DSP BASED BI-DIRECTIONAL INTERLEAVED DC-DC CONVERTER FOR ENERGY STORAGE APPLICATION

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Abstract. The central part of an energy storage system is the DC-DC converter which connects the ultracapacitor pack or the battery pack and a DC bus of an energy system. In this paper the bi-directional converter which operates in discontinuous conduction mode is designed in order to reduce the costs and remove the current control loop in each phase. High current ripples associated with this mode operation are then alleviated by interleaving. In order to control this kind of DC-DC converter the digital signal processor (DSP) is used. Such converter can be used for charging and discharging of accumulators or ultracapacitors. The charging mode of the accumulator differs from that of the ultracapacitor, the discharging mode differs from the charging mode for both devices, too. In the paper the software algorithm is presented that shows how transition from one mode to the other is done. Digital control of the DC-DC converter makes it easy and quickly to configure.

Keywords: interleaved switching converter, digital control, digital signal processors.

Introduction

In the recent years, storage of energy has become extremely important in the renewable energy systems (such as wind energy [1] and photovoltaic plant [2]) because the wind does not always blow and the sun does not always shine at any given location. Therefore, energy storage can be regarded as an essential component of future energy systems that use large amounts of various renewable resources. Also, such an energy storage system can be used to utilize recuperated energy in electric transport [3].

In stand-alone renewable energy microgrids (Fig. 1) energy storage (typically based on electrochemical batteries) together with additional generation systems (such as those powered by fuel engines) maintain the balance between electric power production and consumption. Supercapacitors can have very high discharge rates and could handle fast load changes in the microgrid.

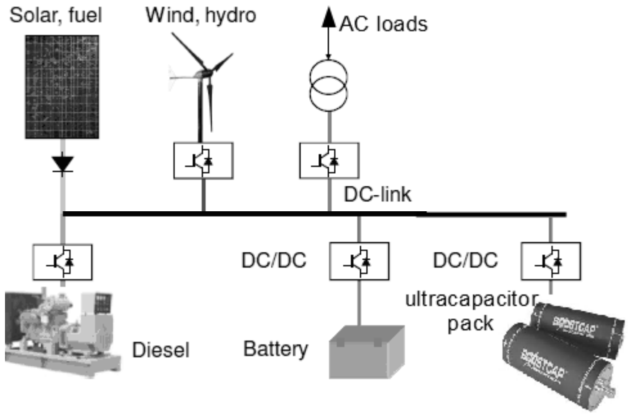

Fig. 1. **Microgrid generating electricity from renewable sources**

Theoretically, energy storage is not necessary in a grid-connected renewable energy system due to the availability of the distribution grid that should work as an ideal container of electrical energy. However, in the recent years, much attention has been paid to the use of energy storage also in grid-connected renewable energy systems, aiming to overcome some important power quality problems of real distribution grids and make renewable energy systems more and more useful and attractive.

The main part of an energy storage system is the DC-DC converter which connects the ultracapacitor pack or the battery pack with the DC bus of the energy grid. The DC-DC converter is always required to allow energy exchange between the storage device and the rest of the system. Such a converter must have bi-directional power flow capability with flexible control in all operating modes. Future solutions to the load balancing problem focus on smart grid technology. The converter can be integrated in smart grid system due its digital communication possibilities.

Materials and methods

In order to control the DC-DC converter the STM32F407VGT6 microcontroller (MCU) is used. This ARM Cortex-M4 32 bit MCU with a floating-point unit has 210 DMIPS, up to 1MB Flash, 194 KB RAM, 17 timers (including the general purpose ones), 3 analog to digital converters (ADC), 15 communication interfaces [4]. MCU maximal operating frequency is 168 MHz. The program code was written in C language and IAR Embedded Workbench software was used.

To measure signals the Tektronix TPS 2024 digital oscilloscope was used. The oscilloscope has 200 MHz bandwidth and 2 $GS \cdot s^{-1}$ real time sample rate. The TPS2024 input connector shells are isolated from each other and from earth ground.

The general-purpose timers (that are a part of a MCU) consist of a 16-bit auto-reload counter driven by a programmable prescaler. They may be used for a variety of purposes, including measuring the pulse lengths of input signals (input capture) and generating output waveforms (output compare and PWM). Pulse lengths and waveform periods can be modulated from a few microseconds to several milliseconds.

