International Journal of Control and Automation
Vol. 8, No. 6 (2015), pp. 327-338
http://dx.doi.org/10.14257/ijca.2015.8.6.32

Research on the Grid-Converter for High Power Permanent Magnet Direct-Driven Wind Turbine

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Abstract

For direct drive synchronous wind power generation system, the converter of direct drive motor is connected to the stator side of permanent magnet synchronous generator side, through controlling the converter, the maximum wind energy can be captured. Main circuit design of the direct-drive grid-converter is studied. Firstly, power grid side filter is designed and calculated, LCL filter is used instead of traditional L type filter, in this way, the value of the inductance, the volume and cost are reduced effectively, and its inhibitory effect on high frequency signal is more obvious. Not only meet the vector triangle, but also grid connection harmonic current is restrained. Secondly, the filter of motor side is also designed, about the problem of voltage reflection for long cable drive motor PWM converter on the motor side, the solution is to reduce the output value of the du/dt and increase the pulse rise time, at the same time the reflected voltage of the motor side is also reduced. Thirdly ,Brake unit is researched, at the instant of the power grid voltage dips is detected, chopper control is started to IGBT of brake unit, making the machine side power in addition to the net from the side of the part, the rest are consumed in the brake unit, to ensure that the equipment can grid-connected operated. The last but one, the pre-charging circuit is included. Finally, based on the control theory of grid side and wind turbine side and design scheme proposed in this paper, mutual feed experiment is completed based on experiment platform of the 1.5 MW direct drive wind turbine power grid connected converter prototype, the experiment results proved the feasibility of the design method of converter in the pater.

Keywords: *direct-driven wind turbine system; line-side LCL filter; generator-side du/dt filter*

1. Introduction

In recent years, China's electric power system proposed construction of a strong, smart grid concept Therefore, the development of new energy technologies has become a hot spot. Connected for direct-drive synchronous wind power systems, direct-drive motor-side converter and permanent magnet synchronous generator stator side, its control, to achieve maximum wind energy capture [1]. Full power converter is an important part of the grid through the converter can be issued by the generator energy better. Direct-drive wind power converters, there are many key technologies need to be studied [2]. Direct-drive wind turbine and inverter theoretical analysis to calculate the parameters of the main circuit, and the machine side and network side converter control method carried out research, and the use of simulation and experiment to prove the thesis proposes development of the feasibility of the method.

ISSN: 2005-4297 IJCA

2. Performance Analysis of Converter of Direct-Drive Wind Power Generation System

Direct-drive wind power system is one of the most popular wind power systems at present [3], in order to facilitate analysis, the current transformer unit of grid side is usually referred to as grid side converter, the current transformer unit of generator side is called generator side converter. Under normal circumstances, the current transformer is connected to grid with unit power factor [4]. Structure of wind power system is shown as Figure 1.

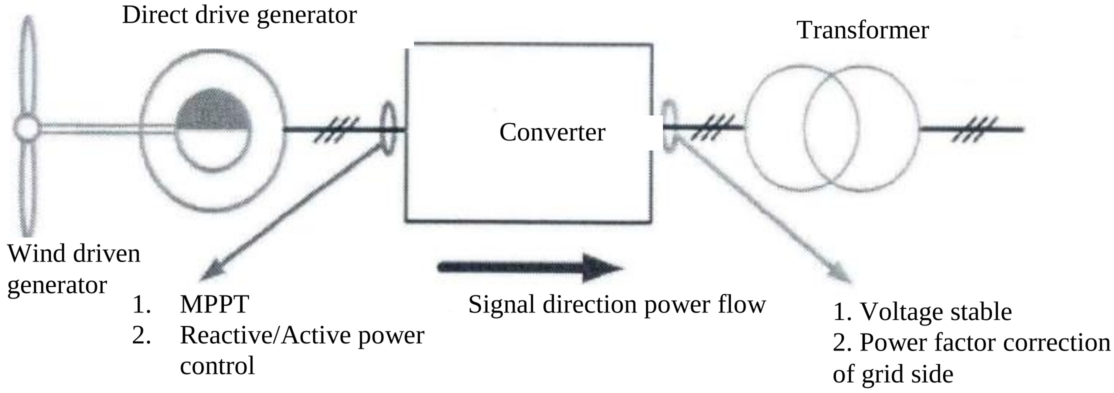


Figure 1. Structure of Wind Power System

2.1. Structure Analysis

Power of wind power system, generated by the generator is transmitted into grid by converter, The converter not only need to meet the relevant requirements that the grid is connected to a generator, but also produce the right PWM voltage to drive the motor, and then stator current and rotor speed can be controlled [5]. The concrete structure is as follows:

2.1.1 Diode Rectifier +Boost Converter +DC/AC Inverter: Firstly AC voltage generated by Permanent magnet direct drive motor is transformed by diode rectifier into direct current, and then the DC voltage is improved by the Boost converter converts to the appropriate voltage level in order to be used by inverter behind of it. And then through the inverter, the high quality AC is transformed and fed into the grid [6].fewer IGBT device is employed with the structure and has certain advantages. However, the power quality of permanent magnet motor side is poor, the efficiency and the power factor of the motor are also be affected [7].

2.1.2 Back-to–back Converter: Two-level and three-level back-to-back converters, can perfect to achieve grid side and motor side control, and to facilitate the realization of LVRT function. Among them, capacitor size of three level H bridge back-to-back converter is reduce effective however, openings winding is needed by motor and transformer windings to increase the weight and loss of the motor and transformer. Higher level voltage, smaller du/dt and more output level number can be realized by five-level H Bridge, volume and loss of the inductance is further reduced [8]. However, the problem of bus neutral point voltage fluctuation and inner and outer pipe loss unbalanced DC is still existing, openings winding motor and transformer are still needed. Multilevel cascaded H bridge back-to-back converter, can achieve higher voltage more than five level H bridge converter, be used in grid voltage to l0kV~20kV voltage grade [9-10]. But each back-to-back unit needs a high-frequency transformer isolation of the motor and the power grid.

2.2. Analysis of Technical Conditions

For the direct drive wind power grid-connected converter, generally the grid side converter works in three-phase system with 690V voltage and then the value is improved through the transformer to 10kV grid. Using IGBT as the switching device, in order to ensure the drive signal well anti-interference characteristic, the optical drive is adopted. Because direct drive converters mainly work in the sea or harsh conditions, each component cabinet internal need to prevent salting out and dust, on the other hand, on account of larger power for the direct drive converter, so the requirements of heat dissipation is higher, if the cooling volume will be great, so often cooled by water cooling [11]. The technical parameters are shown in Table 1.

Table 1. Direct-Drive Wind Power Grid-Connected Prototype Parameters

DC voltage(U_{DC})	1200V(DC)	Power grid voltage	690±15%V
Generator side rated capacity	1450kVA	Power Grid frequency	47.5~51.5HZ
Variations range of voltage of Generator side	189-700vrms	Switch frequency	1.9kHZ
Variations range of motor speed	4-18r/min	Drive Method	Photic dirve

For the voltage type rectifier, it is need to meet the condition of formula 1.

$$U_{DC}>1.412U_l \quad (1)$$

In the paper, 1200V>1.412× 690V.therefore, the design meets the conditions.

3. Direct-Drive Wind Power Converter Main Circuit Design

On the basis of technology conditions of the direct-drive wind turbine converter, the filter of grid side of converter main circuit, the filter of generator side, the brake unit and pre-charging circuit are designed.

3.1. The Filter Design of Grid Side

Three-phase voltage source PWM rectifier output voltage of the PWM wave to achieve and the network must require filtering. Traditional network side of the filter is generally L filter, it has to meet the requirements of vector control: to meet the vector triangle, but also to achieve the inhibitory effect of the grid current harmonics. L-type filter is reliable, relatively simple design, which has been widely used. However, with the power level of increase, the decline of the switching device switching frequency, in order to meet the requirements of harmonic suppression, the amount of inductance you need to be very large. Large inductance L will not only increase the volume of the converter and increase the cost of the converter, but also makes the converter current regulation slows down [12]. LCL filter instead of the traditional L-shaped filter can effectively reduce the total value of the inductance, reducing the size and cost, and the inhibitory effect of high frequency signal is more pronounced.

The line-side converters in this article using the LCL filter structure shown in Figure 2. Where L_1 is the converter side inductance, the CF filter capacitor, L_2 is the transformer leakage inductance. The line-side converter in this article uses the LCL filter structure shown in Figure 2. Where L_1 is the converter side inductance, the CF filter capacitor, L_2 is the transformer leakage inductance.

