A POWER ELECTRONIC CONDITIONER USING ELECTROCHEMICAL CAPACITORS TO IMPROVE WIND TURBINE POWER QUALITY

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The large variability in wind output power can adversely impact local loads that are sensitive to poor power quality. To mitigate large swings in power, the wind turbine output power can be conditioned by using a small energy buffer. A power conditioner is developed to smooth the wind power output by utilizing the energy of an electrochemical capacitor, or ultracapacitor. The conditioner is based on a single phase voltage source inverter connected between the grid interconnection point and the ultracapacitor. The VSI shunt inverter injects or absorbs active power from the line to smooth the wind power output by utilizing the short term storage capabilities of the ultracapacitor. The ultracapacitor is connected to the DC link through a bidirectional DC-DC converter. The bidirectional DC-DC converter and VSI are constructed and field tested on a Skystream 3.7 wind turbine installed at the Missouri University of Science & Technology.

Keywords: power electronics, electrochemical capacitors, ultracapacitors, wind power

INTRODUCTION

Due to the price volatility and carbon impact of fossil fuels, wind power generation is rapidly growing as an alternative energy source in many parts of the world. Due to the variability of wind speed, wind turbine output power can be highly variable. Power fluctuations from the wind turbine may cause severe power quality problems when connected to the grid. The large variability in wind turbine output power can adversely impact local loads that are sensitive to pulsating power, posing a challenge to the use of wind power extensively. The rapid growth of the wind power and its immense potential as a future energy source encourage us to find a way to smooth the variable wind power. Energy storage technologies can be used to improve the quality of the wind power [1], [2]. In this paper, we propose the power quality conditioner with the ultracapacitor to smooth the variable wind turbine output power. The short term storage capabilities of the ultracapacitor can be effectively used to smooth the wind power to minimize rapid power excursions that may damage sensitive local loads.

This paper presents a power conditioner that has the purpose of smoothing the wind power. The power conditioner mainly consists of power converters to shape the injected current at the point of common coupling [3]. The conditioner is based on a single phase shunt connected VSI connected between the grid interconnection point and the ultracapacitor. The shunt VSI injects or absorbs active power from the line to smooth the variable wind power by charging or discharging the ultracapacitor [4]. The ultracapacitor is connected to the DC link through a DC-DC converter. Traditionally, the VSI DC link voltage is maintained relatively constant by the shunt inverter control. In this application, we use a bidirectional DC-DC converter to maintain the DC link voltage. The bidirectional DC-DC converter acts in buck mode during discharge of the DC link and in boost mode during charging to maintain the voltage of the DC link to provide good controllability of the VSI.

Control of the injected active power via the shunt inverter is presented in this paper. The VSI controller calculates the compensating active power, which is then synthesized by using the bipolar pulse width modulation (PWM) switching sequence. The reference signal to the shunt inverter controller is obtained from a low pass filter, which has a large time constant. The fluctuating wind power is passed through the low pass filter to get the smoothed reference value. The conditioner ensures the smooth power is available at the grid interconnection point. The simulation results are presented to show the efficiency of the conditioner in smoothing the variable wind turbine output power.

Fig. 1. Skystream3.7 wind turbine installed at the authors' university

THE WIND TURBINE

The power conditioner design and control will be validated on the Skystream3.7 wind turbine installed at the Missouri University of Science and Technology. The installed wind turbine is shown in Fig. 1. The wind turbine is rated 2.4 kW at a wind speed of 29 mph with a cut-in wind speed of 8 mph. The three rotor blades have a 12 ft spinning diameter. The wind turbine alternator is a slotless permanent magnet brushless motor with passive yaw control. The Skystream3.7 wind turbine output is 120/240 VAC Split single phase, 60 Hz and is connected to the campus grid as shown in Fig. 2. The neutral and ground terminals of the wind turbine are tied together and connected to the neutral of the grid. The power quality conditioner is connected in shunt between the output of the wind turbine and the grid interconnection point.

