Abstract: As the power of wind energy system increases, the control of their active and reactive power becomes increasingly more important from a system standpoint given that these are typical frequency and voltage control parameters. In this paper, a family of wind energy systems with integrated functions of active power transfer, reactive power compensation, and voltage conversion is proposed. The proposed wind energy systems using solid-state transformer (SST) can effectively suppress the voltage fluctuation caused by the transient nature of wind energy without additional reactive power compensator and, as such, may enable the large penetration of wind farm (WF) into the power grid. To this end, a simulation study for WF driven by squirrel-cage induction generators is presented to verify the effectiveness of the proposed system. In addition, a modular-type high-voltage and high-power three-phase SST topology is presented for the pro-posed system, and its basic building block, which is a single-phase SST, is analyzed. The functions of SST in the presented wind energy system are verified in a single-phase laboratory prototype with scaled-down experiments. Lastly, cost issue of the proposed technology is analyzed with comparison to the traditional one.

Index Terms: Power electronic transformer, reactive power compensation, solid-state transformer (SST), voltage regulation, wind energy, wind generation.
1. Introduction:

Given the present world energy state of affairs, it has become apparent that there is an immediate need for a concrete solution to its looming shortage, where wind energy has raised as a perfect solution thus far. In fact, since 2004, wind energy deployment has risen dramatically. Global installed capacity increased from 40,000 MW at the end of 2003 to 94,000 MW at the end of 2007, at an average annual growth rate of nearly 25% [1], [2]. Wind power is an uncontrollable resource, which, when combined with the nature of wind induction generators like the fixed-speed squirrel-cage induction generator (SCIG), makes for a challenging integration of large WFs into the grid, particularly in terms of stability and power quality [3]. To address this issue, utilities generally need to install reactive power compensation devices, such as static compensators (STATCOMs) [3]–[11]. Additionally, a large step-up power transformer is necessary to interface the low-voltage wind generator to the distribution system, as well as any STATCOM used in the system. Solid-state transformer (SST) has been a hot research direction recently owing to the rapid development of power device [12]–[19]. On the one hand, efforts are focused on topology investigation in this new technology for high-voltage and high-power application [12]–[15]. On the other hand, SST is considered as the promising candidate for the applications where low-frequency transformers are dominating, such as traction/locomotives, solar farm, wind farm (WF), charge station, and smart grid, for reducing the volume and weight of the system [16]–[20]. In all the previous applications, only the benefit of reducing volume and weight of SST is considered. Although it is known that SST may provide the reactive power compensation function, to the best of the authors’ knowledge, no literature has explored the SST in these applications, particularly in the wind energy systems with reactive power compensation in addition to the solely voltage-conversion function. In addition, some of the previous SST topologies cannot provide the reactive power compensation due to lack of dc links [18]. Considering the wind generation system architecture and function, that of a STATCOM and power transformer, may be inherently embodied by the SST, thus making it an attractive alternative to interface wind energy system into the grid, which is the key concept explored in this paper. Specifically, this paper contributes to looking at the advantages and possibilities offered by SST-interfaced wind energy systems, focusing on their integrated active power transfer, reactive power compensation capability, and voltage-conversion functions. To this end, a wind energy system with the SCIG is studied as an example with comparison to the conventional wind energy system architecture. Furthermore, this paper addresses the
challenges for such a system: how to design a high-voltage and high-power SST for wind energy system. Correspondingly, a modular high-voltage and high-power three-phase SST topology is presented for this application with its basic single-phase building block analyzed in detail. Scaled-down experimental results with a single-phase SST prototype are presented for validation purposes of the integrated functions of active power transfer, reactive power compensation, and voltage conversion. Lastly, cost issue of the SST is also covered in this paper.

Figure 1: WFs with induction generator interfaced by normal transformer. (a) WF with SCIG. (b) WF with DFIG. (c) WF with DDSG.

2. System Description:

A. Wind Generation System Overview:
Several techniques are used to convert wind energy into electric energy, but the most popular and widely used is based on the induction generator. Presently, there are three main WF architectures, namely, SCIG-based wind energy system [21], doubly fed induction generator (DFIG)-based wind energy system [22], and directly driven synchronous generator (DDSG)-based wind energy system [23], shown in Fig. 1.

