Real-Time Simulation of a Wind Turbine Generator Coupled With a Battery Supercapacitor Energy Storage System

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Abstract—Wind power generation studies of slow phenomena using a detailed model can be difficult to perform with a conventional offline simulation program. Due to the computational power and high-speed input and output, a real-time simulator is capable of conducting repetitive simulations of wind profiles in a short time with detailed models of critical components and allows testing of prototype controllers through hardware-in-the-loop (HIL). This paper discusses methods to overcome the challenges of real-time simulation of wind systems, characterized by their complexity and high-frequency switching. A hybrid flow-battery supercapacitor energy storage system (ESS), coupled in a wind turbine generator to smooth wind power, is studied by real-time HIL simulation. The prototype controller is embedded in one real-time simulator, while the rest of the system is implemented in another independent simulator. The simulation results of the detailed wind system model show that the hybrid ESS has a lower battery cost, higher battery longevity, and improved overall efficiency over its reference ESS.

Index Terms—Energy storage, hardware-in-the-loop (HIL), real-time simulation, wind-power generation.

I. INTRODUCTION

WIND POWER is the fastest growing renewable energy source due to its improving technologies and economical competitiveness. In the Province of Quebec, Canada, alone, wind installations reached 321 MW in 2007 and are expected to be over 4000 MW by 2015. Wind power has its unique impacts when connected to a power system due to its power electronic interface and the nature of wind. The time frame of the phenomena of interest varies from microseconds, associated with power electronics switching, to minutes and hours, related to wind fluctuations.

Simulation is a powerful tool for power system studies. Conventional offline simulation programs are used for electromagnetic-transient analysis (such as EMTP-RV and PSCAD) as well for power frequency electromechanical transient simulation (such as PSS/E, Eurostag, and DigSilent).

Electromagnetic-transient simulation programs are able to evaluate fast transients on system components. These programs are used in studies of insulation coordination, power-system-component specification, controller design, and protection systems, since devices influence and are influenced by fast transients caused by equipment and line switching, as well as by faults. These studies require detailed models of the power electronic systems.

Power frequency analysis programs are normally used in studies of system stability, system configuration at the project planning stage, and the protection-scheme selection. These programs use rather large time steps of 5 to 10 ms and simplified average models of power electronic systems to evaluate the system dynamics and stability. Since they use large time steps, they can simulate a very large interconnected power grid with hundreds of buses in a relatively short period of time.

Real-time simulators are a complementary tool to conventional offline simulation programs for power system studies [1]–[7]. With much more computational power, real-time simulators are able to simulate very complex and large models in real-time or faster. The simulation time step of a real-time simulator can be as low as tens of microseconds at the CPU, and tens of nanoseconds at the field-programmable gate array (FPGA). Therefore, real-time simulators can be used to study phenomena over a broad time frame, from less than 1 ms to minutes and hours.

Real-time enables hardware-in-the-loop (HIL) simulation. As only low power signals are exchanged between a prototype controller and a simulated plant, it is called signal HIL simulation. On the contrary, power HIL simulation is where part of a plant is simulated and connected to real power devices through sensors and amplifiers. The prototype controller and its protection system, taking into account the modulation frequency and dead-time effect, can be tested under normal and abnormal operating conditions in HIL simulations. This is inexpensive when compared with the physical setup or field tests, but valuable as an intermediary step for validating the controller design before implementing it in an actual system [8]–[14].

Associated with its computational power and high-speed input and output (IO), the main advantages of real-time simulation over offline simulation include the following:

1) detailed modeling of specific and critical components, such as high switching power electronics;
2) use of local databases where equations are inadequate;

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3) carrying out a large number of simulations in a short time to do parametric studies (Monte Carlo simulation, stochastic simulations);
4) ability of signal HIL and power HIL simulations and rapid-control prototyping.

In wind system studies, using the offline electromagnetic-transient programs and detailed models is too time-consuming when studying slow phenomena, such as the impacts of wind fluctuations on system voltage and frequency. Using simplified models will allow fast simulation of the slow phenomena. However, loss of details of specific components in a model may cause simulation inaccuracy, which in turn has significant effects on the system design and control test.

In this paper, a hybrid energy storage system (ESS) of a supercapacitor and a flow battery coupled in a wind turbine generator (WTG) is studied for wind power smoothing. The real-time simulator is the most suitable research tool for studies of the integrated wind ESS system due to the following reasons.

1) The nature of the wind is stochastic. Studies may need to conduct repetitive simulations of a large number of wind profiles in a database.
2) The model is complex since the characteristics of the equipment are highly nonlinear, and the battery storage performance is very dependent on previous operating conditions.
3) Modeling WTG and ESS interfaces with detailed insulated-gate bipolar transistor (IGBT) switch bridges is critical. Accurate reproduction of the currents is important for determining the ESS power rating and losses when studying the compromises in sizing the total and individual storage elements (the supercapacitor and battery) under economic, loss and efficiency, and operational constraints.
4) The prototype controller of the ESS can be verified for various normal and fault conditions through HIL tests.

The challenges and solutions of real-time simulation of wind systems that are integrated with power electronics are discussed in Section II. The details of the wind ESS system modeling are given in Section III. The HIL simulation setup and some practical implementation issues are discussed in Section IV, which is followed by simulation results and conclusions.