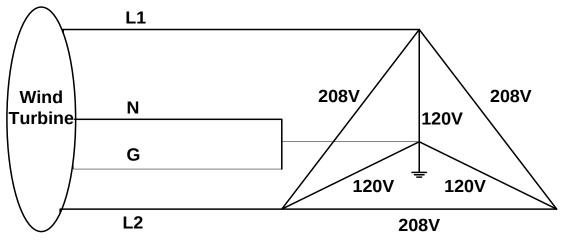

Fig 2. Skystream3.7 Wind Turbine Connections to the Grid

THE POWER QUALITY CONDITIONER

As shown in Fig. 3, the power quality conditioner consists of a shunt inverter and a bidirectional DC-DC converter. The voltage source inverter acts as a shunt active filter compensating the active power of the wind turbine. The VSI is connected to the line through an RL filter which reduces the unwanted harmonics. The shape of the output current of the conditioner depends on the inductor value. The value of the resistor and the inductor determines the damping in the circuit. On the other side, the VSI is connected to the DC link capacitor. The DC-DC converter with the ultracapacitor is used to reduce the size of the DC link capacitor and to maintain the voltage of the DC link relatively constant as the ultracapacitor discharges and charges. The bidirectional DC-DC converter charges the ultracapacitor in buck mode by reducing the voltage of the DC link. In the other direction, it acts in boost mode, discharging the ultracapacitor to increase the voltage of the DC link. The power conditioner injects or absorbs active power from the line through the filter to smooth the variable wind turbine output power. The DC link acts as the voltage source for the VSI.

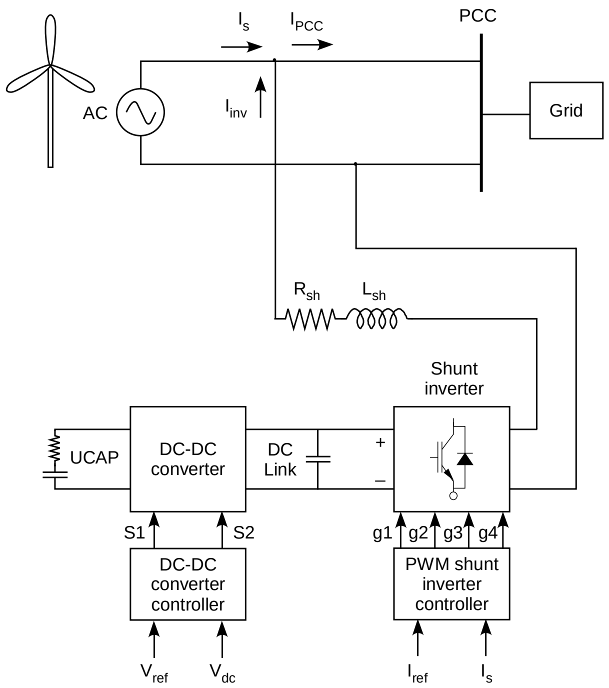

Fig. 3. Power Quality Conditioner

The primary objective of the conditioner is to inject a current $i_{inv}(t)$ at the point of common coupling (PCC) such that the current supplied to the grid is relatively smooth. The smoothed current is obtained by passing the (measured and scaled) wind turbine current through a low pass filter that is tuned to provide the appropriate high-frequency cutoff. The ultracapacitor is charged and discharged rapidly to supply the required current while holding the DC link constant. Note that the reference current is not a constant, but rather a slowly varying current. If the reference current were held constant, this would imply that the electrochemical capacitor would have infinite ability to charge and discharge. By allowing the reference current to slowly vary, the energy supplied to the grid will track the energy supplied by the wind turbine.

DC-DC bidirectional converter

The two primary components of the proposed power conditioner are the shunt inverter to control the injected current and the DC-DC converter to regulate the DC link voltage and control the ultracapacitor injected current. The topology of the bidirectional DC-DC converter is shown in Figure 4.1. The bidirectional DC-DC converter acts a buck converter in one direction and as a boost converter in the other direction [10]-[13]. Power MOSFETS are used as the switching devices in the circuit. The operation of the converter is controlled by the DC link voltage and the voltage of the ultracapacitor. The main purpose of the bidirectional DC-DC converter is to maintain the voltage of the DC link relatively constant at a reference value. The DC link capacitor is used as an intermediate element between the DC-DC converter and the inverter.

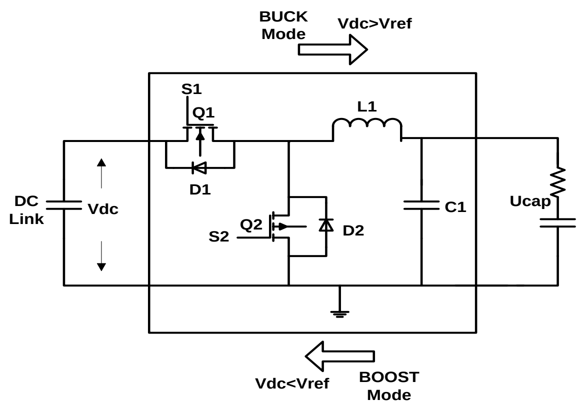

Fig. 4. DC-DC buck-boost converter

The DC-DC converter operating modes can be divided into four modes:

- Mode 1: The DC-DC converter acts in buck mode when the DC link voltage V_{dc} is greater than the reference value V_{ref}. In this mode, the DC-DC converter controls the current to charge the ultracapacitor.
- Mode 2: The DC-DC converter acts in boost mode when the DC link voltage V_{dc} falls below the reference value. In this mode, the ultracapacitor discharges.
- Mode 3: When the ultracapacitor is fully charged, the DC-DC converter shuts down to avoid damaging the ultracapacitor.