The nature of WFs is that their operation is highly dependent on the active and reactive powers transferred to the grid, a condition normally reflected by the fluctuation of voltage magnitude at the point of common coupling (PCC). This sensitivity is exacerbated in the case of SCIG, since this type of generator is an inherent consumer of reactive power [2]. Additionally, in the case of faults causing a voltage drop at PCC, the induction generator speeds up consequently due to imbalance between the mechanical shaft torque and the generator’s electromagnetic torque, in which case it draws more reactive power acting as a positive feedback contributing to the grid destabilization and PCC voltage collapse [21].

As seen, the modern power system has to confront some major operating problems such as voltage regulation, power flow control, transient stability, damping of power oscillations, etc. Reactive power compensators, such as STATCOM, are hence good solutions for regulating the PCC voltage [3]–[8], and it is also shown in Fig. 1. The downside of these WFs however is the use of bulky power transformers for both STATCOM and WF generators, although a low-cost solution. The SST, on the other hand, has been regarded as a promising technology integrating active power transfer, reactive power compensation, and voltage conversion, while no literature has explored the application of SST with full utilization of all the functions [12]. Accordingly, the major contribution of this paper is to propose a new family of SST-interfaced WF architectures effectively replacing the conventional transformer and reactive power compensator.

**B. SST:**

Conventional copper-and-iron-based transformers have been challenged by solid-state technologies. Specifically, a conventional transformer in ideal terms represents a simple input–output voltage and current transformation; thus, disturbances on one side, which are typical active and reactive powers, are fully reflected on the opposite side. Overcoming this seeming drawback, the SST has been a promising technology in recent years [13]–[20]. Potential advantages of SST over conventional transformers include low volume and weight
(due to its high-frequency operation compared with 60-Hz transformer), fault isolation, voltage regulation, unsusceptible to harmonics, easy integration of renewable energy resources and energy storage, etc. [12]. As functionally shown in Fig. 2, the SST is typically composed of a high-voltage ac/dc rectifier that regulates a high-voltage dc bus (and ac voltage when for reactive power compensation), an isolated high-frequency-operated dc/dc converter to regulate the secondary dc bus, and a dc/ac inverter to regulate the output terminal ac voltage. With this structure, the active power transfer, reactive power compensation, and voltage conversion may be inherent if appropriate topologies are chosen.

Admittedly, this technology has its penalties, such as reliability, which is addressed by the possible solution of this paper. Moreover, a high-voltage and high-power SST that can be interfaced with the distribution system is also not easy with state-of-the-art technology. Numerous technologies are being investigated and may be feasible for this high-voltage and high-power application, such as advanced power device, multilevel converter, converter series/parallel connection, etc.[12]. A 2.75-MVA 13.8-kV-to-465-V three-phase SST has already been designed, and 1-MVA single-phase SST has been developed, which verifies the feasibility of high-voltage and high-power field application of the technology [24]. In this paper, a three-phase modular-type high-voltage and high-power SST suits for the presented application is also proposed together with its single-phase building block implementation illustrated. The following sections will introduce the proposed novel WFs interfaced by SST in detail.

![Figure 2: Functional representation of SST](image.png)
A family of wind energy systems has been proposed as shown in Fig. 3. Fig. 3(a) shows the case of a WF with SCIG, where the SST acts as the grid interface. The local capacitor bank, two conventional transformers, and the STATCOM as shown in Fig. 1(a) are all functionally integrated into a single SST, which will be illustrated in the later case study. Fig. 3(b) shows the case with DFIG, where the ac/ac back-to-back converter is retained for full utilization of advantages of DFIG- based WF, while two transformers and STATCOM are replaced by the SST. Lastly, Fig. 3(c), featuring DDSG with full-power converters, shows how the SST can be used to replace the ac/ac converter, both step-up transformers and STATCOM. From these diagrams, it is easily seen how the proposed SST- interfaced WFs represent a possible more compact and cable solution and, as such, can be deemed to be a promising technology. This will be investigated in what follows.