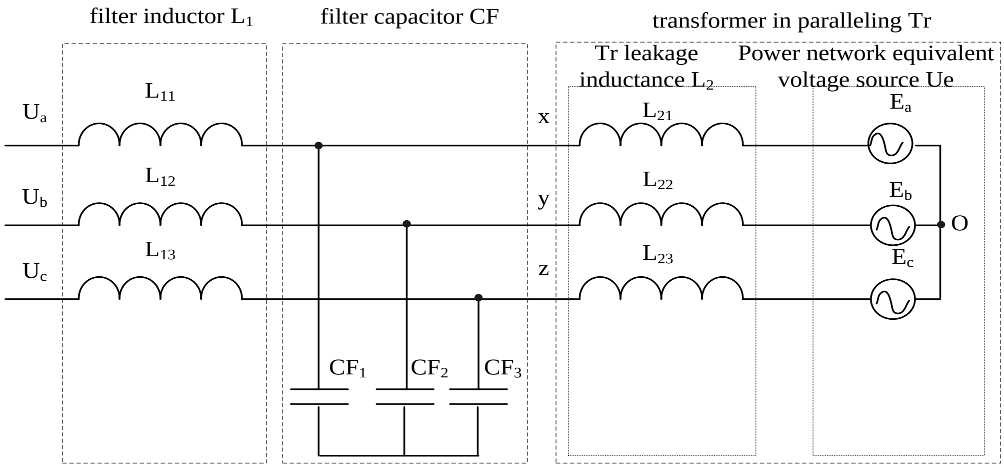


Figure 2. Line-Side LCL Filter

When VSR works in unity power factor, known by the vector triangle:

$$E_m^2 + (\omega L_{11} I_m)^2 = U_m^2 \tag{2}$$

Where E_m for the grid phase voltage peak, the peak of the U_m using SVPWM control strategy for AC output voltage, I_m is the peak of the AC output current. The value of L_{11} can be calculated: $L_{11} < 652\,\mu H$.

When VSR works in condition of pure capacitive reactive power:

$$E_m + (\omega L_{11} I_m) = U_m \tag{3}$$

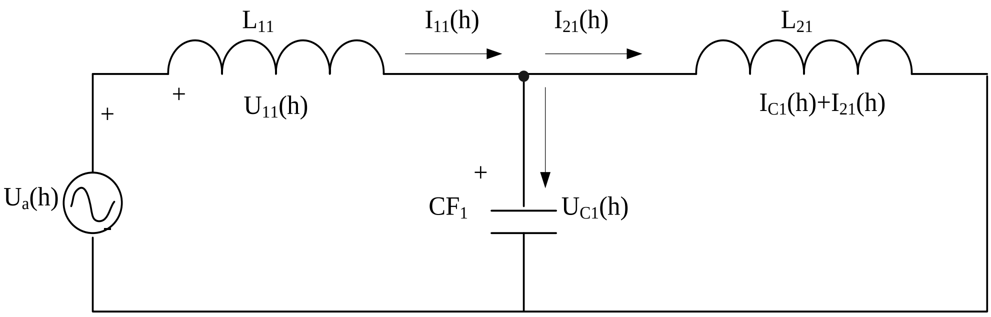


Figure 3. Line-Side LCL Filter for One Phase

$$L_{11} < 210\,\mu H \tag{4}$$

Therefore, the converter side inductance value must be less than 210 μH .

The single-phase filter circuit schematic shown in Figure 3 that only fundamental content of the line-side voltage harmonic component is the short circuit.

And the inductor L_{11} should also meet the following formula:

$$L_{11} \geq \max\ L(n) = \max\ \frac{U(n)}{n\omega I(n)}, n = 2,3, \tag{5}$$

U(n) is the n-th harmonic of the converter output voltage, I(n) is the requirements for the grid harmonic current maximum, ω is the angular frequency of the fundamental. Values of the filter capacitor CF_1 varies depending on the location of the voltage and current sensors. The current sensor measurements in this paper are the network-side converter current, the voltage sensor to measure the voltage on the AC filter capacitor CF_1.

When the converter with unity power factor converter parallel operation, is equivalent to an equivalent resistance, the definition of the impedance of the baseline impedance Z_b:

$$Z_b = 3 \times \frac{(E/\sqrt{2})^2}{P} = 1.5E^2/P \qquad (6)$$

E: the gird side of the line voltage peak

P: the rated power of the system.

