

Research Article

Studies on Ultra-capacitor Based Energy Storage and Power Conversion System for Three-phase Electric Drives

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Abstract

Most of modern controlled electric drive applications, such as lifts, cranes, and tooling machines are characterized by a high ratio of the peak to average power. In addition, such applications have high demand for braking at the full rated power. In ordinary drives, the braking energy which represents 30%–50% of the consumed energy is dissipated on a braking resistor. Apart, from this energetic issue, power supply interruption, input current quality and power conversion system are the additional issues to be solved. It has been long known that three-phase electrical equipment such as three-phase induction motors are significantly more efficient, economical and easy to control than their single-phase counterpart. Also, the sizes of three-phase motors are significantly smaller than its single-phase version with the same kVA rating. However, in many instances three-phase power is rarely available in the rural or light industrial areas due to the high cost of extending three-phase service. So the only available power in these areas is in the form of single-phase and there exists a need for phase converters for powering induction motor driven fans, pumps and other irrigation equipment. Some solutions have been proposed to convert a single-phase power to three-phase power. The ultra-capacitor with an interface DC-DC converter is used to store and recover the braking energy. Moreover, the DC bus voltage is boosted and controlled to be constant and ripple free regardless of the load and the mains voltage variation. In comparison to state-of-the-art solutions, the new solution has better performance, regarding size, cost and efficiency. The presented solution is theoretically analyzed and experimentally verified. The results are presented and discussed. All these solutions provide an efficient way to save the braking energy and improve the global efficiency of variable speed drive systems.

Keywords: Ultra-capacitor, Power Conversion, DC-DC Converters.

1. Introduction

Today, 70 % of the world's electricity production is consumed by controlled electric drives, traction and transportation drives, industrial drives, home appliance drives and so on. This indicates the importance of controlled electric drives in everyday life (*T. de Almedia, F. J. T. E. Ferreira and D. Both, 2004*). Modern low voltage controlled electric drives are exclusively based on three-phase motors, either Induction or Permanent magnet synchronous motors. The motor is powered from a power converter, so-called the drive converter, having variable output voltage and frequency. The drive converter is supplied from low voltage industrial or distributive three-phase mains 230V to 690V, 50Hz to 60Hz. The most common converter topology is a cascade-connected diode front-end rectifier and voltage source Pulse Width Modulated (PWM) inverter (*J. R. Rodriguez, J. W. Dixon, J. R. Espinoza, J. Pontt and P. Lezana, 2005*). In this

paper, three-phase induction motors are used as the electric drive, because they are the most common and frequently encountered machines in industry.

In ordinary variable speed drives, the mechanical energy of the motor load rotating mass is usually realized and wasted in a brake resistor. The energy losses in such applications go upto 30% to 50% of the consumed energy. Now-a-days, due to energy crisis, efficiency of variable drives has become an issue that needs an urgent solution. The concept of diode front-end drive converter equipped with an energy storage device, is shown in Fig.1. Recently, this concept has become the focus of interest with the broad application of a new generation of Electrochemical Double Layer Capacitors (EDLCs), also called ultra-capacitors (*C.Attaianesse, V.Nardi and G.Thomasso,2004*). The braking energy is stored in the ultra-capacitor during the drive braking phase. The energy is restored from the ultra-capacitor during the next motoring phase. General purpose variable speed drives with such an energy-saving concept can be used in lift applications, with high demand for fast start or stop sequence, and many similar applications with a demand for frequent braking. The ultra-capacitor efficiency strongly depends on the capacitor size and conversion power; smaller the

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capacitor, lower is the efficiency. Moreover, the ultra-capacitor can provide energy for uninterruptible power supply function or extension of the drive ride-through capability in critical industrial applications in which power interruptions are very costly (P. J. Grbović, P. Delarue, P. Le Moigne and P. Bartholomeus, 2011). The single-phase supply of three-phase variable speed drives is a topic that arises from the power quality issue. However, single-phase operation could be the normal working condition in specific applications such as irrigation pumps in rural areas. Hence, the power conversion is achieved in this proposed methodology from single-phase to three-phase supply.