Figure 3: Proposed WFs with induction generators interfaced by SST. (a) WF with SCIG. (b) WF with DFIG. (c) WF with DDSG

C. A Family of SST-Interfaced WF Systems:
3. System Case Study:

A. Three-Phase SST for System Evaluation:

Although different topologies can be adopted to implement the SST for the proposed application, the overall control objectives intrinsic to its operation are the same regardless of its circuit topology, namely, ac voltages for reactive power compensation and the dc voltages for active power transfer. For the sake of better illustration of control objectives of the SST in the proposed system, which are active power transfer, reactive power compensation, and voltage conversion, a simple three-phase SST topology is initially adopted and analyzed, neglecting the physical limitation of the power device and magnetic materials.

Fig. 4 shows a cascaded-type three-phase SST. Its first stage is a three-phase bidirectional ac/dc pulse width modulation (PWM) rectifier, which can also be used in the dc/ac power conversion stage as depicted. Its dc/dc stage is embodied by a dual active bridge (DAB) converter, which represents the most attractive candidate for high-power applications requiring isolation, as it can perform zero-voltage switching in a wide operation range [25], [26]. In the aforementioned SST configuration, vhabc is the PCC voltage, ihabc is the PCC current flowing into the SST, vhdc is the high dc bus voltage, vldc is the low dc bus voltage, vlabc is the output voltage of inverter, and ilabc is the output current of inverter.

Fig. 5 shows the control system adopted with the integrated active power transfer, reactive power compensation, and voltage-conversion functions with load connected at low voltage side. The controllers for all three conversion stages are conventional ones and thus only brief description is included as follows.
A d–q axes vector controller is used to regulate the input currents of the three-phase ac/dc rectifier, where the d-axis loop is used to regulate the dc bus voltage, and the q-axis loop to regulate the SST reactive power generated, which in turn is governed by the PCC voltage magnitude loop. It is also shown in the Fig. 5 that the couplings between d-axis and q-axis control loop have also been taken into consideration as this is also necessary for a high-performance system. This control structure is exactly the same as that used in the well-known STATCOM, evincing how the SST integrates this compensator functionality. To regulate the active power flow, a phase regulation scheme is adopted for the DAB using a simple PI controller, which adjusts the phase shift between high- and low-side H-bridge converters. Lastly, the inverter stage is controlled using a dual loop strategy in d–q coordinate, as shown in Fig. 5. The inductor current loop is cascaded as the inner loop such that fast dynamic responding can be guaranteed. The controller for converter at the low voltage side can be modified correspondingly when connected with different wind generators and the integrated functions can still be maintained. Due to the bidirectional power transfer characteristics of the system, this controller can also transfer the power from the low voltage side to the high voltage side, which is the case in the presented system.

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*Figure 5: Control logic of three-stage SST*
Figure 6: Power system plus WFs used in the case study. (a) Conventional-transformer-interfaced WF with SCIG. (b) SST-interfaced WF with SCIG

B. System Study in SCIG-Driven WFs:

A system study is carried out in a typical WF system, as shown in Fig. 6 (this system is a demo from MATLAB 2008b). The SCIG-driven WF was adopted as the example since it presents the largest demand of the reactive power, and hence compensation needed, among the three types of generators under consideration. Nonetheless, the conclusion drawn from the case study can also be applied to WFs driven by DFIG and DDSG since the control objectives are exactly the same for all three systems.

In this system, two 3.3-MVA 575-V WFs with SCIGs are connected to a 25-kV distribution system. Fig. 7 shows the power characteristics of the wind turbine as a function of turbine speed under varying wind speeds. The base wind speed for the wind turbine is 9 m/s (the cut-in speed of wind turbine is 4 m/s and the cutoff speed of wind turbine is 25 m/s), and the base rotational speed at the base wind speed is 1 p.u. with the base of generator speed. The active power generated by the wind turbine at base wind speed is 3 MW, which corresponds to a power factor of 0.9. The pitch angle is set to zero, and no pitch control is implemented in this study for simplification. The parameters of the SCIG are set as shown in Table I. The parameters of the 120-kV generator impedance and the transmission line are also listed in
Tables II and III, respectively, which give the detailed description of studied power system. For the evaluation, Fig. 6(a) shows a WF interfaced by a conventional 10-MVA power transformer (25 kV/575 V) without any additional compensator at the PCC. A 0.8-MVar capacitor bank is installed at the generator terminal for local reactive power compensation.

