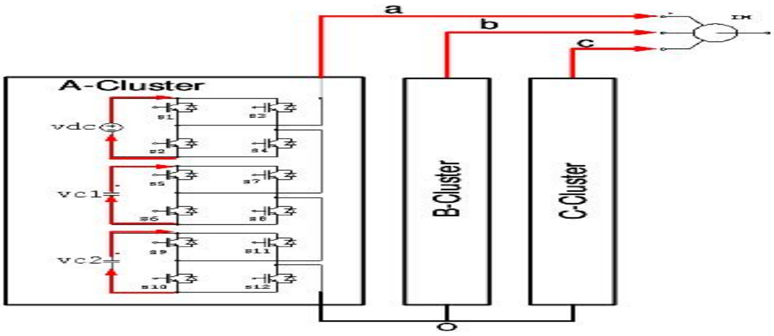

Figure.8: Real power flow during acceleration mode.

iii) Deceleration Mode:

The deceleration period, in which regenerative energy from the induction machine flows back into the system. Due to its quick recharge capability, the ultra-capacitor assists the battery during this period in recuperating the regenerative braking energy. Some of the regenerative energy captured is used to recharge the capacitor up to its maximum voltage. The ultra-capacitor is sized to be large enough to absorb as much of this energy as possible. The charging and discharging periods and states are shown in below Fig.9.

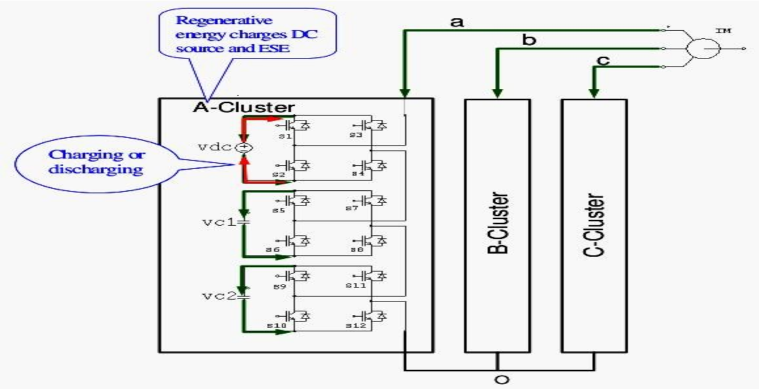

Figure.9: Real power flow during deceleration mode.

iv) Startup Mode:

The energy storage system will require pre-charging of the ultra-capacitors during machine start-up, a process that normally lasts several seconds. This section examines a fast and very efficient method for pre-charging the ultra-capacitors. During start-up, the dc energy source will be controlled to supply energy only to the ultra-capacitors. After the ultra-capacitors have been charged up to the desired operating voltage, the system control will switch to normal operation, supplying power to the induction motor. The control strategy will also ensure a smooth transition from start-up mode to normal operation mode.

v) Standstill Mode:

During standstill, neither the dc energy source nor the ESE supplies any power, since there is no power requirement for the motor drive during this period.

IV. Simulation Result

Simulation results were obtained by co-simulation using Matlab and PSIM software, and also using the same induction motor models to proposed topology shown in below Fig.10.

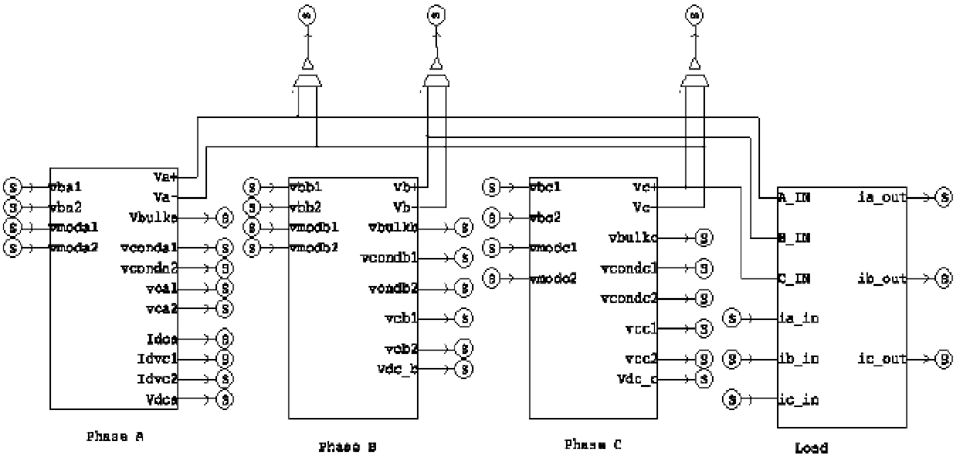

Figure.10: Modified proposed topology (HCMI) circuit model in PSIM.