A 12-bit ADC has up to 19 multiplexed channels allowing it to measure signals from 16 external sources. The analog to digital conversion of the channels can be performed in single, continuous, scan or discontinuous modes. The main features of ADC are interrupt generation at the end of conversation and dual and triple mode with configurable direct memory access (DMA) to data storage.

The switching frequency of the DC-DC converter is variable. Therefore, it is necessary to calculate the length of the period and the pulse length before each switching action of the transistor of the first channel. The PWM signals of other channels equal the signal of the first channel shifted by 60 degrees. In order to have more time for calculation the ADC conversion is started at the beginning of a new period right after setting the new period and the PWM values of all the timers. As the time required for setting does not change ADC starting time against the beginning of the period is constant and the time between two samples t_{sample} is equal to the length of the previous period.

The current is measured by using the hall-effect based current sensor with liner output voltage and the voltage is lowered by using the voltage divider. Then all the analog signals are amplified with operational amplifiers and adjusted with potentiometers in order to make voltage equal to 3,3 volts at the maximum value of the signal and to set zero.

Results and discussion

A switching converter transforms one voltage level into another for a given load by switching action of semiconductor devices. In the past, most of power electronic converters employed analog control methods. The reason is that digital controllers of the previous era had bandwidth problems. In the recent years the situation has changed significantly. The speed and functionality performance of the DSPs has improved. They are also available at a much lower cost. The advantage of the digital controller is that it is programmable and offers more functionality to the system compared to the analog controllers. Novel control algorithms and methods with DSP can be realized.

Interleaving control schemes are widely used in converter applications. Merits of such control methods are reduction of input/output current ripples and volume, and increase in the processed power capacity of converters. In discontinuous conduction mode (DCM) the reverse-recovery losses of the boost diode are eliminated and the switching losses can be reduced [5]. Current in choke only depends on the on-time of the transistor but does not depend on the current in the previous periods. This allows improving dynamic and stability of the converter even without current sensors in each phase [6].

In the boundary conduction mode (BCM) the peak current in choke is twice the average current [7]. Therefore, this mode is the most economical and control will be designed to ensure work of the converter in the DCM mode as close as possible to the BCM mode. The summary output current I_{out} of n phase converter is the sum of all choke currents. In the BCM peak current in choke can be expressed as shown below.

$$I_m = \frac{2 \cdot I_{out}}{n} . \tag{1}$$

The disadvantage of the BCM is variable opertating frequency but it can be implemented with digital control algorithms. Using the inductance (L) as well as the input (V_{in}) and output (V_{out}) voltage the required on-time (t_i) and off-time (t_p) can be calculated by (2) and (3) to ensure operation in the boundary conduction mode. Inductor current in BCM is shown in Fig. 2.

$$t_i = I_m \frac{L}{V_{in} - V_{out}}; \tag{2}$$

$$t_p = I_m \frac{L}{V_{out}}. \tag{3}$$

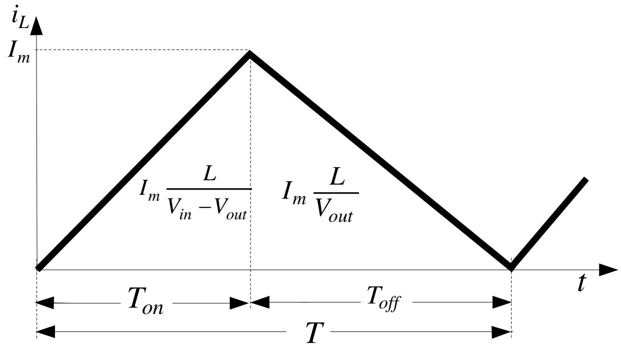

Fig. 2. **Inductor current at boundary conduction mode**

I_m can be used not only to maintain the desirable output current but also to control the input current and output voltage. It can be done if I_m is output of the proportional-integral (PI) regulator that is shown in Fig. 3 and can be calculated by (4) where K_P is the proportional coefficient, T_i is the integral coefficient, t_{sample} is time between two samples and *DELTA* is difference between the reference and real value of the controlled parameter. Approximate values of both coefficients are determined by using the PSIM software; they are specified during the experiment. The current tracking can be done via open-loop control and no current sensing in each phase is necessary.

$$I_m[k] = DELTA[k] \cdot K_P + I_{m,i}[k-1] + DELTA[k]\frac{t_{sample}}{T_i} \tag{4}$$

An error in the voltage measurement could cause a drop out of the BCM. In such a case entering into continuous conduction mode (CCM) has to be avoided to prevent overcurrent. Therefore, it is beneficial to stay into DCM. Inductance is multiplied by the coefficient to get a little enlarged switching period and to stay into DCM.