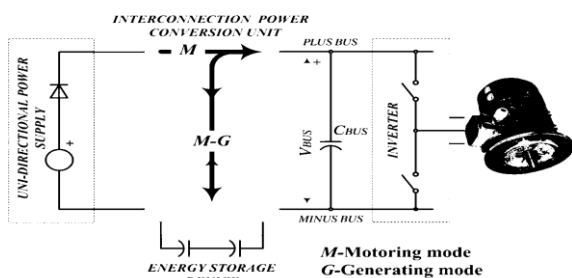


Fig. 1: Electric drive with an ultra-capacitor-based energy storage device.

There are five technical issues in the application of controlled electric drives:

- Saving of the drive braking energy.
- Extension of the drive ride-through capability.
- The drive input current harmonics and quality.
- The voltage quality and controllability, and
- Single-phase operation of three-phase variable drives.

The first two issues have been treated in numerous publications earlier. The problems of power quality, including the current harmonics, DC bus voltage control, and single-phase operation of three-phase electric drives are well-known problems. However, energy storage device and power conversion system gives a solution that solves all the five problems by storing dissipated energy in the ultra-capacitor, thus saving the braking energy and maintaining the constant voltage with two DC-DC converters, the harmonics of the drive input current is also reduced and drive ride-through capability will be improved too (P. J. Grbović, P. Delarue, P. Le Moigne and P. Bartholomeus, 2010).

2. Ultra-Capacitor

Ultra-capacitor is a high power density energy storage device. Comparing with a conventional capacitor, ultra-capacitor with the same weight can store 2000 to 6000 times energy. The ultra-capacitor discharged current value reaches thousands amperes and the energy density is several hundreds of times of an electrolytic capacitor. Furthermore, its instantaneous discharge power is a dozen

times of the battery. In addition, ultra-capacitor has high efficiency and excellent operational life.

Ultra-capacitors, as energy storage devices, have found very wide application in power conversion due to their advantages over the conventional capacitors and electro-chemical batteries; high energy and power density, high efficiency, high cycling capability and long life. Ultra-capacitor is promising energy storage device that positioned between conventional electrolytic and rechargeable battery. High power, high energy and long-term reliability feature of ultra-capacitor enables this component to be used in various applications such as backup power unit, auxiliary power unit. It is preferred for instantaneous power compensation, peak power compensation and energy storage purposes as well.

A basic idea of the regenerative controlled electric drive system using an ultra-capacitor as an energy storage device is illustrated in Fig. 2. The drive system consists of an ordinary variable speed drive converter (the input diode rectifier, voltage DC link and output inverter) and a parallel connected energy storage device. The rectifier is connected to the single-phase distribution network, while the inverter feeds a three-phase motor. The energy storage device is composed of an ultra-capacitor C_{C0} and bi-directional DC-DC power converters. The energy storage could be another type of storage device, such as flywheel or battery. However, the battery is not an appropriate solution because of limited power density, while the flywheel is a system that is more complex in comparison to the ultra-capacitor system. For generality of the analysis, in the first part of this section the DC-DC power converter will be considered as a controllable bi-directional DC-DC power converter with one input (the DC bus voltage V_{BUS}) and one output (the ultra-capacitor voltage u_{C0}). The DC-DC converter is for example, non-isolated two-level or three-level converter, multiphase interleaved converter or an isolated DC-DC converter. The DC-DC converter is controlled by the control variable m which can be duty cycle, phase shift or switching frequency, depending on the converter topology.