The three sub-circuits label Phase-A, Phase-B, and Phase-C represents the three phases of the cascaded multilevel inverter. The fourth sub-circuit labeled load passes the cascaded inverter load current to Simulink, and also receives the induction motor load current from Simulink.

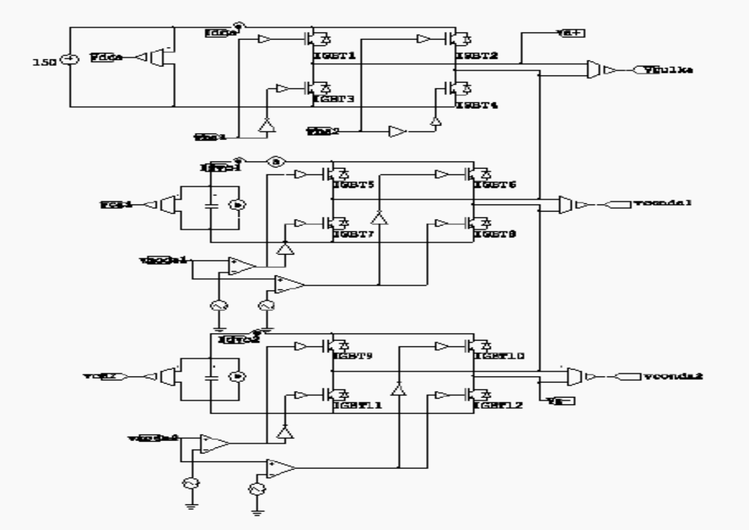

Figure.11: Detail view of phase-A Modified proposed topology (HCMI).

Simulation results give the Real power supply by dc source and ultra-capacitors, main and conditional converters output voltages and developed torque and load torque shown in below Fig.12, Fig.13 and Fig.14 respectively.

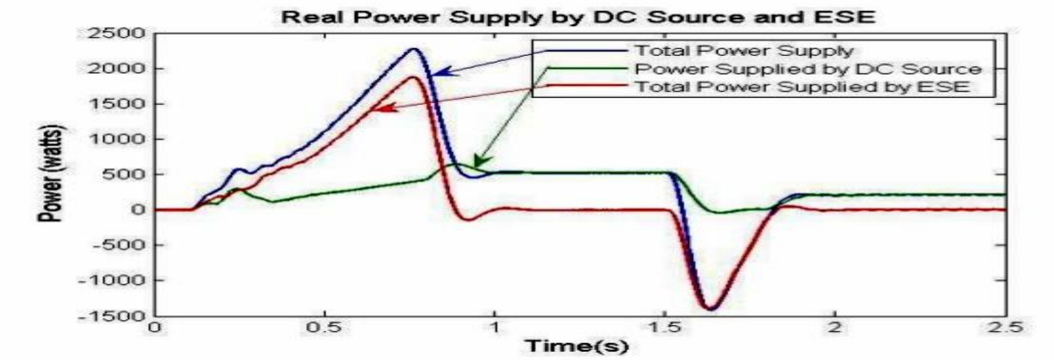

Figure.12: Real power supply by both dc source and ultra-capacitors.

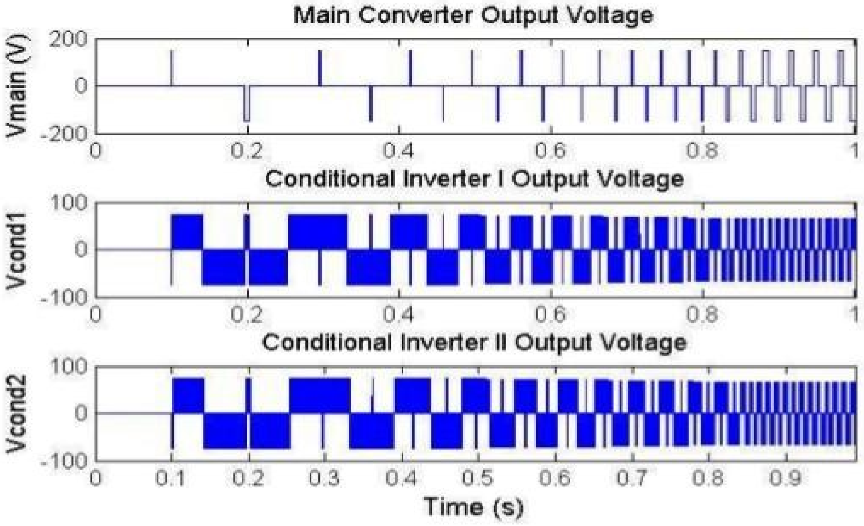

Figure.13: Main and conditional inverters output voltages.