- Mode 4: When the ultracapacitor is fully discharged, the conditioner shuts down until the wind turbine produces sufficient current to resume charging of the ultracapacitor.

The bidirectional DC-DC converter shown in Fig. 5 was constructed from IXFK80N50P power MOSFETS as the switching devices in the circuit. The Microchip PIC24FJ128GA010 microcontroller along with the Explorer16 development board was used in implementing the control scheme and to obtain the gate signals for the MOSFETs in the bidirectional DC-DC converter. LEM LV 25-P voltage sensors are used to measure the voltages of the DC link and the ultracapacitor. The ACNW3190 5.0 Amp High Output Current Gate Drive optocoupler is used to drive the MOSFETs. A TP-75C DC power supply is used to supply power to the LEM sensors and gate drivers. The voltage measurement circuits and the gate driver circuits are built on the vector board and are soldered permanently. The high current inductor used in the circuit is manfactured by West Coast Magnetics.

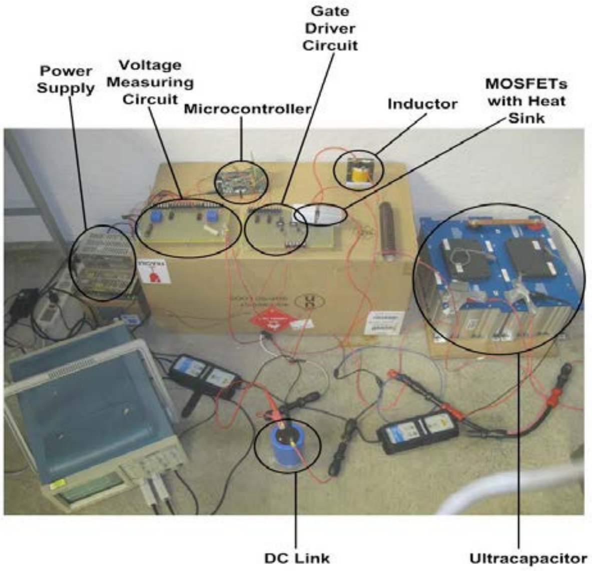

Fig. 5. DC-DC buck-boost converter hardware

The Ultracapactor

Ultracapacitors are electrochemical double layer capacitors that have unique characteristics when compared to other energy storage devices. Ultracapacitors have high energy density and large time constants as well. Although multiple time-scale models of ultracapacitors have been developed, a simple ultracapacitor model such as the one in Fig. 3 containing only one RC branch was used in the simulation of the converter system. This model is composed of an equivalent series resistor (ESR) and a capacitor (C) [5]. The ESR represents the ohmic losses in the ultracapacitor. Higher order ultracapacitor models are essential for simulation studies in which the timescale of interest is on the order of microseconds. In the current application, the timescale of interest is on the order of minutes; therefore the single RC branch model is sufficient to capture the ultracapacitor behavior of interest.

The benefits of using ultracapacitors are quite extensive. Ultracapacitors have low losses while charging and discharging. They have a very low ESR, allowing them to deliver and absorb very high currents and to be charged very quickly, making them well suited for energy buffer applications. Ultracapacitors are highly efficient components even at very high currents. The characteristics of the ultracapacitor allow it to be charged and discharged at the same rates, something most batteries cannot tolerate. Ultracapacitors have a wide voltage window and can be deeply discharged. The energy storage mechanism of an ultracapacitor is a highly reversible process. The process moves charge and ions only. It does not make or break chemical bonds like batteries; therefore it is capable of millions of cycles with minimal change in performance. It is therefore capable of many years of continuous duty with minimal change in performance. These advantages made ultracapacitors well suited for power quality conditioning applications.

The power conditioner was constructed using two series-connected Maxwell ultracapacitor modules of 165F nominal capacitance and rated voltage 48.6V.

Shunt inverter

A full-bridge IGBT based inverter topology is used in this application. The full-bridge inverter consists of four switching devices, which are connected to form the full-bridge inverter circuit shown in Fig. 6. The gating signals for the IGBTs are obtained by the pulse width modulation controller. Anti-parallel diodes are connected across the power IGBTs to protect the devices and to provide the power flow in the reverse direction [6], [7]. The voltage source inverter connected in shunt to the line acts as a current source, injecting or absorbing the compensating current from the line [8]. The shunt inverter is connected to the line through a series interference RL filter, which reduces the unwanted harmonics. The filter provides smoothing and isolation from high frequency components. On the downstream side, the full-bridge inverter is connected to the DC link. The injected current is in phase with the line voltage to produce a unity power factor.