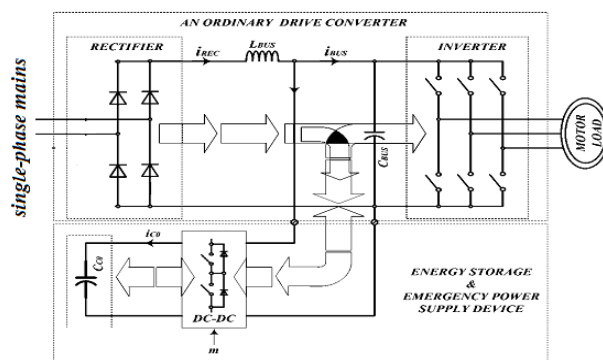


Fig. 2: Concept of regenerative controlled electric drive based on an auxiliary energy storage device and an interface DC-DC converter.

The topology is composed of two DC-DC converters namely, DC-DC1 and DC-DC2 and two series connected capacitors C_{B1} and C_{B2} . The role of DC-DC1 is to regulate the rectifier current i_{REC} and generate the voltage V_0 in

order to boost the DC bus voltage V_{BUS} . The DC-DC2 converter has two roles. The first one is to assist the DC-DC1 converter when the drive is supplied from the mains. More precisely, the DC-DC2 converter has the role to maintain the V_{C1} to V_{C2} ratio constant ($V_{C1} = V_{C2} = V_{BUS}/2$).

The second role of the DC-DC2 converter is to be an interface between the ultra-capacitor C_{C0} and the drive DC bus and control the energy flow between the drive and the ultra-capacitor whenever it is necessary.

3. Rectifier used in Power Conversion System

A bridge rectifier makes use of four diodes in a bridge arrangement to achieve full-wave rectification. This is a widely used configuration, both with individual diodes wired as shown and with single component bridges where the diode bridge is wired internally. The simple function of the diode is to conduct when forward biased and not to conduct in reverse bias. The forward bias is achieved by connecting the diode's positive with positive of the supply and negative with negative. The efficient circuit used is the full wave bridge rectifier circuit. The output voltage of the rectifier is in rippled form, the ripples from the obtained DC voltage are removed using other circuits available. The circuit used for removing the ripples is called filter circuit. The simple capacitor filter is the most basic type of power supply filter and also for energy storage to maintain constant voltage. For this purpose the ultra-capacitor is used in the present work to store the energy.

4. DC-DC Converters

Two DC-DC converters are used to boost up the voltage to the required level. The basic operation of the DC-DC converter is to provide a DC regulated output voltage. It can also be used to provide voltage isolation. DC-DC converters are designed to transfer power in only one direction i.e. from input to the output. However, almost all DC-DC converter topologies can be made bi-directional. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking. The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of ON/OFF time of the switch). Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power. For the sake of better flexibility and higher efficiency of the controlled electric drive with the ultra-capacitor energy storage, the ultra-capacitor cannot be directly connected to the drive DC bus. An interface power converter is necessary. The converter is controlled in the way, depending on the system control objectives; control of the DC bus voltage, the ultra-capacitor state of charge, active sharing of the energy between the drive and ultra-capacitor and so on. The voltage boosted in two stages as two DC-DC converters are used in this topology. The converter topology used is the boost converter. The boost converter is capable of producing a DC output voltage greater in magnitude than the DC input voltage. In general, converter

requires two control loops (input current and output voltage) to achieve this goal.

DC-DC1 converter

The DC-DC1 converter is composed of a switch–diode cell and an inductor L_0 . The inductor is connected on the rectifier plus rail, the diode D_0 is connected on the DC bus plus rail, and the switch S_0 is connected to the midpoint of the capacitors C_{B1} and C_{B2} . The input rectifier is modelled by a voltage source V_{REC} . The capacitors are modelled as constant voltage sources V_{C1} and V_{C2} . The capacitors are large enough, so that they behave as constant voltage sources over a short period (order of switching period). However, on the long term, the voltage V_{C1} has the tendency to increase, and V_{C2} has the tendency to decrease, because the midpoint current i_{co} is a non-zero positive current. To compensate the current i_{co} and keep the voltages V_{C1} and V_{C2} in the constant ratio, an auxiliary converter DC-DC2 is employed. Selecting a proper topology, it is possible to maintain the voltages V_{C1} and V_{C2} in constant ratio regardless of the input current. The complete circuit diagram of a DC-DC1 converter is depicted in Fig. 3.