Suggesting $X_{21} = \omega L_{21}$, $X_{11} = \omega L_{11}$, $X_c = 1/\omega CF_1$, the equivalent resistance looking at from the grid side is:

$$\begin{aligned} Z_{grid} &= jX_{21} + \frac{-jX_c Z_b}{-jX_c + Z_b} \\ &= \frac{[jX_{21}(-jX_c + Z_b) - -jX_c Z_b](-jX_c + Z_b)}{(-jX_c + Z_b)(jX_c + Z_b)} \\ &= \frac{X_c^2 Z_b + (X_{21} X_c^2 + X_{21} Z_b^2 - X_c Z_B^2) j}{Z_b^2 + X_c^2} \end{aligned} \qquad (7)$$

To ensure that the network side equivalent impedance into resistance characteristic, must request the $X_{21}X_{c2} + X_{21}X_{b2}\text{-}X_cX_{b2}$ equal zero, the available capacitance. Generally the leakage inductance of the transformer is regarded as L_{21} of LCL filter, and for direct drive grid-connected converter, the leakage inductance of the transformer is determined, so it is not need to be designed.

MATLAB simulation software is used to design LCL filter. Fourier analysis (FFT) is also used to decompose a phase current of the grid side just as shown in Figure 4, the harmonics are mainly distributed around the switching frequency fs_1 = 2.1kHz around, That THD equals 3.92% meets harmonic requirements of the grid-connected.

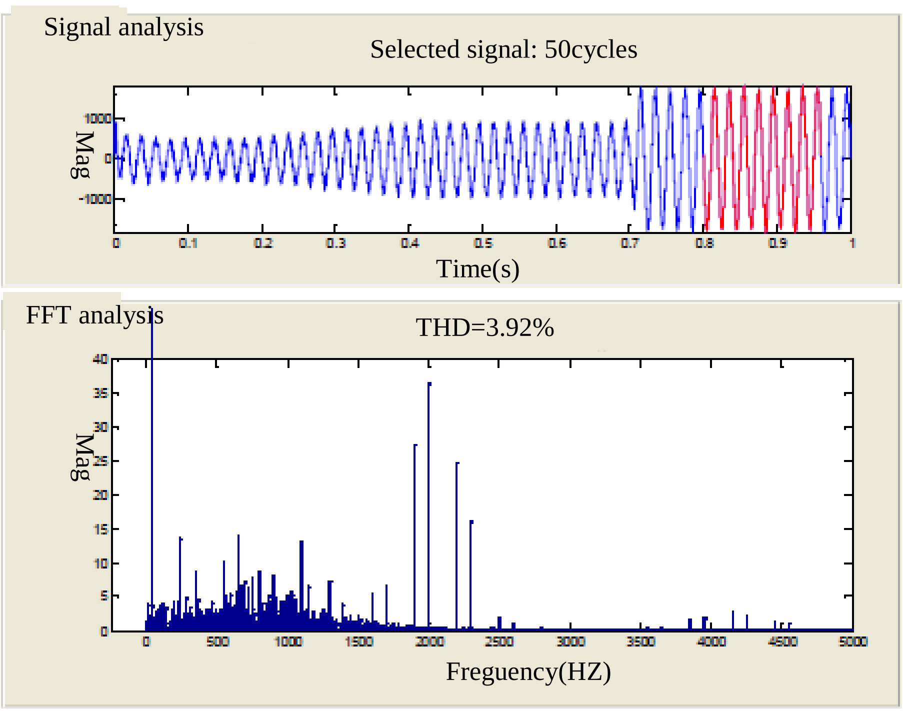


Figure 4. Current FFT Analysis of Line-Side

In wind power applications, the converter is located in the bottom, while the generator is installed in the tower, inverter-driven generator stator require a longer cable PWM drive pulse transmitted to the generator terminals. Motor-side converter output for high-frequency PWM wave, due to the distribution characteristics of the long cable, namely, the existence of the leakage inductance and coupling capacitance, high frequency differential mode du/dt of the PWM output voltage will cause voltage reflection at the motor end, making the motor side over-voltage can be up to twice that of the original value [13]. Reflection over-voltage will destroy the insulation of the motor, and motor common-mode du/dt, voltage is intensified.

3.2 The Filter Design of Motor Side

For PWM converter long-term drive motor in the motor side of the voltage reflection [14], the solution of this paper is to reduce the output of du/dt values, so that the pulse rise time increases, so can reduce the motor side reflected voltage. In general, the RLC circuit filter, its structure is shown in Figure 5.

