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Review of Ultracapacitor Application in Energy Saving Elevator System

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***ABSTRACT*: Ultracapacitor or Supercapacitor is an electrochemical double-layer capacitors (EDLC) having high energy and power density. Due to unique properties of Ultra-capacitors, they find applications in many areas. In this paper, two applications are specifically stressed upon namely ride through and energy efficiency. This paper studies and compares various energy-saving elevator systems using Ultracapacitors, capable of storing regenerated energy and capable of discharging the stored energy during operation. Based on literature review six different drive configurations has been discussed. In all eight different DC-DC converter topologies have been discussed to be used for ultra-capacitor energy saving systems.**

Keywords: Ultracapacitor, Supercapacitor, DC-DC converter

I. INTRODUCTION

Ultracapacitor/Supercapacitor is an electrochemical double-layer capacitors (EDLC) having high energy and power density. The Ultracapacitors have power densities greater than batteries but lesser than electrolytic capacitors, and energy densities greater than electrolytic capacitors but lesser than batteries and fuel cells. At present, ultracapacitors are most applicable for high peak-power, low-energy situations. Ultracapacitors find applications best in starting of automobiles, trapping energy during regenerative braking of motors and some pulsed power applications where very high power is required in short time with substantial energy. Due to unique properties of Ultra-capacitors, they find applications in many areas. However in this report, two applications are specifically stressed upon namely ride through and energy efficiency. Due to its properties, Ultra-capacitor is most ideal to be used in these applications. In [2] specifically talks about ride-through alternatives for Adjustible Speed Drives (ASD) in most detail. It is among the most referenced paper in the literature and provides a good comparison of ride through alternatives in terms of advantages, disadvantages and cost/KW rating. In [3] compares a line generative drive system with line non-regenerative system and concludes that former is much more energy efficient than the later. In [4] summaries the capabilities of various energy storage system in terms of application in stability improvement, regulation and power quality improvement for various electrical systems. In [5] proposes a bi-directional DC DC converter with soft commutation conditions and discusses use of Ultra-capacitor for power smoothening in elevator applications. In [7] proposes Ultra-capacitor based ride-through system using Unified Power quality conditioner (UPQC) and chopper. In [8] Ultra-capacitor system for and electric vehicle has been implemented which improves the acceleration capabilities of electric vehicle, reduces battery sizing and increase battery life. It also provides regenerative braking and improved energy efficiency. In [9] proposed a predictive control of a supercapacitors storage system and tested in the field of the automatic warehouse. In [10] proposes a hybrid system for Gantry crane comprising of Ultra-capacitor and diesel engine Generator. Due to Ultra-capacitor, smaller generator could be used reducing emission up to 40 % and overall energy efficiency improved up to 20%. A three-legs bidirectional dc–dc converter is used for Ultra-capacitor.

In [11] Combined PEM Fuel Cell and Ultracapacitor System for Stand-Alone Residential Application is proposed. In [14] A hybrid system using fuel cell, ultra-capacitor and batteries is proposed for elevator system. Simulations are carried using dynamics modeling tool Modelica-Dymola. In [18] This paper implements a low power ride through system up to 75 watt using Ultra-capacitor. A good detail of hardware used is available. In [21] This paper proposes the Supercapacitor-Based Energy Storage Control System for elevator motor drives using bi-directional converter. However fuzzy logic based control scheme for the drive is proposed and supply-line voltage variation is also taken into account for full utilization of ultra-capacitor storage capacity. In [22] This paper proposes and implements a voltage ride-through solution for variable speed drives in oil field applications. Ultra-capacitor based ride through system using DC-DC unidirectional boost converter is used in parallel to DC bus. In [23] also discusses a regenerative controlled electric drive having extended ride-through capability is discussed. But unlike other papers it proposes bidirectional three-level dc–dc converter.

Rest of the paper is organized as follows. Section-II presents introduction of ultra-capacitor, its properties, applications, advantages and disadvantages. It also discusses two issues faced in VSDs (Varible speed drive) based industries, that is ride through and energy efficiency. Section-III discusses various configuration options for elevator drive system. Section-IV provides various DC to DC converter topology options . Section-V concludes the paper.

II. ULTRA-CAPACITOR APPLICATION IN VSDS

Ultracapacitors represents one of the newest innovations in the field of the electrical energy storage. The ultracapacitor is an electrochemical double-layer capacitors (EDLC) having high energy and power density. Today's ultracapacitors are composed of two electrodes separated by a porous membrane, which is the so called separator, and impregnated by a solvent electrolyte. The electrodes are made of porous conducting material such as activated carbon. The typical specific surface area of the electrode is as high as 2000 m2/g. Such a large surface area and very thin layer of the charges, on the order of nanometers, give a specific capacitance up to 250 F/g. The rated voltage of the ultracapacitor cell is determined by the decomposition voltage of the electrolyte. The typical cell voltage is 1–2.8 V, depending on the electrolyte technology. To obtain higher working voltage, which is basically determined by the application, elementary cells are series connected into one capacitor module.

At present, ultracapacitors are most applicable for high peak-power, low-energy situations. Ultracapacitors find applications best in starting of automobiles, trapping energy during regenerative braking of motors and some pulsed power applications where very high power is required in short time with substantial energy. In such applications drawing high power from batteries shortens its life and electrolytic capacitors cannot supply energy for more than few milli-secs without compromising on cost and volume. The ultra-capacitor is being applied in many fields, such as power smoothing in elevator applications, peak power demand and regenerative braking in hybrid-electric vehicles, and voltage sag compensation in unified power quality controller (UPQC). These are also widely used in industry, electric vehicles, renewable energy applications (solar farms and wind turbines), individually or in combination with batteries.

As discussed above, due to unique properties of Ultra-capacitors, they find applications in many areas. However specifically in this report two applications are discussed namely ride through and energy efficiency. Due to its properties, Ultra-capacitor is most ideal to be used in these applications

The application of adjustable-speed drives (ASD's) in commercial and industrial facilities is increasing due to improved efficiency, energy savings, and process control. However, ASD's are often susceptible to voltage disturbances, such as sags, swells, transients (e.g., due to capacitor switching), and momentary interruptions (outages). According to survey reports, voltage sags of 10%–30% below nominal for 3–30-cycle durations account for the majority of power system disturbances, and are the major cause of industry process disruptions [2]. Depending on the application, and the characteristics of the disturbance, the ASD-controlled process may be momentarily interrupted or permanently tripped out. The cumulative cost estimates of power disturbances in the U.S. range from $20 000 000 000 to $100 000 000 000 per year, where industries have reported losses ranging from $10 000 to $1 000 000 per disrupting event [2].

The electric machine of a traction elevator either consumes or produces electric energy depending on the moving direction of the cabin and its weight in relation to counterweight. Maximum energy consumption is attained when the elevator cabin is moving up with full load or moving down empty. Whereas, maximum energy is produced by the elevator motor when the cabin is moving down with full load or moving up empty. In conventional elevators, the produced electrical energy, which is referred as braking energy, is dissipated to a braking resistor. However, this energy can be temporarily accumulated in an energy storage device and then it could be recovered when the elevator turns to motoring operation. Therefore, the energy that is provided from the grid is reduced and thus, the total efficiency of the elevator motion system is improved.

III. ULTRA-CAPACITOR APPLICATION IN VSDS

In the referenced papers from [1] to [23] in total 5 different drive configurations has been discussed.

A. Passive Rectifier, Smoothing inductance or capacitance and Inverter configuration

This configuration is discussed in [1] and is obsolete in present times. The biggest drawback in this configuration is regenerative braking is not possible as no feature of braking resistor provided. This system is comprised of a converter to convert the constant frequency ac power from the power source to dc power, a dc reactor (Ld) to smooth the dc current, and an inverter to convert the dc power to the variable-voltage variable-frequency ac power. The overvoltage absorption capacitors, ***(Cc, Ci),*** which are connected to the ac input and output terminals, function as filters; therefore, the input and output currents have sinusoidal waveform to a certain degree.

B. Passive rectifier, smoothening inductor/capacitor, Inverter with resistive braking

This is most common type of configuration still popular in today's elevator drives. Almost all elevator drives discussed in reference papers uses this configuration. However it was first mentioned in [3]. Figure below shows the non-line regenerative VVVF (Variable Voltage Variable Frequency) drive for elevators.

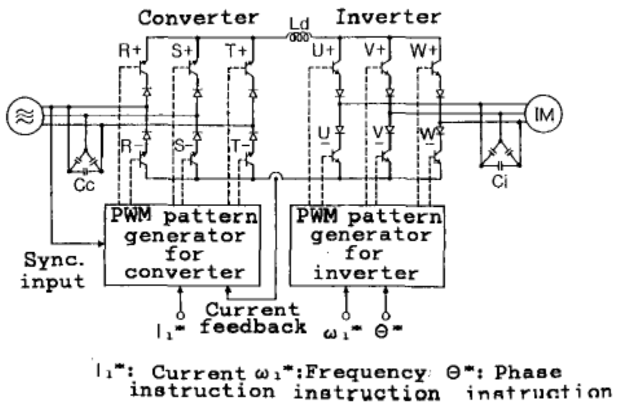

Figure 1: Main Circuit Design

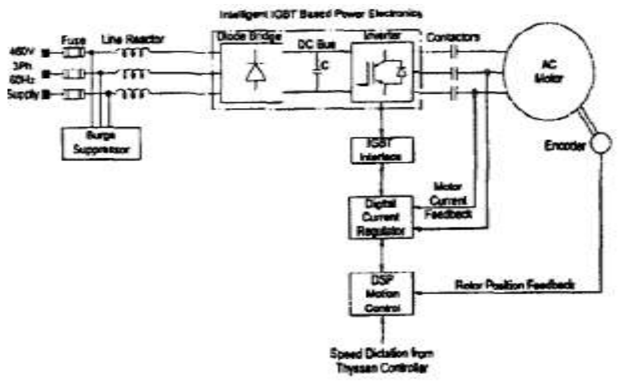

Figure 2: Thyssen VVVF Non-Regenerative Drive System

A diode bridge is used to convert AC to DC. The inverter uses intelligent **IGBTs** (Intellimods) that include over current, under voltage and over temperature protection actions built into the IGBT module. The inverter is current controlled. A resistor bank is used to burn the regenerated energy at the DC bus (not shown in the figure).

C. Active Rectifier Adjustable Speed Drive (ASD) Front end

As discussed in [2], Fig below shows an ASD with an active pulse width modulation (PWM) rectifier.

Replacing the diode rectifier with an active PWM rectifier has the following advantages: 1) regulated dc bus which offers immunity to voltage sags and transients; 2) low input current harmonics and compliance to IEEE 519 harmonic limits; and 3) power flow in both directions, enabling regenerative braking. So in this configuration regenerated energy can be flown back to grid which can be used by other equipments on the grid.

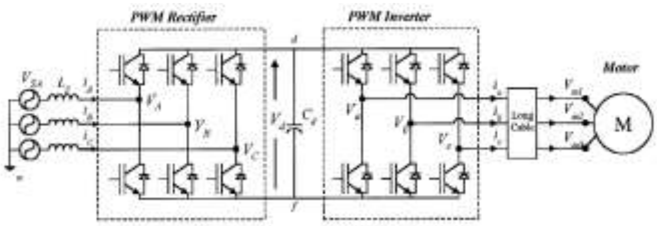

Figure 3: ASD with PWM Rectifier

D. Passive rectifier, smoothening inductor / capacitor, Inverter with resistive braking and energy storage module as add on for ride-through with separate charging

This configuration is mentioned in [2] and [22]. Refer the diagram as mentioned in [2] below:

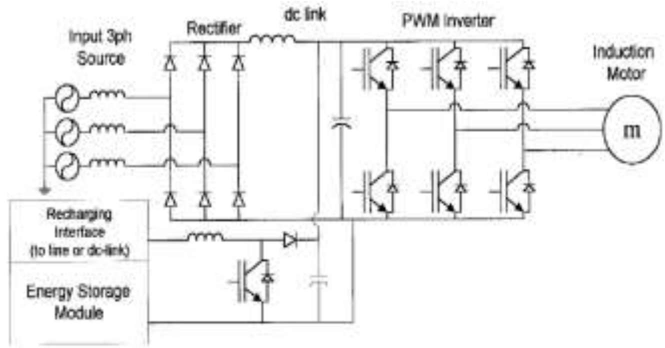

Figure 4: Energy Storage as an Add-on for ASD ride through

As shown above, Energy module is charged by a separate charging interface from the AC line or some DC-link. In case of voltage sag or black outs, energy will flow from storage module through DC-DC converter shown into the DC Bus. So Motor works as long as storage module can maintain voltage at DC Bus. So this configuration can successfully ride-through the system for specified time as designed by storage module specifications. Major disadvantage of this configuration is, it is energy inefficient as regenerative energy is not saved but still dissipated in resistive banks. Similar configuration used in [22] is shown below :

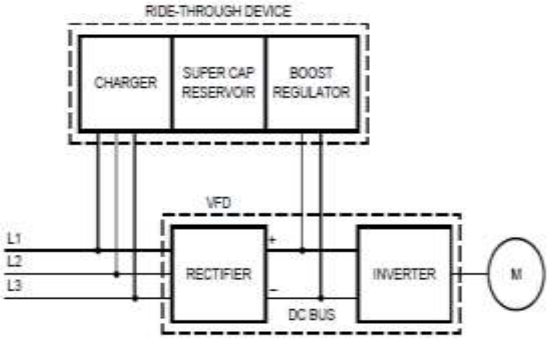

Figure 5: AC Charged Capacitor Circuit

Also same configuration is mentioned in [24] as shown below:

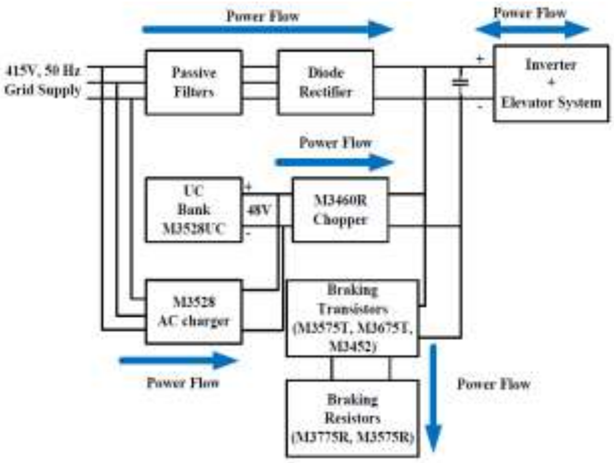

Figure 6: Block Diagram of the Bonitron M3460UC System

E. Passive rectifier, smoothening inductor/capacitor, Inverter with resistive braking and energy storage module as add on for ride-through charged by DC Bus using bi-directional DC-DC converter

Majority of referenced papers recommends this type of configuration. The only difference in this configuration as compared to other configuration is that energy storage module uses the DC Bus to charge itself. Hence it allows regenerative energy to get stored in storage module. As a result energy efficiency improvement feature is also added along with ride through capabilities. Some diagrams following this configuration is mentioned in [12], [22], [23], [24]. The respective diagrams are shown below:

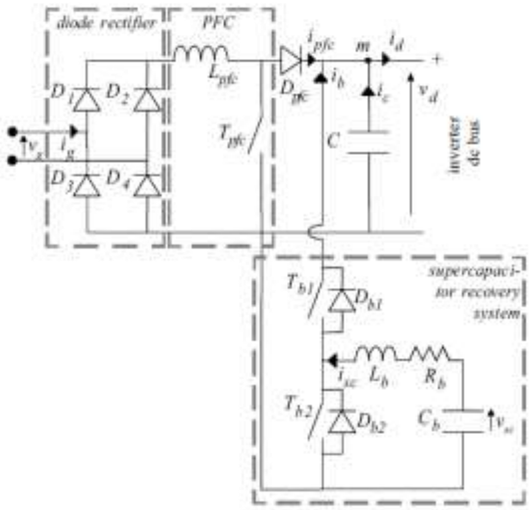

Figure 7: Proposed Conversion Scheme

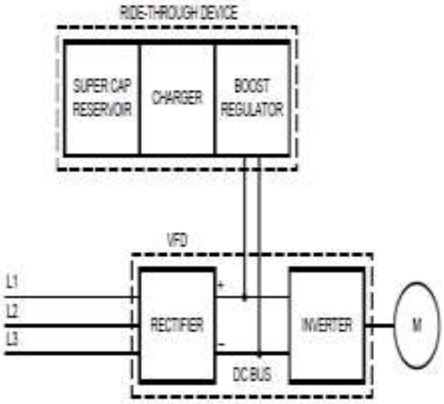

Figure 8: Capacitor Charged with Existing Drive Charging Circuit

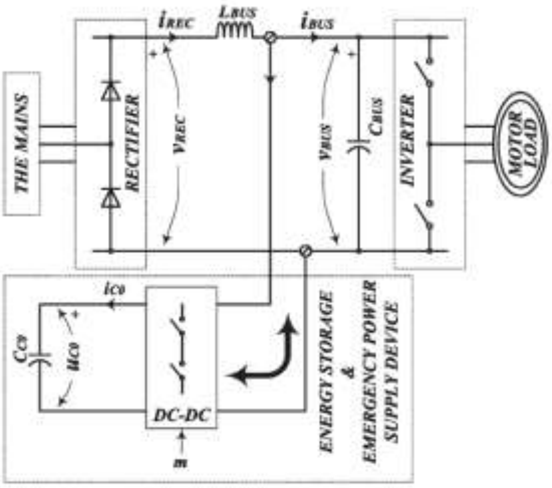

Figure 9: Regenerative Variable Speed Drive based on an Energy Storage Device

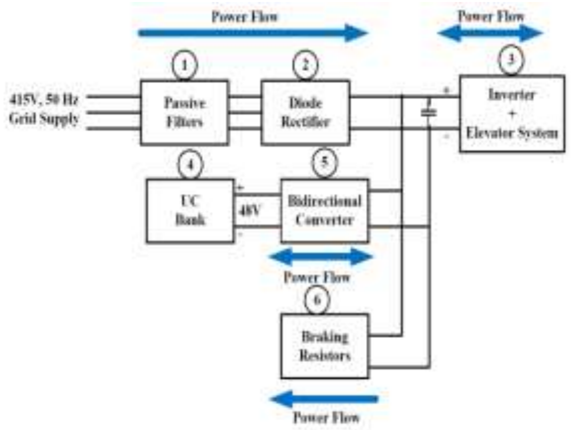

Figure 10: System Configuration- UC back Connected to the DC Link through a Bi-Directional Converter

IV. BI-DIRECTIONAL DC-DC CONVERTER TOPOLOGIES FOR ULTRA-CAPACITOR

DC-DC Bi-directional topologies can be broadly classified into two main types namely non-isolated converters or isolated converters. Non isolated converters can be further categorised as one leg, two leg or three leg converters. Also they can be categorised as two level, three level etc. based on stages. Similarly Isolated converter essentially have a transformer to boost voltage. Various converter topologies are discussed in detailed below.

A. Non-Isolated Converter Types

Classical Bi-directional Buck Boost converter: This is most popular converter type and quiet widely used. Many papers have used this topology. As mentioned in [8] classical bi-directional topology is shown below.

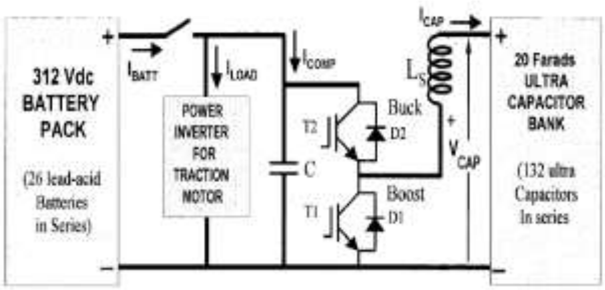

Figure 11: Ultracapacitor System

As shown in diagram converter has three basic components, two MOSFETS/IGBTs and an inductor. In buck mode high voltage battery charges Ultra-capacitor. In this mode, transistor T1 is always off. T2 switches on off with certain frequency and duty cycle based on voltage difference between battery voltage and ultra-capacitor charging voltage. In boost mode, Ucap charges the battery. In this mode T2 is always off and T1 switches between on and off with certain frequency and duty cycle. When T1 is on inductor is charged by Ucap. When T1 is off Ucap along with inductor charges the battery through diode D2 of transistor T2.

The interleaved boost converter with IPT (Interphase transformer): The major drawback of the non isolated boost converters is the discontinuous output current resulting in a larger capacitor requirement. The majority of designs therefore operate multiple converters in parallel with an interleaved switching pattern. A variation of this approach is used by Calderon-opez and Hirakawa where a single inductor is used along with an interphase transformer (IPT) or inversely coupled inductor shown in Figure below [20].

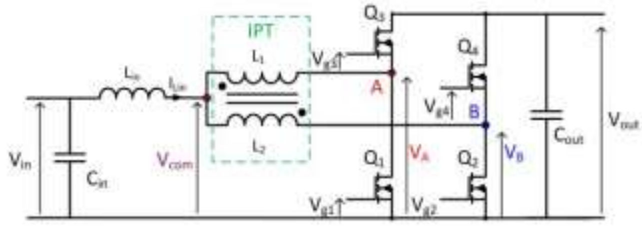

Figure 12: Interleaved Boost Converter with IPT

The interleaved boost converter with IPT switches with a phase shift of 180 ° and uses the PT to reduce the AC voltage across the input inductor. Furthermore, the input inductor is subjected to operation at twice the switching frequency, reducing the inductance requirement for a given input current ripple and allowing the use of smaller magnetic cores. A cancellation of the DC flux is also experienced by the IPT allowing its design to be optimized for AC excitation. The IPT circuit is therefore likely to produce lower losses and lower mass magnetic components which should result in a higher power density converter [20].

Three legs bi-directional DC-DC converter: Three legs bi-directional converter is discussed in [10] and [17]. Many applications require handling of several hundred amperes of load current. The high current requirement is best met by using parallel converter modules. The three-phase inverter stack as shown in Fig. 4 has many advantages [10].

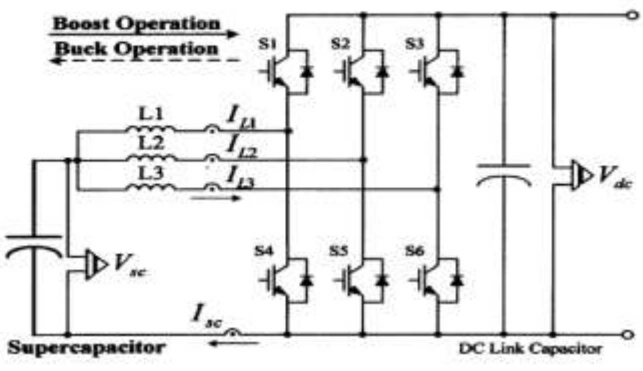

Figure 13: Bidirectional DC-DC Converter

First of all, it is commercially available. Second, the converter can be operated in the interleaved manner, for it has three buck–boost converter modules. Therefore, the current is distributed among three converter modules. With an appropriate phase shift among the switching sequence of converter modules, three switching ripples cancel one another greatly reducing the input and output current ripples. Third, the modular approach provides the system with fault tolerance against the failure of a single module. Finally the whole stack size including three inductors is smaller than that of a single buck–boost converter [10].

Three Level Buck Boost DC-DC converter: Fig. below shows a circuit diagram of three-level bidirectional converter that is used as the interface power converter [23].

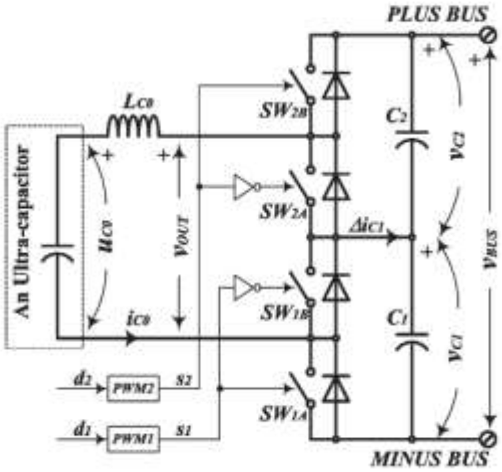

Figure 14: Bidirectional Three Level Buck Boost DC-DC Converter Circuit Diagram

The converter is composed of four current-bidirectional switches *SW*1*A*, *SW*1*B*, *SW*2*A*, and *SW*2*B*, a filter inductor *LC*0, and two input filter capacitors *C*1 and *C*2. The switches are the insulated-gate bipolar transistor (IGBT) or MOSFET with freewheeling diodes. The input filter capacitors play a role of the capacitive voltage divider that splits the dc bus voltage *v*BUS into two equal voltages *vC*1 and *vC*2. The capacitor midpoint is connected to the switching-cell midpoint.

Compared with the ordinary two-level dc–dc converters, the three-level converters have two important advantages: the size of the filter inductor *LC*0 and the switch voltage rating. The inductance is 25% of that of the two-level dc–dc converter for the same current ripple. In other words, the inductor volume is one-fourth of that of the conventional one hence losses will be lesser too. Another advantage is the switch voltage rating, which is one-half of that of the conventional two-level converter, hence lesser switching losses.

B. Isolated Converter Types

Isolated Buck –Boost using transformer (full bridge *)*

This topology is discussed in [13].

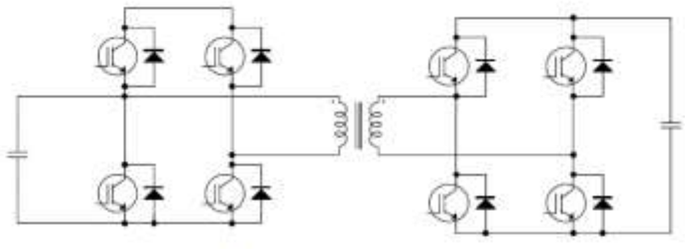

Fig 25 Isolated Buck Boost converter transfomer (full bridge)

Figure 15: Isolated Buck Boost Converter Transformer (Full Bridge)

Voltage adaption with an intermediary AC-link with MF transformer, topology with resonant mode

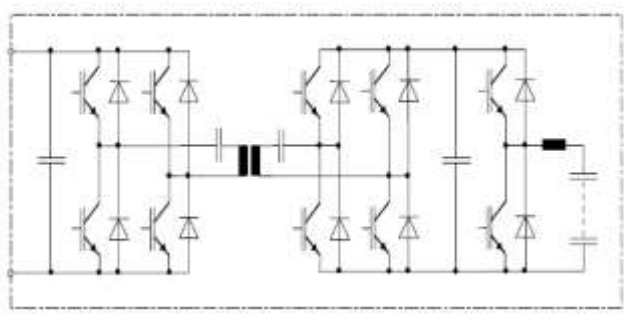

Figure 16: Voltage Adaptation with an Intermediatary AC- Link with MF-Transformer, Toplogy with Resonant Mode

MF transformer with a static conversion topology based on resonance is given in Fig. 26, where the high-voltage side of the transformer is interfaced with the DC link of the frequency converter via a four-quadrant H-bridge operating in resonant mode. The low-voltage side has also the same converter scheme, with in addition a buck converter needed because of the typical variation of the supercapacitor voltage by loading and unloading [5].

Modern soft-commutated converters with AC link at medium frequency: In the scheme of Fig. 17, the alternative solution for the voltage adaptor is shown [5].

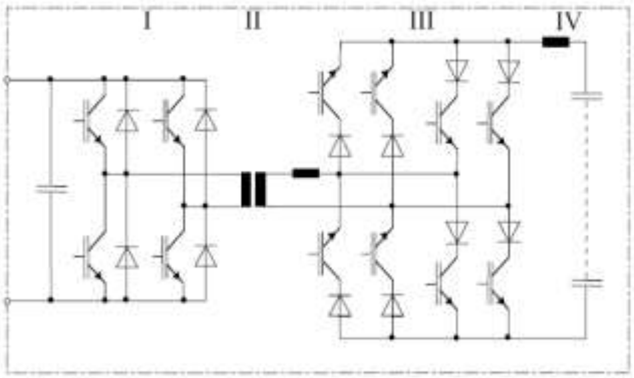

Figure 17: MF-AC Link with ZVT/ZCS Converters

Two static converters are used. The first one (I) is between the DC link of the drive and the primary side of the MF transformer (II). The second converter (III) is placed between the secondary winding of the transformer and the storage circuit composed by a series connection of a smoothing inductor and the supercapacitors (IV).

The first converter-bridge of Fig. 17 is a voltage inverter operating in the fundamental-frequency switching-mode. It is also called ZVT-converter, or also VSI with Dual-Thyristors. At the secondary side of the transformer, a naturally commutated current converter (or ZCS current-converter) is represented, in a current-reversible topology using 2 anti paralleled TCR bridges. The operation frequency of these bridges, which is the frequency of the MF transformer is designed in the lower kilohertz range.

V. CONCLUSION

This paper introduces Ultracapacitor, its properties and applications in energy storage elevator system. It exhaustively studies Various Drive configurations presented in the referenced papers. Also it studies various non-isolated and isolated DC to DC converter topologies to be used for ultracapacitor storage systems. Various Ultra capacitor modeling circuits are also explained. This work will be very useful to study detailed topologies used in a quick manner, saving lot of time in studying different literatures.

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