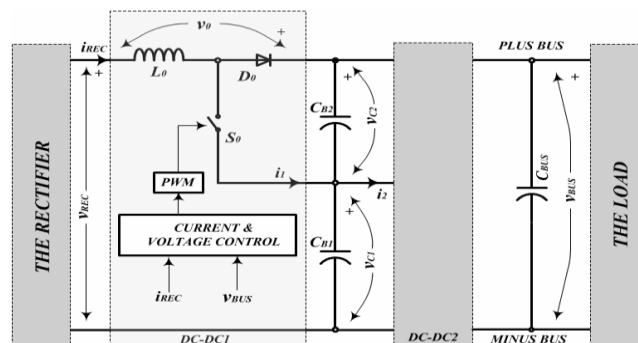


Fig. 3: Circuit Diagram of DC-DC1 Converter.

DC-DC2 Converter

The DC-DC2 converter has two roles

- The first role is to control the power flow between the drive and the ultra-capacitor, when the drive operates in the braking and ultra-capacitor motoring mode
- The second role is to assist the DC-DC1 converter and balance the voltages V_{C1} and V_{C2} whenever the drive system operates in the mains motoring mode.

Hence, the role of the DC-DC2 converter is to balance the voltages V_{C1} and V_{C2} . The circuit diagram of the proposed converter is given in Fig. 4. Basically, the converter is a variant of a switched capacitor converter. A switch leg $S1$ $S2$ is connected across the bottom capacitor C_{B1} , and a diode leg $D1$ $D2$ is connected across the top capacitor C_{B2} . The capacitor C_S is the main switched capacitor that transfers the energy, while inductor LS is an auxiliary inductor used to reduce conduction losses and achieve zero current switching (ZCS). The switches $S1$ $S2$ are driven with complementary control signals at period $TS2$. The duty cycle $d2$ is constant, around 50%.

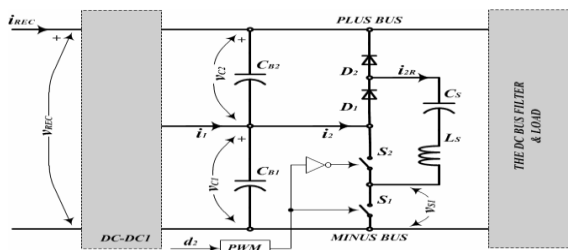


Fig. 4: Circuit Diagram of DC-DC2 Converter.

5. PWM Inverter Fed Variable Speed Drives

The PWM inverter is used to convert the boosted DC voltage to three-phase AC in order to drive the induction motor. PWM is used in all sorts of power control and converter circuits. Some common examples include motor control, DC-DC converters and DC-AC inverters. There are numerous PWM controllers available that make the use and application of PWM quite easy. SG3525 is used extensively in DC-DC converters, DC-AC inverters, home UPS systems, solar inverters, power supplies, battery chargers and numerous other applications. With proper understanding, SG3525 is used in such applications or any other applications which really that demands PWM control. In the present paper, PWM controller is used to generate the pulses to trigger the MOSFETs used in two DC-DC converters to boost the voltage in two levels. For three - phase conversion from single - phase supply PWM controller IC generates the pulses to trigger the MOSFETs based on the switching delay, the two MOSFETs get triggered at a time. PWM controller IC uses Sinusoidal Pulse Width Modulation technique (SPWM) to convert the DC voltage to three- phase AC supply to run the three-phase induction motor with constant speed and constant voltage without any fluctuation, thus reducing losses and harmonics.