Fig. 6(b), on the other hand, shows the proposed WF with a 10-MVA three-phase SST, using the circuit topology shown in

![Figure 7: Power characteristics of wind turbine](image)

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Nominal power</td>
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<tr>
<td>Nominal frequency</td>
<td>60Hz</td>
</tr>
<tr>
<td>Stator inductance (pu)</td>
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</tr>
<tr>
<td>Rotor inductance (pu)</td>
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</tr>
<tr>
<td>Inertia constant (s)</td>
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Table 1: Parameters of a Single Scig

<table>
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<th>Parameter</th>
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<th>Zero sequence</th>
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<td>1.7280</td>
</tr>
<tr>
<td>Inductance (H)</td>
<td>0.0153</td>
<td>0.0459</td>
</tr>
</tbody>
</table>

Table 2: Parameters of 120-kV Generator Equivalent Impedance
Table 3: Parameters of Transmission Line (Three-Phase Pi Section) Fig. 4 and control method shown in Fig. 5. The high-voltage dc bus of SST is regulated to 38 kV, and the low-voltage dc bus is regulated to 1200 V. It is worth to remind again that, although the power and voltage of the studied system are high, the simple topology shown in Fig. 4 is adopted for demonstrating the concept proposed in this paper, and this will not affect the conclusion drawn from the simulation results. In addition, the average modeling approach is adopted for this large time-scale simulation, which is also valid for the verification purpose.

The simulation conducted for the conventional WF system is to demonstrate the natural power flow from the conventional WF to the distribution system in order to explore its impact on the PCC in terms of voltage regulation particularly. The simulation for the proposed WF system, on the other hand, demonstrates the capability of proposed SST-interfaced WF system to perform reactive power compensation in order to suppress voltage fluctuation.

Fig. 8 shows the electrical characteristics of the WF under study, where the wind speed profile shown in Fig. 8(a) is continuously changing around 8 m/s. Accordingly, the active power transferred by the wind generator follows the same trend as shown in Fig. 8(b). Fig. 8(c) shows the reactive power at the induction generator terminal, which indicates a significant amount of reactive power consumption by the SCIG.

Fig. 9 shows the simulation results of the WF interfaced by the conventional transformer, where the wind speed profile is the same as that shown in Fig. 8(a). Fig. 9(a) and (b) shows the PCC voltage and current in the presented system.

Due to the fluctuation of the wind speed, the magnitude of current is changed accordingly. As a result, the PCC voltage is also affected, as shown in Fig. 9(c), which is less than the rating value and fluctuated.
As a comparison, Fig. 10 shows the simulation results of the proposed SST-interfaced WF with integrated active power transfer, reactive power compensation, and voltage-conversion functions. Fig. 10(a) and (b) shows the 38- and 1.2-kV dc voltages of three-phase SST, respectively. It can be seen that the dc voltage is regulated well although there are some dynamic responses caused by the active power fluctuation. Fig. 10(c) and (d) shows the PCC voltage and current in the proposed system. Compared with Fig. 9(b), the current is a little smaller since the PCC voltage is higher in the SST-interfaced system. In Fig. 10(e), the rms value of PCC voltage is shown, which is within 1% of the nominal value as expected. Fig. 10(f) shows the reactive power sent by the SST at PCC. The trend of reactive power is similar with that of the wind profile, thus compensating for the voltage fluctuation at PCC.

The results in Figs. 8–10 evince the effectiveness of the SST as a potential WF interface for the integration of wind energy into the grid with less voltage fluctuation. It is clear that the proposed wind energy conversion system can fulfill the tasks of active power transfer, reactive power compensation, and voltage conversion.