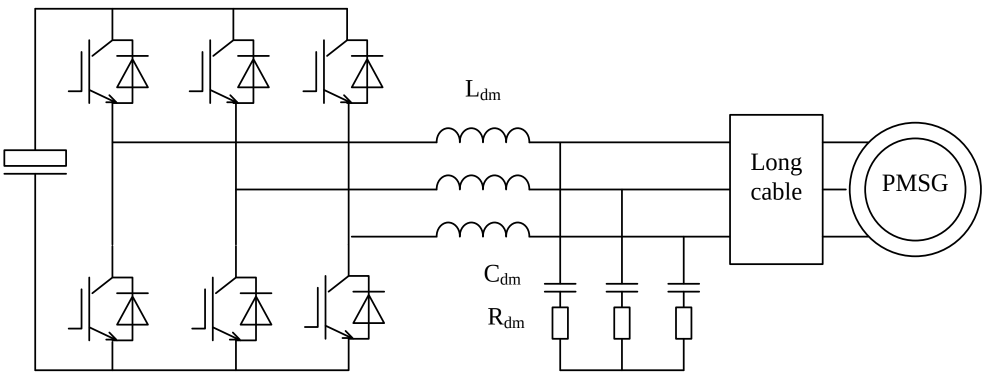


Figure 5. A Du/Dt Filter Circuit of Generator-Side

According to the voltage reflection theory tells us, when $t_t < t_r/3$, line voltage peak value is:

$$V_p = \frac{2lV_{dc}N_2}{vt_r} + V_{dc} = V_{dc}(1 + \frac{2lN_2}{vt_r}) \tag{8}$$

t_t is the required time output pulse transmission from the inverter to the generator side; t_r is the time of output pulse rising; N_2 is terminal reflection coefficient (with the cable characteristic impedance is approximately equal to 1); v is the speed of pulse transmission; l is cable length (assuming the cable length 90 m).The du/dt of wind generator is 800V/us, according to previous formulas t_r and V_p are calculated respectively 1.375μs and 2060V. Line voltage of the generator terminal voltage is 2060V peak. From the above calculation, the generator-side converter output pulse rise time must be greater than 1.375us, generally time of IGBT switching is 100ns, obviously if requirements cannot be meet, the total reflection of voltage occurs in the motor side. RLC resonance is employed to reduce the rate of change of voltage when the IGBT fast switching, the resistance R plays a damping role. LC resonant cycle is generally set to the following equation:

$$\sqrt{L_{dm}C_{dm}} \geq t_r \tag{9}$$

Considering the resonant over-voltage, need to set the damping resistance, damp resistance is larger, over voltage suppression effect is better, and can also limit the capacitor current pulse peak, but too big damping resistance will reduce suppression effect of du/dt, generally restricted to near critical resistance, resistance is set for:

$$R_{dm} \geq 2\sqrt{\frac{L_{dm}}{C_{dm}}} \tag{10}$$

3.3. The Brake Unit Design

Direct drive inverter braking unit structure as shown in Figure 6, which consists of a switch tube T_1,a resistor R_1(braking power resistor, through calculation and test selection 1.0 Ω) and diode D_1. Switch tube used for chopping control, resistance energy consumption unit, in order to prevent the chopper process current mutations produce over voltage, diode D_1 is applied to the freewheeling role. In order to structure of unity, general switching tube T_1 and a diode D_1 are same as power module. Upon detection of the voltage sag moment, start on the braking unit IGBT chopper control, so that the machine side emitted power except to network side part, the rest being consumed in the brake unit, to ensure normal operation of grid connected inverter device.

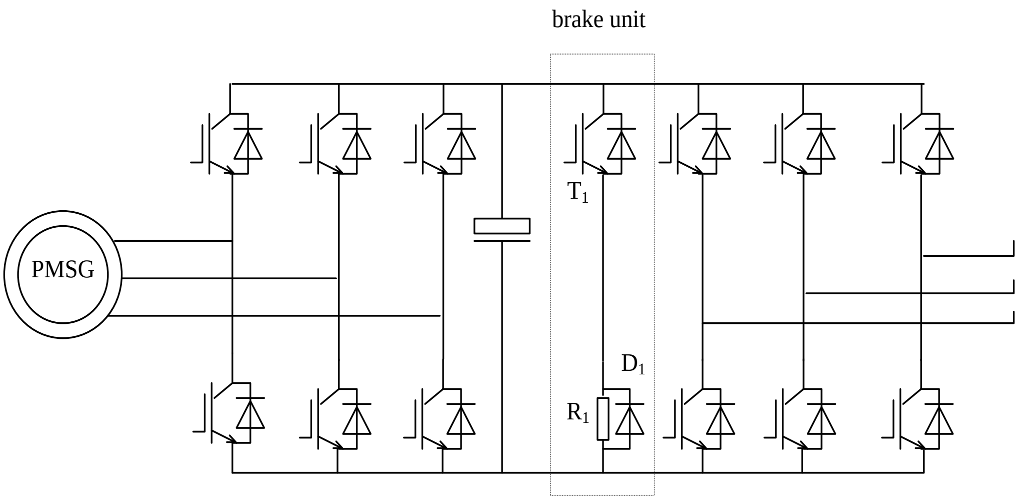


Figure 6. Brake Unit Structure

3.4. Pre-charging Circuit Design

Converter just started on the middle of the DC filter capacitor voltage is zero, then closed the grid side of the main circuit breaker, the grid voltage directly through the network side IGBT anti-parallel diode added to the middle of the DC filter capacitor, the capacitor voltage on the mutation, the capacitor will have a big impact on current, this impulse current will reduce the life of the capacitor. Thus the main breaker is closed to the intermediate DC filter capacitor charging. Pre-charge circuit structure is shown in Figure 7. K_2 contactor is closed before the closure of the main circuit breaker Q_1, the LCL filter capacitor branch; do not put the case for pre-charging. The intermediate DC filter capacitor is charged by the grid voltage through pre-charge resistor R (calculated and experimental) to charging.

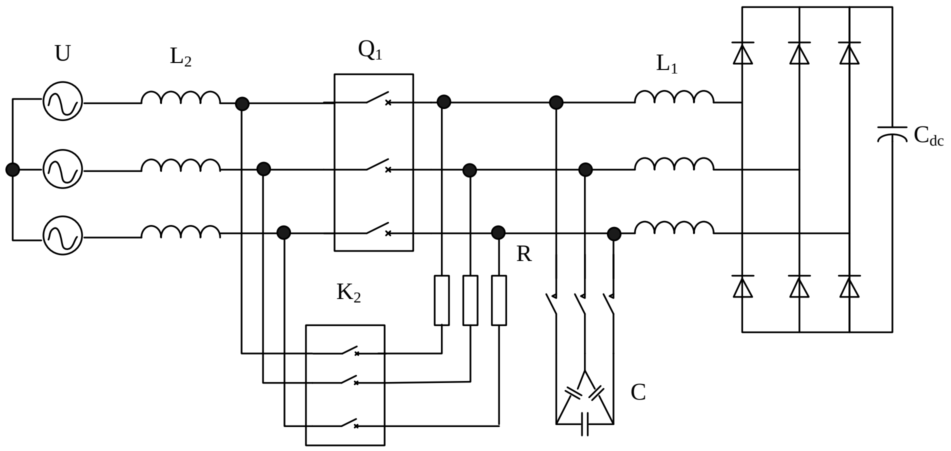


Figure 7. Circuit of the Pre-Charge

4. Cross Feed Experiments

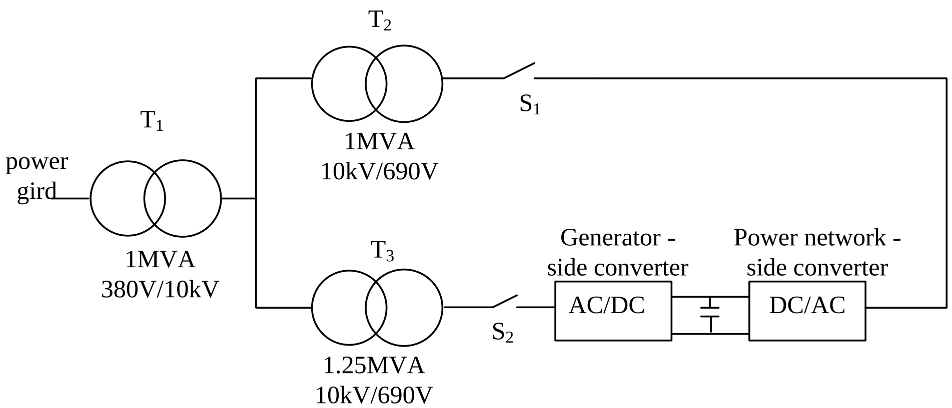


Figure 8. Topology of Experimental Platform

Whether the converter meets the requirements of direct-drive wind power system experimental is need to verify. Generally wind power converter experiment is divided into three areas: cross feed power experiments, the motor drag experiment, and the wind field experiments. In this article, the development of 1.5MW direct-drive wind power converter prototype cross feed power experiments. During the motor to drag before the experiment, we generally use the gird side and the generator side converter contributes to the energy experiment to test the performance of the converter, the experimental platform shown in Figure 8. 380V AC grid firstly is transformed by T_1 into a 10kV AC, which is transformed through the transformer T_3 into 690V, and connected to received generator-side converter trough the circuit breaker S_2, finally trough circuit breaker S_1 is received by a grid-side converter.

Straight called back-to-back power experiment, is the generator side converter work in rectifying state, absorbed from power grid and power to the DC side active power, and then through the grid side converter inverter, the DC power inverter to the grid. The machine side power absorption through the network side and the inverter to the grid experiment called back-to-back feedback power experiment. Due to experimental transformer power restriction reasons, unable to achieve full power converter, here given a converter in1MW waveform graph. The direction of current outflow is positive direction of Grid side converter, the direction of current inflow is positive direction grid side converter, just as shown in Figure 9 and Figure 10, the DC voltage U_{DC} is 1200V, effective value of current is 857A, current effective value. As can be seen, the DC voltage is stable, the grid side current waveform is better, and the net side current I_a lead U_{bc} voltage about 90degrees, for inverting the condition, to realize the machine. The power inverter power function is:

$$P = \sqrt{3}U_{bc} \times I_b = 1.024 \ MW \tag{11}$$

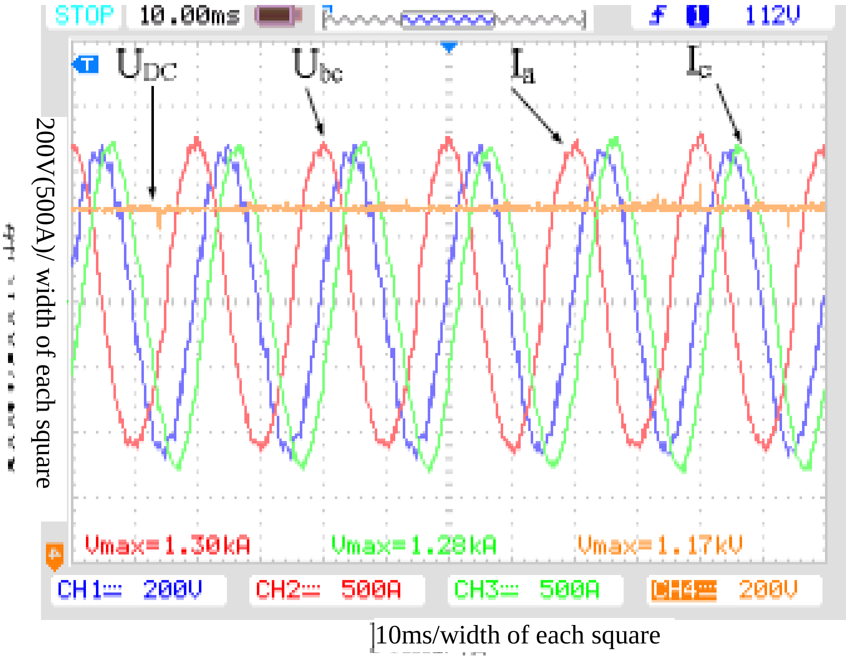


Figure 9. Waveform of the Line-Side When 1MW

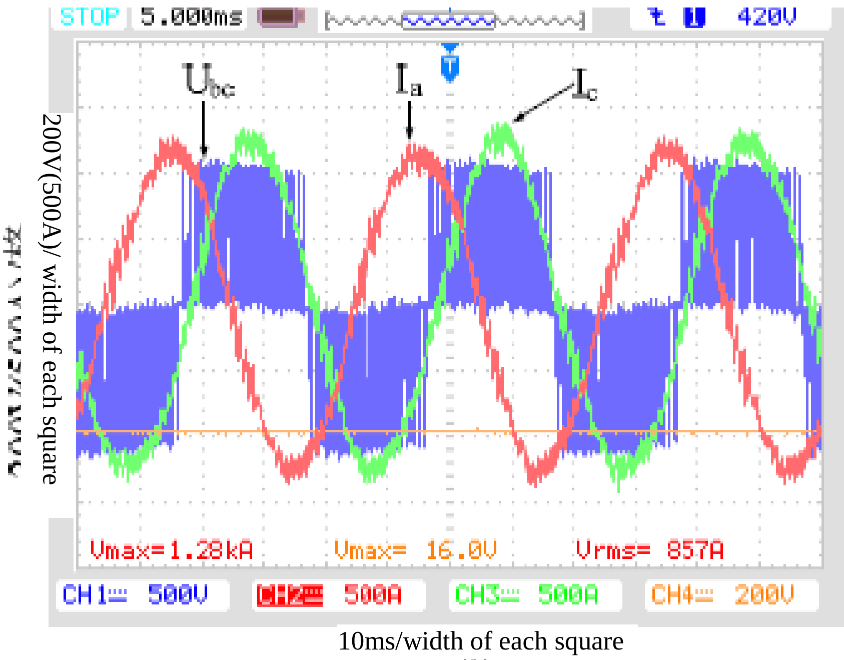
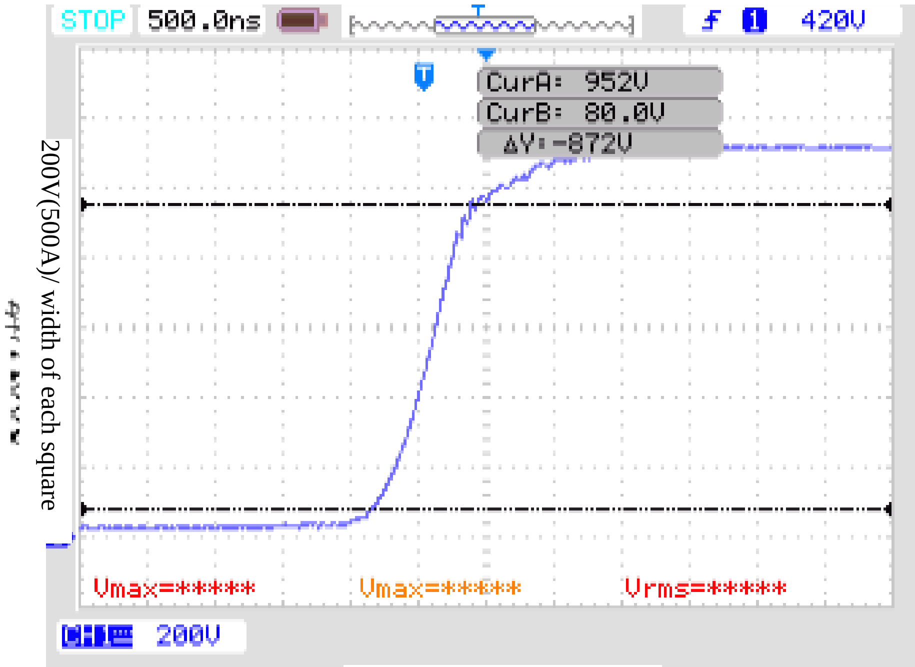


Figure 10. Waveform of Generator-Side Converter When 1MW

In Figure 10 the wave of U_{bc} is pulse of PWM the current waveform of generator side is better, and Ia is ahead of the the U_{bc} voltage 90 ° for the rectifier operating conditions, the power of the generator is fed to the DC side. Figure 11 shows the rising edge of the generator-side PWM waveform can be seen from the figure:

$$\frac{d_u}{d_t} = \frac{872\,V}{1\,\mu s} = 872\,V\ /\ \mu s \tag{12}$$



500ns/width of each square

Figure 11. Waveform of the Generator-Side Converter Line Voltage

Basically meet the requirements of the du/dt filter is designed in this paper. In short, from the above diagram, the 1.5MW direct drive wind power converter prototype properties to meet the design requirements. The proposed design has been verified, and can continue in-depth research and development in the test platform.

5. Conclusion

This paper presents the design and development of the 1.5MW direct drive wind turbine generator and converter prototype cross feed power experiments, but also due to experimental conditions, only to achieve a 1MW. Hope to be able to do full-power experiments, and hope that it can meet the requirements of the motor drag experiment and wind field experiments.

Acknowledgements

The authors wish to thank Professor Jianwei Ji providing theory support. The authors also acknowledge the data support of Liaoyang Power Company of Liaoning province Power Company. Paper is supported by science and technology project of State Grid in China, project number KJ (2013) 412.

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