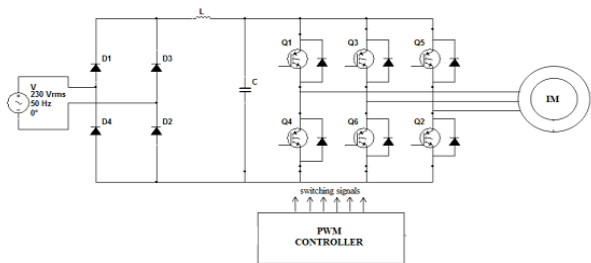


Fig. 5: Power Conversion System configuration for electric drive.

6. Results and Discussions

The ultra-capacitor selection is based on three main parameters: rated voltage, rated capacitance and ultra-capacitor losses. The ultra-capacitor rated voltage has to be selected as close as possible to the DC bus voltage. As the ultra capacitor is charged when the drive DC bus voltage is maximum (the drive is in braking mode) and discharges when the drive DC bus voltage is minimum. The ultra-capacitor losses in the general case can be decomposed into two essentially different frequency ranges, very low frequency and high switching frequency

losses. Very low frequency losses originate from the energy transfer between the drive and the ultra-capacitor and high switching losses from the driver circuits. The PWM controller IC is used to generate the pulses to trigger the MOSFETs. An energy storage and power conversion system for controlled electric drives was designed and experimentally verified. The control scheme, Pulse Width Modulation, and all protection functions were implemented. The control algorithm is executed at 50 kHz. The SG3525A Pulse Width Modulator control circuit is implemented. It offers improved performance and lower external parts count when implemented for controlling all types of switching power supplies.

Hardware Components

The concept of energy storage and power conversion for three - phase electric drives is implemented using the following components

- Diode Bridge Rectifier - Rectification of the AC input voltage with constant amplitude and frequency coming from the power grid consists of power diodes of (230V ,10A).
- Energy storage device - ultra-capacitor (400 V, 220micro farad)
- MOSFET -Inversion of the voltage coming from the DC link into an alternate signal of variable amplitude and frequency (IRF540).
- PWM control IC - To invert single-phase to three-phase by generating pulses (SG3525).
- Microcontroller - programming for LCD display. (The Atmel AVR ATmega8L is a low-power CMOS 8-bit microcontroller based on the AVR RISC architecture).
- Frequency Tuning Knob (0 to 60 Hz)
- Three - phase Induction Motor – 0.18HP, 1340 RPM, 60 Hz, 0.2 A.



Fig.6: Photograph showing the overall module of power conversion system developed in the present work.

Using these components the proposed topology is experimentally verified. The input is single phase supply (AC) which is rectified into DC by diode bridge rectifier. Two DC-DC converters are used to boost the voltage upto 250V as single phase output and 415V as three - phase output.

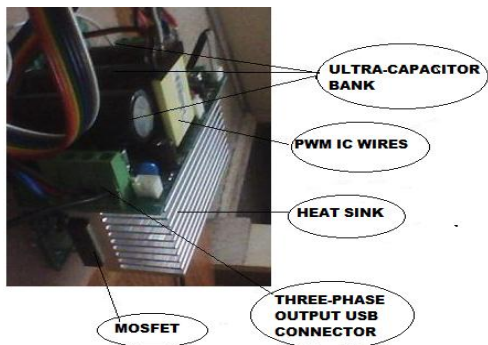


Fig. 7: Main Circuit of ultra-capacitor based energy storage and power conversion system.

The main circuit of ultra-capacitor based energy storage and power conversion system consists of power MOSFETs, three-phase output USB connector, heat sink, PWM IC and PWM driver wires and ultra-capacitor banks. Power MOSFETs are used for power conversion system with PWM IC to convert single - phase voltage to three-phase voltage to run three-phase induction motor. Power MOSFETs are used in DC-DC converters also. Three-phase output USB connector is connected to LCD display and from there to three-phase induction motor. Ultra-capacitor bank is arranged as shown in the block diagram in Fig.3.1.Heat sink which is made of aluminium is used to remove the excess heat in the circuit. The circuit also contains full wave bridge rectifier of power diodes, resistor, inductor and two DC-DC converters.