The reactive power compensation capability of the SST is mainly limited by the power rating of it since both active and reactive powers flow through the converter. Based on this consideration, the power stage should be designed so that the maximum current stress is within the range of the power device and passive components selected. Furthermore, since the proposed system can provide reactive power compensation, it is also expected that the presented system can ride through the fault by injecting reactive power to the system as that of the STATCOM. However, this topic is out of the focus of this paper and will not be discussed here.

4. High-Voltage And High-Power SST:

In order to realize the proposed wind energy system, the high-voltage and high-power SST is required, and this is a challenge considering the capability of power semiconductor devices. In this section, a promising high-voltage and high-power modular-type SST topology is presented and analyzed for achieving the proposed wind energy system.
Figure 8: Electrical characteristics of WF under study. (a) Wind speed profile. (b) Active power of WF (10-MVA base). (c) Reactive power of WF (10-MVA base).

Figure 9: Simulation results of WF interfaced by conventional transformer. (a) PCC voltage. (b) PCC current. (c) PCC voltage rms value (25-kV base)
Figure 10: Simulation results of WF interfaced by SST. (a) 38-kV dc voltage. (b) 1.2-kV dc voltage. (c) PCC voltage. (d) PCC current. (e) PCC voltage rms value (25-kV base). (f) Reactive power of SST (capacitive, 10-MVA base).

Figure 11: Proposed high-voltage high-power three-phase SST

A. Topology of a Modular Three-Phase SST:

Fig. 11 shows the presented modular high-voltage and high-power three-phase SST topology in the proposed application. Three single-phase SSTs are connected to compose a three-phase SST, in which a high-voltage and high-power modular-type single-phase SST is adopted as the basic phase building block. In the single-phase building block, the cascaded multi-level converter is utilized in the high-voltage side with identical (low voltage) H-bridges; thus, low-voltage power device can be adopted. Several DAB converters with relatively high switching frequency (in the range of kilohertz to more than 10 kHz decided by the power devices) are then parallel connected to each high-voltage dc link, regulating a common low-voltage dc bus. In the last stage, conventional low-voltage high-power inverter technologies, such as device parallel or converter parallel, can be used to integrate with WFs.

It is worth to point out that there is no limitation for the number of modules since this is the key feature of the cascaded-type multilevel converter; the number of the modules depends on the operating voltage and power device adopted [13].

The aforementioned converter structure represents a highly modular design and, as such, opens the path to redundant operation, for reliability improvement. For instance, the N + 1 redundant design can be incorporated to achieve fault-tolerant operation [27]. In addition, it opens the path to modular manufacturing with its potential cost reductions due to economies.
of scale. In this way, it tackles two of the main problems haunting the development of the SST, namely, high-voltage and high-power operation and reliability.

The control of the proposed three-phase converter can actually be simplified to the control of single-phase converter shown in Fig. 12 due to the phase building block configuration. Due to the circuit complexity of the single-phase SST in each phase, the following control goals need be met except for the following mentioned in Section III-A: 1) dc voltage in each rectifier should be balanced, and 2) current in each DAB converter should be balanced.

Practical controllers for the rectifier stage and dc/dc stage of SST have already been presented in the previous works [28], [29], where the voltage and current in the SST can be effectively balanced. The method can be modified to incorporate the reactive power compensation functions by adding the PCC voltage loop for the rectifier stage for the proposed wind energy system application which is similar as shown in Fig. 5. The detail of the control method is not repeated here since it is not the focus of this paper.

![Figure 12: Single-phase SST building block](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
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</thead>
<tbody>
<tr>
<td>Line inductance</td>
<td>280 mH</td>
</tr>
<tr>
<td>High voltage DC capacitance</td>
<td>37.5 µF</td>
</tr>
<tr>
<td>Rectifier switching frequency</td>
<td>1080 Hz</td>
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<tr>
<td>Low voltage DC capacitor</td>
<td>2 mF</td>
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<tr>
<td>Transformer leakage inductance</td>
<td>68 mH</td>
</tr>
<tr>
<td>Transformer turns ratio</td>
<td>9.5 to 1</td>
</tr>
<tr>
<td>DAB switching frequency</td>
<td>3000 Hz</td>
</tr>
<tr>
<td>Inverter LC filter</td>
<td>1 mH 5 µF</td>
</tr>
<tr>
<td>Inverter switching frequency</td>
<td>10000 Hz</td>
</tr>
</tbody>
</table>
### B. Simulation Results:

A 20-kVA single-phase SST with three H-bridges in the cascaded front-end rectifier and three DAB converters as the intermediate stage has been considered in this paper, with the topology shown in Fig. 12. The SST is rated as single-phase input voltage of 60 Hz and 7.2 kV and output voltage of 60 Hz and 120 V. The 7.2-kV distribution voltage is first rectified to three 3.8-kV dc by the cascaded seven-level rectifier, then converted to 400-V dc by three DAB converters, and finally inverted to 120-V ac. The circuit parameters are shown in Table IV.

Simulations have been run as well for the SST converter in question. Some results are shown in Figs. 13–16, where four scenarios have been considered: the first one with reactive current set to 0.4 p.u., the second one set to −0.4 p.u., the third one changed from −0.4 to 0.4 p.u., and the fourth one with active power changed from 0.6 to 0.9 p.u. The active power transferred from distribution system to the low-voltage side of the system is set to 0.8 p.u. for the first three scenarios, and the reactive power is set to zero for the fourth scenario. The results for demonstrating the integrated functions of active power transfer, reactive power compensation, and voltage conversion are recorded.

Fig. 13(a) shows the PCC voltage at the distribution system side, PWM voltage generated by the seven-level rectifier, and the current at the input terminal of the SST. As observed, the SST current leads the voltage, which indicates the capacitive operation mode. The three high-voltage dc links are regulated to 3.8 kV, as shown in Fig. 13(b). Fig. 13(c) finally shows the regulated 400-V dc bus and 120-V ac output. Similarly, the inductive operation mode is also tested and documented, as shown in Fig. 14, and similar conclusion can be obtained.

Fig. 15 shows the operation of the SST with reactive power changing from −0.4 to 0.4 p.u. Shown in Fig. 15(a), the phase of current is regulated with satisfactory dynamics when the reactive current reference changes, and this change is reflected in the high-voltage dc links since they also couple with the high-voltage ac side, as shown in Fig. 15(b). Fig. 15(c) shows the low-voltage-side dc voltage and output ac voltage, which are all regulated well without any disturbance because of the transformer isolation.
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Figure 13: Operation waveforms of SST under capacitive-mode operation. (a) PCC waveforms (7.2-kV 20-kVA base). (b) High-voltage dc link. (c) Low-voltage-side waveforms.
Figure 14: Operation waveforms of SST under reactive-mode operation. (a) PCC waveforms (7.2-kV 20-kVA base). (b) High-voltage dc link. (c) Low-voltage-side waveforms.

Fig. 16 shows the SST dynamics in the load change condition. In this scenario, the load is changed from 0.6 to 0.9 p.u. at 1 s. It is observed from the simulation results that there is a dynamic response for both high- and low-voltage dc buses. The output voltage is regulated well with only a little sag when load changes. Current at PCC increases because of the load power increasing. The whole system exhibits a good dynamic performance.
It is clear that the presented single-phase SST can regulate the reactive power to a desired value as well as transfer the active power from the distribution system to the low-voltage ac side with high conversion ratio. Due to the bidirectional characteristics of the topology, the reverse power flow is also easily achievable; thus, the proposed application is feasible.

![Figure 15: Operation waveforms of SST with reactive power change. (a) PCC waveforms (7.2-kV 20-kVA base). (b) High-voltage dc link. (c) Low-voltage-side waveforms.](image)
Figure 16: Operation waveforms of SST with load change. (a) PCC waveforms (7.2-kV 20-kVA base). (b) High-voltage dc link. (c) Low-voltage-side waveforms.
C. Experimental Results:

A laboratory prototype of the presented 7.2-kV 20-kVA single-phase SST was built for validation purposes [30]. This unit is shown in Fig. 17. The system parameters are the same with those of the simulation model and hence given in Table IV. A 6.5-kV 25-A silicon-based dual insulated-gate bipolar transistor (IGBT) has been customized and adopted for the rectifier and primary side of DAB stages. It is packaged by POWEREX with a chip supplied by ABB. For this package design, the minimum clearance distance in air is 19 mm, and the creepage distance is 78 mm which complies with IEC- 60077-1 standard. Six-hundred-volt commercialized intelligent power modules were adopted for the secondary side of DAB and inverter stage. Thermal management of the power device is also introduced in [30], which is based on forced-air convection method. Eight inductors are connected in series to distribute the high voltage, and as such, the normal copper wire can be used for winding the inductor. Metglas AMCC 1000 core was used for the high-voltage and high-frequency transformer. The transformer is naturally cooled with the maximum temperature around 45 ° C [31]. Based on the detailed test results of the power device used in the power stage, PLECS simulation tool is used to estimate the efficiency of the converter, and the efficiency for this prototype at full-power rating is about 88.06% [30]. However, with the power rating increasing and an optimized design, we are expecting the efficiency higher than 95% with the presented topology for a megavolt-ampere-level SST prototype. In the experimental setup, Texas Instrument series 28335 DSP is used for each power stage, generating the

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Figure 17: Prototype of single-phase 20-kVA 7.2-kV SST. (a) Cascaded seven-level rectifier. (b) Primary side of DAB. (c) High-frequency transformer. (d) Secondary side of DAB and inverter.
PWM signals for each building block with desired synchronization and phase shifting. However, with the number of building modules increasing, FPGA can be used to generate the signals. It is also needed to point out that the experiments presented in this paper hereinafter are carried out in a relatively low power and voltage rating for the verification purpose. The full-power test is still carried on. However, this will not affect any conclusion made from the paper for the proposed wind energy application.

i. Voltage Balancing of Cascaded Multilevel Rectifier: Fig. 18 shows the dynamic voltage balancing process for the cascaded seven-level rectifier. The input voltage is set to 600 V, and the total high-voltage dc bus is set to 1100 V. The load connected to the first H-bridge is 1800 Ω, and the load connected to the second and third H-bridges is 1000 Ω. Before the PWM control mode, the system operates in diode rectifier mode with voltages diverging to different value naturally. When PWM-mode control is triggered, the three dc voltages converge into the same value immediately; thus, the voltage balancing is achieved.

ii. Current Balancing of Parallel-Operated DAB: The prototype is also tested for verifying the current sharing among paralleled DAB converters. The primary-side dc voltage of each DAB is 633 V (total of 1900 V), and the secondary side is regulated to 60 V with a 6-Ω load.

Fig. 19(a) shows the three high-voltage-side dc-link voltages, which are identical and regulated to 633 V. The 60-V low-voltage-side dc link is also captured in the figure. Fig. 19(b) shows the 60-V low-voltage-side dc link and three DAB inductor currents.
It can be observed that the magnitude of currents is the same; thus, the current balancing is achieved.

iii. Integration of Active Power Transfer, Reactive Power Compensation, and Voltage Conversion: Since the wind turbine is not available for the testing, only the SST experimental results are demonstrated to validate its functions as a WF grid-interface device. Scaled-down experiments are carried out for verifying the function of SST in integrating active power transfer, reactive power regulation, and voltage conversion, which are valid and sufficient to validate the effectiveness of the proposed concept.

Figure 19: Current sharing of DAB converter. (a) High-voltage-side and low-voltage-side dc voltages. (b) Low-voltage-side dc voltage and DAB current.

In the experiments, the PCC voltage is set to 1000 V, and high dc voltage link is regulated to 1900 V (633 V each). The low-voltage dc link is set to 60 V, and the inverter output is set to 23 V (same conversion ratio with the presented power system). A resistive load of 3.6 Ω is connected to the low-voltage ac terminals.

Experimental results are shown in Figs. 20 and 21, depicting capacitive and inductive operation modes, respectively, under a power factor of ±0.866. Fig. 20(a) shows the waveforms at PCC as well as the high-voltage dc links for the capacitive case, including the...
PCC voltage and current, the rectifier seven-level PWM voltage, and the three high-voltage dc-link voltages. As observed, the three dc voltages are identical and all regulated to 633 V. Fig. 20(b) shows the 60-V low-voltage dc bus and 23-V regulated ac output. Fig. 21(a) shows the operating waveforms under inductive operating mode, depicting the PCC voltage and current, the SST PWM voltage, and the high-voltage dc links. Just as shown in the previous case, the three dc voltages are identical and all regulated to 633 V. Fig. 21(b) shows the 60-V low-voltage dc bus and 23-V regulated ac output.