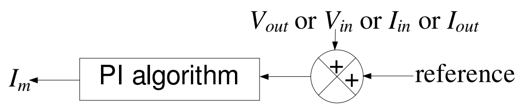

Fig. 3. **Calculation of I_m by PI regulator**

Fig. 4 shows the structure of the DC-DC converter. It is a six-phase converter, which is bi-directional as it can work in both, the buck and boost mode. If the boost mode is selected, transistors VT1...VT6 are being switched on and off but VT7...VT12 remain turned off and vice versa. In order to control the converter seven analog values are measured and converted into digital signals. Buttons and LCD display provide the user interface. A DC-DC converter is used to charge and discharge an accumulator or an ultracapacitor pack.

The power transistors are controlled by PWM signals of the microcontroller. The Interrupt Service Routine (ISR) of a timer is the heart of the control software. The ISR has the highest priority of execution. In overload ISR of the timer counter of the first channel (IRQ1) the new period and pulse width values of all timers are recorded in the corresponding register but they are updated when an update event occurs. This event is generated when counter overload of the corresponding timer occurs. In the capture/compare ISR of the first timer (IRQ2) ADC conversion is started and the new period and pulse length values are calculated. As shown in Fig. 5 the time required for calculations is less than critical.

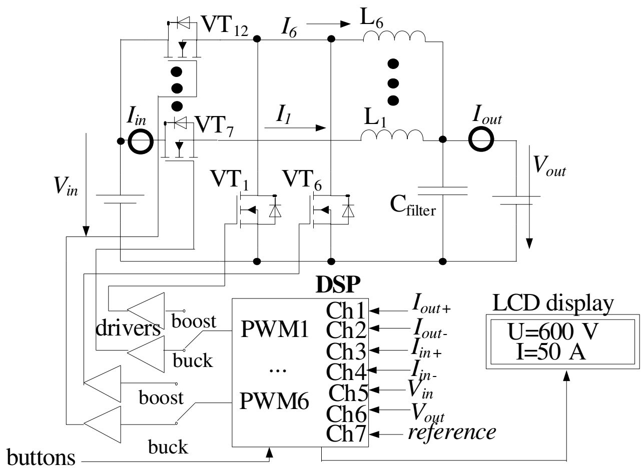

Fig. 4. **DSP controlled DC-DC converter structure**

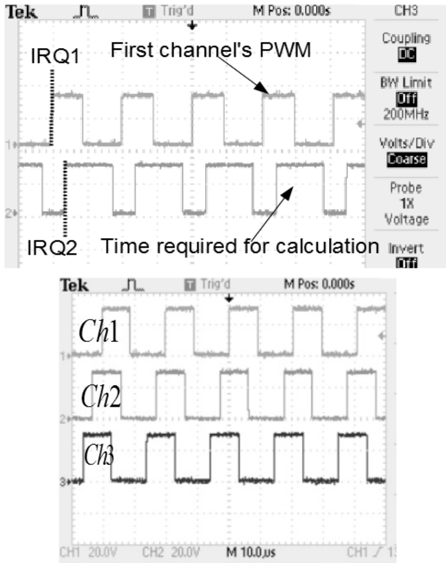

Fig. 5. **Oscillograms of ISR starting time and PWM signals**

The required phase shift value of the six-phase converter to guarantee optimal ripple cancelation is 60 electrical degrees. The phase shift can be implemented by artificial shortening or lengthening of the period of the timer which is determined by the value of the auto-reload register (ARR). A corrected value of the period is selected so that it ensures the overload of the n-channel timer in time that corresponds to the required phase shift. The ARR value that must be set to provide a correct phase shift can be calculated from the previous and new period value. Fig. 5 shows resulting PWM signals by using this method.

Fig. 6 shows how transition from one mode to another is done. The input voltage is regulated in the charging mode of the accumulator but the output current is regulated in the charging mode of the ultracapacitor. So, the configurations of both modes differ. When the switch KON is turned on the transition to the precharge mode is being done. In this mode the filter capacitor is charged through resistance. If the capacitor is charged to the input voltage the contactor is switched on and transition to the READY state takes place.

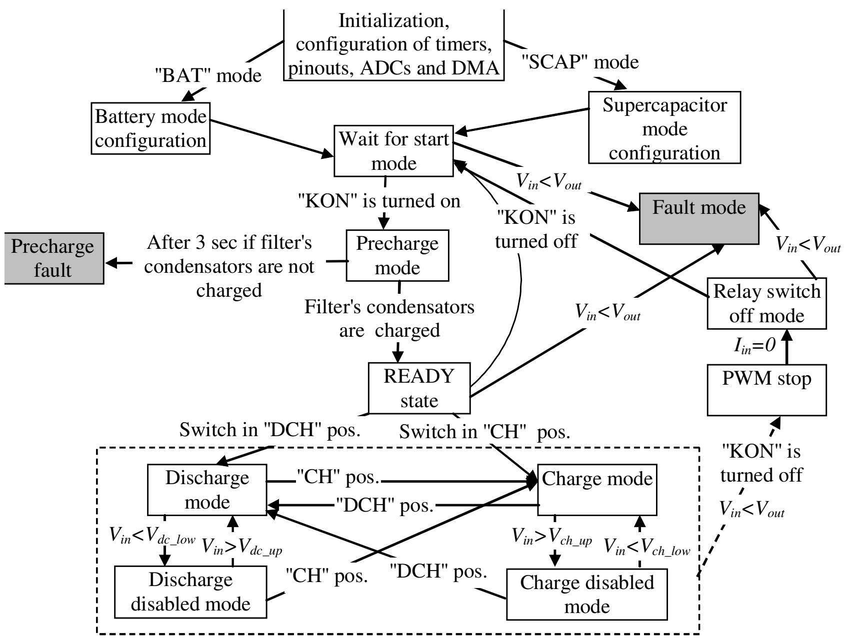

Fig. 6. **States of DC-DC converter**

Depending on the position of the switch (CH or DCH position) the converter works in the charging or in discharging mode. If in the discharge mode the voltage is lower the upper threshold the message “Discharge disable” is shown on the LCD and PWM signals are stopped. If in the charge mode the voltage is higher than the highest threshold then the message “Charge disable” is shown on the LCD and the PWM signal is stopped. The contactor of the converter can only be switched off if the current is zero. If the current does not reach zero, transition to the fault mode is done. In the fault mode the reason of a failure is shown on the LCD display.

Fig. 7 shows hardware implementation of a DSP controlled six-phase interleaved DC-DC converter. It is possible to communicate with a device via USB, CAN, I2C, UART, SPI, touch screen, digital microphone, etc. The LCD display (1), LEDs (5) and buttons are selected in this case as the cheapest solution. The power transistors (4) are mounted on the radiator plate. The DSP board (3) is connected to the buttons via the cable (2).

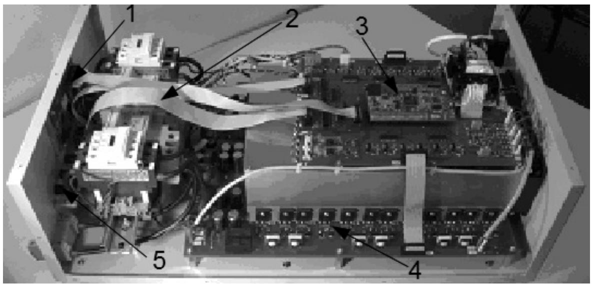

Fig. 7. **Hardware of interleaved DC-DC converter**

Conclusion

It is possible to design an interleaved DC-DC converter without current sensing in each phase. For this reason it is necessary to implement digital control to realize open-loop control. Digital control of a DC-DC converter makes it easy and quickly to configure. It is possible for this device to communicate with other devices in a simple way to manage the energy storage device.

This paper has presented methods to implement digital control with a variable frequency that enables interleaving of a converter with bi-directional power flow. The ripple of the total output current does not exceed a few percents. An optimal number of phases and tuning of the DC-DC converter at nominal load requires future investigations as less than 10 ultracapacitors were available to test the prototype.

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