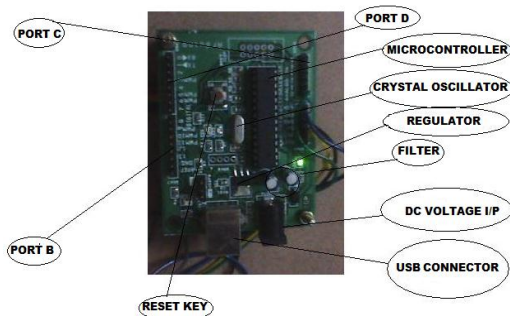


Fig. 8: Snapshot of AVR Microcontroller used for programming of LCD.

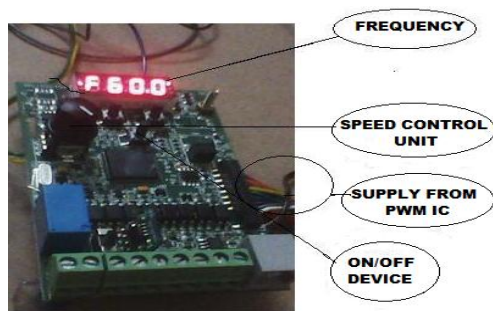


Fig. 9: Snapshot Frequency tuning knob for varying frequency.

The AVR ATMEGA8L microcontroller is used for programming of LCD display which consists port A, port B,port D,reset key, crystal oscillator 16MHz, Regulator

(5V,7805 IC), filter, DC input and USB connector for program the microcontroller. The microcontroller is used to program for LCD display of both single-phase and three-phase voltage therefore, showing the power conversion.

Frequency tuning knob is used for varying the frequency as depicted in Fig. 3.5 consists of frequency LED display, speed control unit with we can vary the speed of the motor, supply of PWM integrated chip and on and off device.



Fig. 10: Snapshot of LCD displaying single-phase boosted voltage and speed of the induction motor.

The single-phase AC supply which is 230V and it is boosted to 250V by DC-DC converters displayed in LCD in the Fig.10. The voltage will be maintained constant which is converted into three-phase output voltage. Along with the single-phase voltage, speed and frequency of the motor is also displayed.



Fig. 11: Snapshot of three-phase output voltage displayed in LCD.

Three-phase output voltage is displayed in LCD as shown in the Fig.3.9. The single-phase voltage is converted into three-phase output voltage by the action of PWM controller IC which consists of power MOSFETs. Single-phase voltage is converted to three-phase voltage to run the three-phase induction motor. Hence, the power conversion is achieved without any fluctuation in the running of the motor by reducing the losses and heat, the efficiency of the motor will increase. The speed and frequency of the motor is also displayed in the CRO.

Conclusion

The ultra-capacitor is used to store the drive braking energy and restore the energy whenever it is possible. Moreover, the ultra-capacitor can be utilized as emergency

energy storage in case of the mains power interruption. In last part of the dissertation, a compilation of the parallel-connected energy storage device is discussed. Important observations made during the investigations made in the present work are:

- Implementing an hardware module using an ultra-capacitor) energy storage device (Ultra- capacitor) for induction motor drives using bridge rectifier and two DC-DC (boost) Converters, constant voltage is maintained.
- Using Pulse Width Modulated (PWM) controller Integrated Chip (IC) single - phase to three - phase conversion is achieved.
- By Programming AVR ATMEGA8L microcontroller the voltage, frequency and speed of the motor is displayed in LCD.
- The proposed solution intents to successfully solve the following technical issues that still exist in application of controlled electric drives:
 - Saving of the braking energy.
 - Extension of the drive system ride-through capability (immunity on the mains interruption).
 - The voltage control.
 - Single-phase to three-phase conversion, and
 - Smoothing of the mains peak power.

The proposed solution is theoretically analysed and design guidelines are given. The concept has been validated by industrial prototype circuit.

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