These results show that the developed SST can indeed transfer power between the grid and load terminal while providing the required reactive power to compensate for the fluctuating active power load demand. In this way, the SST is expected to be capable of suppressing all voltage fluctuation in WFs using SCIG under the proposed system architecture.

Figure 20: Operation waveforms of SST under capacitive-mode operation. (a) PCC voltage, current, PWM voltage, and three dc-link voltages. (b) Low-voltage dc-link voltage and ac output voltage.
Figure 21: Operation waveforms of SST under inductive-mode operation. (a) PCC voltage, current, PWM voltage, and three dc-link voltages. (b) Low-voltage dc-link voltage and ac output voltage.

D. Cost Analysis of the Proposed Wind Energy System:

Although SST has caught tremendous attention in the recent years, its cost issue is still a major concern which utilities always question. It is not easy to compare the accurate cost of two transformers since the SST is still not commercially available and the cost of the traditional distribution transformer is not open to the academic community. In order to provide some useful information of the cost of SST, this section gives the cost estimation of the established prototype. Fig. 22 shows the cost breakdown of the laboratory prototype, and the total cost of the prototype is around $10,726. The major cost comes from the high-voltage power device, high-voltage high-frequency transformer, and dc capacitors. It is worth to point out that it is not a surprise to see a five to ten times cost reduction when the estimated cost is based on the large-quantity production; thus, the cost of the 20-kVA 7.2-kV–120-V SST is
about $1000–2000. As the comparison, the market price for a single-phase 25-kVA 7.2-kV–120-/240-V pole-mount transformer is around $1500. The cost of it should be much lower than the market price. It is concluded that the cost of traditional transformer is lower than that of SST.

![Cost breakdown of the SST laboratory prototype](image)

**Figure 22: Cost breakdown of the SST laboratory prototype**

It is admitted that the cost of traditional transformer is much lower than that of the SST. The cost gap between the two technologies can only be filled if advanced features of SST are explored. That is the reason why we look into the application of SST in the wind energy system. As shown in Fig. 3(a), the SST can replace two transformers and one STATCOM, with the power rating larger than single transformer depending on the reactive power compensation requirement. In this condition, the cost difference between the traditional wind energy system and the proposed one is much smaller, or the SST-based WF maybe even cheaper, thus presenting a promising market for the SST technology.

### 5. Conclusion:

Energy crisis calls for a large penetration of renewable energy resources, among which wind energy is a promising one. Voltage and frequency regulation is vital to meet the grid code. This paper has covered many key issues to compose the proposed wind energy system, including the system architecture, control objective, and component designs, specifically the following.
i. A family of wind energy systems with integrated active power transfer, reactive power compensation, and voltage-conversion capabilities has been proposed. Compared with the previous applications which utilize only the active power transfer and voltage-conversion functionalities, reactive power compensation capability is fully investigated.

ii. The proposed family of wind energy systems was demonstrated in the presence of SCIGs, by far the most demanding case in terms of voltage fluctuation and reactive power demand. Under the SST interface, the WF was rendered free of distribution power transformer and mandatory passive and active static power compensators.

iii. A modular-type high-voltage and high-power three-phase SST topology was presented, and its control strategy was investigated and shown to successfully carry out the tasks needed to interface WFs to the grid.

iv. A single-phase SST building block prototype rated at 20 kVA and 7.2 kV–120 V was built and tested for verification purposes.

However, there are still a lot of issues needed to be addressed, thus opening possible research opportunities.

i. The high-voltage and high-power system operation is still not fulfilled yet, although there is no technique limitation in this topic.

ii. Fault operating condition is not studied yet, which is a key issue in wind energy system. Similar issues, such as how to realize the fault-ride through of the traditional wind energy system, can also be studied in the proposed SST- interfaced wind system.
References:


