Solar power is not the only attractive energy, but a wind turbine generator is also an attractive energy option from the point of view of reducing double carbon oxide emission. However, to connect the wind turbine generator system to the grid, the independent power producer (IPP) must compensate the power disturbance caused by the wind turbine. Thus, it is necessary to install a power conditioner for stabilizing power disturbance. In this study, the authors have developed a new power conditioner using batteries. The control technique, specifications, circuit configuration, and prototype test results are described.

**Keywords:** power conditioner, battery, control and three-level topology

1. **Introduction**

A wind turbine system is one of the attractive renewable energies, because the cost of power generation is quite lower than that of the solar power. In addition, it is possible to build a few 100 MW wind farm, because the capacity of the wind turbine can be increased up to a few MW (1). The problem of the wind turbine system is that the power disturbance caused by the wind turbine influences the quality of the grid; i.e. frequency and voltage (2), because the capacity of the wind turbine generator system is quite larger than that of the normal mega solar system. Therefore, electric power companies, who are responsible for stabilizing the grid, order the IPP to install the power conditioners for stabilizing the power disturbance caused by the wind turbine.

Figure 1 shows a typical power conditioning system for wind turbine generator system. As a wind turbine, Permanent Magnet Synchronous Generator (PMSG) is shown. Doubly Fed Induction Generator (DFIG) can be also applied in this system. The power disturbance caused by the wind turbine is absorbed to the battery by using the power conditioner. The capacity of the power conditioner is about 30% of the nominal power of the wind turbine. The battery can be lead-acid battery, Li-ion battery, NAS battery (3) and so on. These batteries can be charged and discharged more times than the battery for stand-by use.

Several manufacturers have already developed power conditioners for battery system (8) (9). In general, improving conversion efficiency is desired not to waste the power during charge and discharge. In addition, in the wind turbine system, the stand-by efficiency, which is an efficiency of the power conditioner during waiting until the wind turbine starts, should be improved.

The authors have developed a new power conditioner for stabilizing power disturbance. Its circuit topology is Advanced T-type NPC three-level circuit (4), which uses a Reversed blocking IGBT (RB-IGBT) (5). In this paper, as a control technique of the power conditioner, how to enable the fault ride through capability and how to control output power are described. Furthermore, to improve stand-by efficiency, a new operation mode, such as idling-stop mode, has been developed. This operation mode is introduced and evaluated. After that, the specifications and characteristics of the power conditioner are described. Finally, as the experimental results of the prototype (500-kVA and 600-kVA converter), the efficiencies and transient response are discussed.

2. **Control Techniques**

2.1 **Inverter Control for Enabling Fault Ride Through**

Now, a Fault Ride Through (FRT) requirement for battery power conditioners is not existed. Thus, in this product, the inverter control has been developed to enable FRT requirements for Photovoltaic power conditioners. The inverter control consists of d-q current reference calculation and current control. Figure 2 shows an inverter-control diagram except...
for the calculation of the d-q current reference ($i_d^*$ and $i_q^*$). In this inverter, a phase reference ($\cos \theta$), which is necessary for changing the current reference d-q axis to abc axis, is calculated from the grid voltage ($v_{uvw}$). The $v_{uvw}$ is filtered with a Band-pass filter to eliminate a high harmonic component, and the phase of the $v_{uvw}$ is set forward to compensate the phase delay caused by the output filter. In the phase reference calculation, $\cos \theta$ is calculated with the following equation (i).

$$\cos \theta = \frac{1}{3A} \left\{ v_{fu} + \left( -v_{fu} - \frac{\sqrt{3}}{2} v_{fw90} \right) + \left( -v_{fu} - \frac{\sqrt{3}}{2} v_{fw90} \right) \right\},$$

where $A$ is amplitude of the $\cos \theta$ without standardization, $v_{fu90}$ and $v_{fw90}$ are 90 degree delayed with v-phase and w-phase of $v_{uvw}$ respectively. The amplitude is the same with the amplitude of the $v_{fu}$, when the grid voltage is balanced. Though the detailed calculation about $\cos \theta$ is not described (refer (6)), $\cos \theta$ is in phase of $v_{fu}$, which is u-phase voltage of the filtered grid voltage, even if two-phase short-circuit occurs. This means that the inverter can flow a balanced current without changing phase, even if the phase of the grid voltage is suddenly changed because of two-phase short-circuit.

In addition, to flow a balanced current, the trapezoidal base voltage ($v_{uvw}$) is added to the output of the current control ($\Delta v_{uvw}$). The $v_{uvw}$ is calculated by using $\cos 3\theta$, which is calculated with $\cos \theta$, and each amplitude of three trapezoidal base voltages is changed according to the grid voltage ($v_{uvw}$).

Finally, the sum of the $v_{uvw}$ and $\Delta v_{uvw}$ ($v_{uvw}^*$) is used in a pulse width modulation unit, which generates gate signals of the inverter by comparing a triangle-wave carrier.

Figure 3 shows experimental results of the small scaled model (5 kW) of the power conditioner. During the three-phase short-circuit, 15% of the grid voltage remains. When the grid voltage increases or decreases, the inverter current increases. However, the instantaneous gate block keeps the inverter current below an over current level. Thus, the inverter can achieve the FRT requirement.

In addition, during the grid fault (two-phase short-circuit), the inverter current is balanced as shown in Fig. 4, even if the grid voltage is unbalanced. This verifies the inverter current control proposed in this paper works well.

### 2.2 Active Power Control

Usually, the power conditioner receives the active power reference from a grid controller. The grid controller is responsible for battery management, grid frequency compensation and grid voltage compensation. The power conditioner generates the active power according to the reference, when the battery voltage is inside the specified range, which depends on the characteristics of the battery. When the battery is outside the range, the power conditioner rejects the active power reference as shown in Fig. 5. If the DC voltage is near the lower output limit or upper output limit, active power is limited to nearly zero. Furthermore, if the DC voltage reaches under voltage level or upper voltage level, the power conditioner stops the operation.

### 2.3 Reactive Power Control

To stabilize the grid voltage, the power conditioner possesses two reactive power control modes.

1) Constant power factor mode

The power conditioner changes the reactive power according to the active power and the power factor. The power factor can be set from Lead 0.8 to Lag 0.8.

2) Variable reactive power mode

In this mode, the power conditioner generates the reactive power according to the reactive power reference from the grid controller. The grid controller gives the reference as an analog current. If the apparent power according to the reference is beyond the capacity of the power conditioner, the reactive power is limited.

### 2.4 Idling Stop Mode

A wind turbine sometimes stops due to weak wind. During this time, a power conditioner does not need to output. However, the conventional power conditioner continued switching due to the lifetime of the magnet contactor shown in Fig. 7. This switching
deteriorated the stand-by losses.

This control mode is developed to reduce the stand-by losses. During this mode, magnet contactors do not open, and the switching of the power conditioner stops. Thus, the stand-by loss occurs only in the AC filter. The effect of this control will be discussed in the prototype test section.

3. Power Conditioner

### 3.1 Specifications

Table 1 shows the specifications of the power conditioner. The differences between the two models are capacity, AC voltage and DC voltage range. The two models are selected according to the battery voltage range.

<table>
<thead>
<tr>
<th>Model</th>
<th>PV650-3/500</th>
<th>PV860-3/600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>500 kVA</td>
<td>600 kVA</td>
</tr>
<tr>
<td>AC voltage</td>
<td>210 V ± 10%</td>
<td>270 V ± 10%</td>
</tr>
<tr>
<td>DC voltage during operation</td>
<td>345 V – 650 V</td>
<td>489 V – 800 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 / 60 Hz</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Power factor</td>
<td>Lead 0.8 to Lag 0.8</td>
<td></td>
</tr>
<tr>
<td>THD</td>
<td>Less than 5 %</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>W 2400 mm, D 900 mm, H 1950 mm</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>2000 kg</td>
<td></td>
</tr>
<tr>
<td>Opc. Temp</td>
<td>-5°C to 40°C</td>
<td></td>
</tr>
</tbody>
</table>

The outlook of the power conditioner is shown in Fig. 6. From the bottom of the right-side cabinet, the DC cable is connected to the DC input. And, the AC cable is connected through the bottom of the left-side cabinet. On the center cabinet, the operator can monitor the power conditioner by using touch panel and operate by using the ON/OFF switch.

### 3.2 Circuit Configuration

The circuit configuration is shown in Fig. 7. The power conditioner has a DC input, a DC breaker, two power units, two magnet contactors and an AC breaker. Each power unit is controlled by using each output current and all PWM pulses of the units are generated by using one carrier. When the power conditioner starts operation, all units generate the AC voltage in phase with the grid voltage. After that, the magnet contactors close. By this start up method, the surge current during start up can be reduced.

The power unit and LCL filter of the inverter is shown in Fig. 8. The capacity of this unit is 250 kVA in the case of PV650-3/500. In the power unit, the AT-NPC inverter is configured by using AT-NPC IGBT modules. To enlarge the capacity of the power unit, five AT-NPC IGBT modules are connected in parallel for each phase. The differences of the current among five modules are limited less than 10%.

As shown in Fig. 8, the neutral point of the LCL filter is connected to the DC-link voltage in this inverter. Actually, this inverter is always connected to AC mains through step up transformer. Therefore, the electromagnetic disturbance voltage of the inverter including the transformer is not limited according to the standard (CISPR11). However, EMC problem can be happened in the actual field caused by the coupling capacitance of the transformer. Thus, to maintain the electromagnetic disturbance voltage of the inverter below the limit of Group 2 (> 75 kVA), the neutral point of the LCL filter is connected to the DC-link voltage. A switching frequency component of the output voltage against the earth potential is eliminated by this circuit configuration. The drawback of connecting the neutral point of the LC filter to the DC-link voltage is that the zero-sequence current flows in the case of the trapezoidal modulation. This zero-sequence current deteriorates the conversion efficiency. Though the software is configured to use the trapezoidal base voltage as shown in Sect. 2.1, a sinusoidal base voltage is used, if the grid voltage is less than the nominal value.

4. The Prototype Test

In this prototype test section, the 500-kVA and 600-kVA prototypes were evaluated. To avoid from describing the similar results, in the 500-kVA prototype test, only the efficiency results are discussed. In the 600-kVA prototype test, the efficiency and transient response are described.

#### 4.1 500kVA Prototype Test

In this section, the test results obtained by using a 500kVA prototype converter are described.

The efficiency curves are shown in Fig. 9 and Fig. 10. The efficiency according to the DC input voltages during charge mode is shown in Fig. 9. In addition, the efficiency during discharge mode is shown in Fig. 10. The efficiency during discharge mode including internal control power source reaches about 97.6%, in the case of minimum DC input voltage.
The efficiency during charge mode is about 0.2% lower than that of the discharge mode. The reason of achieving the highest efficiency in the case of DC 345 V is that the switching loss becomes minimum and the conduction loss is not changed according to the DC input voltage.

4.2 600 kVA Prototype Test

In this section, the test results obtained by using a 600 kVA prototype converter are described.

The efficiency curves are shown in Fig. 11 (Charge mode) and Fig. 12 (Discharge mode). The efficiency during discharge mode including internal control power source reaches about 97.8%, in the case of minimum DC input voltage. The efficiency during charge mode is almost equal to the efficiency during discharge mode.

Figure 13 shows the measurement results of stand-by losses. Figure 13(a) shows the losses when active and reactive power references are zero. Figure 13(b) shows the stand-by loss during the idling stop mode. By changing idling stop mode, the stand-by loss is reduced by 94.3%.

Figure 14 shows the transient characteristic according to changing the active power reference. The active power reference is given through the analog current input. In the figure, the output voltages, the output currents and the active power reference are shown respectively. The response time is about
5 ms. This response time satisfies the transient characteristic (less than 30 ms) without any problems. Figure 15 and Fig. 16 show the transient waveforms after recovering from idling stop mode to charge mode and discharge mode respectively. In this test, the active power reference is changed to 100% before canceling the idling stop mode. In the case of charge mode, the drop of the grid voltage occurs, but the power conditioner can flow the current properly.

5. Conclusions

In this paper, the power conditioner for stabilizing the power disturbance caused by the wind turbine generator is developed. This power conditioner achieves the fault ride through capability by adopting phase references which are calculated from the grid voltage. In addition, the PQ control method and specifications of the developed 500-kVA and 600-kVA power conditioner are described. As the prototype test results of the 500-kVA converter, the efficiency curves during charge mode and discharge mode are shown, and the influence to the efficiency from the DC input voltage is discussed. Furthermore, the efficiency curves of the 600-kVA prototype are described. Finally, the transient response according to the active power reference and transient waveforms after recovering idling stop mode are shown respectively. These waveforms show that the power conditioner possesses the enough performance from the point of view of stabilizing the power disturbance caused by the wind turbine generator.

References


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