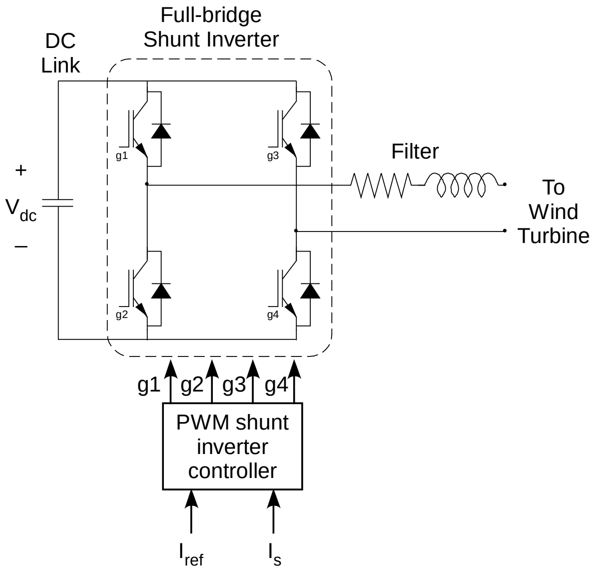

Fig. 6. Shunt Inverter Circuit

The VSI operates in the following two modes:

Mode 1: When the wind turbine power is greater than the reference value, the converter acts like a rectifier drawing active power from the line and charging the DC link capacitor.

Mode 2: When the wind turbine power is less than the reference value, the converter acts like a VSI injecting active power into the line by discharging the DC link capacitor.

The variable wind power is passed through a low pass filter to get a smoothing reference signal for the inverter controller. The output of the low pass filter is given to the shunt inverter controller as the reference value [9]. The reference signal I_{ref} is obtained

$$I_{ref} = \frac{I_s}{1 + sT_s} \tag{1}$$

where T_s is the time constant of the filter. The smoothing performance of the wind turbine output power depends on the time constant of a low pass filter. The time constant of the low pass filter is in the range of several seconds and is tuned to provide the desired smoothing. The power fluctuation is smoothed by drawing or injecting the difference of the reference power and the variable wind power.

The experimental setup and different components in the construction of the single phase shunt inverter are shown in the Fig. 7. A SEMIKRON SK 30 GBB 066 T IGBT module is used as the switching devices for the circuit. A 2.5mH inductor is used as the output filter of the shunt inverter. A TI TMDSDOCK28335 DSP is used in the closed loop control of the shunt inverter. The current and voltage sensors measures and sends signals to the DSP through the signal shaping circuit. DSP drives the IGBTS with the ACNW3190 drivers.

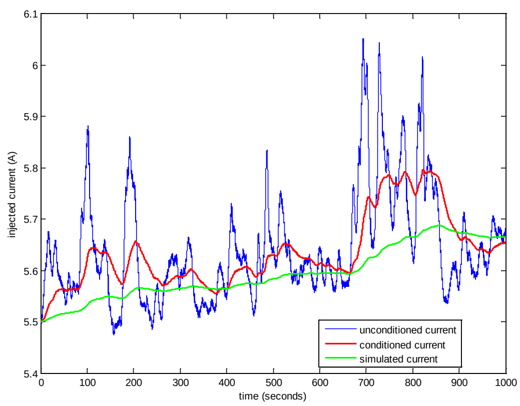

Fig. 8. Power Quality Conditioner Output Currents

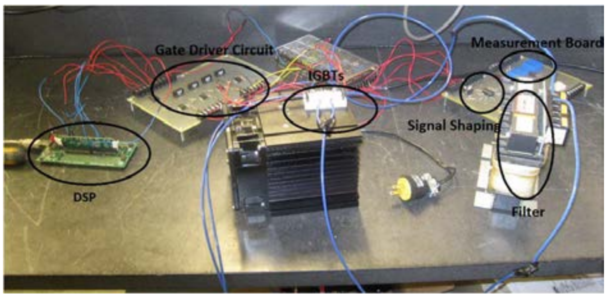

Fig. 7. Shunt Inverter Circuit

EXPERIMENTAL RESULTS

The measured injected current of the conditioner is shown in Fig. 5. The blue trace is the measured unconditioned (raw) output of the wind turbine. It is highly variable with large pulsations in power and with considerable high frequency noise. The red trace is the actual measured conditioned output current of the conditioner with a 60 second filter time constant. The green trace is a simulated conditioned output current if a 5 minute filter time constant were used.

CONCLUSIONS

This paper describes a residential scale power quality conditioner that can be used to smooth the injected currents from a wind turbine by using an ultracapacitor to provide an energy storage buffer. This conditioner would be especially appropriate for applications in which the residence is connected to a weak radial system (such as a farm) or an off-grid system.

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