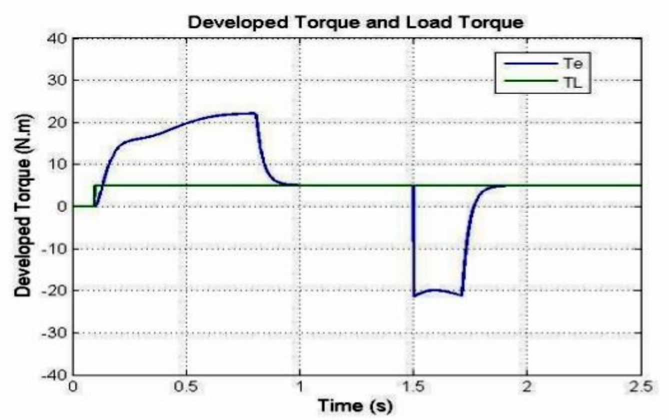

Figure.14: Developed torque and load torque.

From the above discussion, the energy storage using ultra capacitors is most advantageous compared with the other energy storage devices. In comparison to electrochemical batteries, the energy density is lower while the power density is larger than that of conventional batteries. Cycling capability is also significantly better compared to batteries. Table 2 compares the most important properties of the ultra-capacitor versus batteries and other type of capacitors.

Table-2: Properties of the existing energy storage devices.

	Capacitors	Ultra capacitors	Electro chemical batteries
Energy density[wh/kg]	~0.1	1-6	~100
Peak power density[kw/kg]	10^4	2-20	0.1-0.5
Number of cycle	10^{10}	10^6	-10^2
Life time[years]	-10	-15	-5

V. Power Distribution

The power requirement of a regenerative motor drive depends on the different drive modes, which include standstill, startup, acceleration, deceleration, and constant speed, which were explained in above proposed topology. This section focuses mainly on the peak power requirement during acceleration and braking and how to distribute the supply or absorption of peak power between the dc energy source and the ESE. Fig.15 shows the real power, electromagnetic torque, and the capacitor voltage variation during acceleration and braking periods. During the constant drive period, the dc source supplies all the power required by the motor drive and also charges the energy storage elements. At the same time, the ESE also provides harmonic compensation to the main converter output voltage. During acceleration, both the ESE and the dc source supply peak power to the motor drive. As shown in Fig.15, the UC voltage is allowed to vary between VCmax and VCmin in order to supply real power to the motor drive. During deceleration, the regenerative energy from the motor drive is captured by the ESE and used to charge both the ESE and the dc energy source.

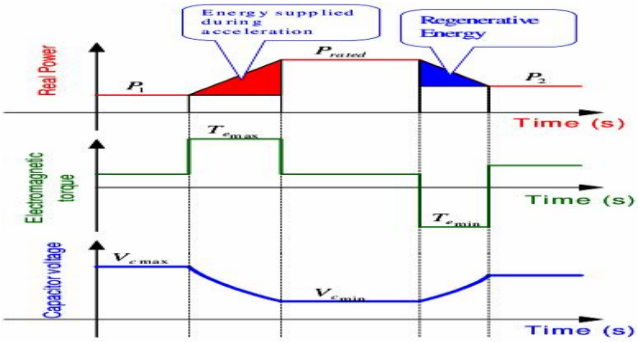

Figure.15: Real power, electromagnetic torque and capacitor voltage during acceleration, deceleration, and constant drive periods.

In this way, the dc source provides real power proportional to the magnitude of the fundamental voltage output of the main converter. This method guarantees a smooth transition from one drive mode to the other when compared to the constant current supply control method, especially in low power induction motor drive applications that have a small mechanical inertia.

VI. Perspectives For Future Work

1. Extend the modulation index range of operation of proposed topology by using a combination of different switching schemes to achieve the fundamental voltage component while eliminating the 5th and 7th harmonics.
2. Battery mode control needs to be incorporated into the system to regulate battery discharge during acceleration, and battery charging during deceleration, for longer life and better system performance.
3. With increasing the number of levels at the output voltage to obtain near sinusoidal wave and propose more power distribution strategies and do a comparative analysis to show the most optimized method.

VII. Conclusion

In this paper a new topology has been provided for energy storage and power distribution using ultra-capacitors as they have higher power density, higher efficiency, longer life and greater cycling capability with hybrid cascaded multilevel inverter topologies for high performance motor drive applications. In this topology, this is totally focused on the energy storage, harmonics elimination, and power distribution. With the proposed topology, the ultra capacitors provide reactive power to eliminate 5th and 7th harmonics by maintaining the capacitor voltage at the desired value, even in the transient state. And with the modified proposed topology, the capacitors are controlled to not only supply reactive power compensation during constant drive, but to be able to provide real power compensation to the main converter during peak power demands. Finally, and overall system level simulation is provided to verify the working principle of the proposed topologies.

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