II. ISSUES ON REAL-TIME SIMULATION OF POWER ELECTRONICS INTEGRATED SYSTEMS

A. Challenges Introduced by Power Electronic Converter

In real-time simulation, a model must be simulated within a fixed time step that must be greater than the actual execution time of the simulator. The actual execution time includes the anticipated computation time to solve the system, synchronization and signal exchange time, and other overhead. Once the actual execution time exceeds the time step, it causes an “overrun.” Overruns will introduce errors to simulation results when the simulator is hardware synchronized, such as in the case of HIL simulation.

For conventional power systems, a 50-μs time step is accurate enough to simulate system steady state and transients. This is because in steady state, the system frequency is 50 or 60 Hz, and in transients, the electromechanical phenomena usually have a time constant larger than tens of milliseconds.

Increased challenges are involved in real-time simulation of integrated systems of flexible ac transmission system (FACTS) devices and renewable energy with high-frequency power electronic interfaces. On one hand, the complexity of the system increases the simulator execution time, and on the other hand, high-frequency-switching behavior requires a decreased simulation time step.

As a rule of thumb, the simulation sampling frequency (one over the simulation time step) must be greater than the larger of the following two: 20 times the maximum frequency of transients or harmonics to be represented at acceptable accuracy, and at least 50 to 100 times the pulse-width modulation (PWM) carrier frequency. The latter enables the simulation of a variation of the duty cycle by an increment of about 1 ~ 2%.

A low simulation-frequency/PWM-frequency ratio would cause simulation inaccuracy. In conventional digital simulation, the intrastep events become effective only at the next time step, leading to delays in IGBT switching. The maximum delay is one time step, which may cause significant distortion and jitter to the converter current, which does not exist in an actual system. When the simulated system is used to test converter-control performance, the false current distortion and jitter may be observed in the closed loop of the converter and its control, making it difficult to tune the control parameters.

B. Multiprocessor Simulation and Limits

Current real-time simulators commonly address this system-complexity issue by decoupling the simulated system and dispatching the computation loads onto a distributed multiprocessor system. However, this approach has two limitations.

First, decoupling will introduce a one time-step delay on the signals being exchanged between two decoupled subsystems. Therefore, it is preferable to decouple power systems using a natural propagation delay or on slow-varying signals. Otherwise, the decoupling approach may introduce errors or even cause system instability. Usually, a system cannot be decoupled into too many subsystems. Secondly, dispatching computation loads among an increasing number of processors add signal-exchange time and other overhead, which could eventually become a significant part of the simulator execution time.

Therefore, parallel computation of the decoupled system in multiple processes can reduce the execution time to a certain limit. Further decoupling of the system will not reduce the time below this limit (around 10 to 30 μs, depending on the simulator and the model) [15]. At times, even though this limit is technically feasible, it may be cost prohibitive, depending on the number of processors required.

C. Switch Event Interpolation Technology

For a typical 60-Hz system with 21 times carrier frequency (1260 Hz), the simulation frequency has to be at least 63 kHz (= 1260 * 50), i.e., using a time step of 16 μs or lower, which approaches or is below the execution time required to simulate...
implies that a time step below 4 µs should be used for the PWM carrier to avoid glitches on converter currents [15]. This time step should be about 0.25% to 0.5% of the period of the systems. In practice, it was reported that the simulation time step due to the following reasons.

The time step can, however, be achieved using an FPGA processor, such as Mitsubishi have challenged real-time simulator manufacturers to develop fully digital simulators capable of simulating high-speed converters such as a high-speed motor drive. This is above the capability of a high-end real-time simulator based on commercial processors, due to the communication latency between the processors and the IO system. Such a very low time step can, however, be achieved using an FPGA processor, but the model implementation is more complex [16].

Different switch-event interpolation approaches are proposed in [17] and [18] to address the errors associated with the switch events occurring in the middle of the simulation time steps. Those approaches, however, delay the switch events by one time step. A unique technology, RT-Events (RTE), is used in the RT-LAB simulation platform to avoid the one-time step delay. As shown in Fig. 1, instead of “snapping” the intrastep events into the next time step, this technology uses linear interpolation to stamp every event with its estimated time of occurrence. These time-stamped signals, or RTE signals, can be treated by logic or math operators, or can be used to drive IGBT bridges with time-stamp functionality, as shown in the simple two-level one-arm IGBT bridge and controller in Fig. 2.

In an RTE signal, the use of linear interpolation will also introduce a time error, as shown in Fig. 1. However, the modulation signal varies slowly (usually at a grid or machine frequency). A time step of 50 µs corresponds to 1.08° of a 60-Hz sinusoidal waveform. Thus, the modulation signal can be linearized piecewise within each time step. The curvature of the modulation signal and the time error of the RTE signal in Fig. 1 are exaggerated for the purpose of a clear demonstration.

The RTE technology enables the reduction of the simulation-frequency/PWM-frequency ratio to 5 ∼ 10, but it still provides the same accuracy as that achieved by conventional digital simulation at a ratio of 200. A power electronic system with PWM carrier frequencies of 1260 Hz and 10000 Hz can then be simulated with a time step of 80 and 10 µs, respectively, which enables the use of conventional CPU processors and SIMULINK/RTW automatic C-code generators instead of FPGA chips.

D. Hardware IO of Switch-Event Signal

A real-time simulator enables HIL simulation to validate with flexibility the functionality, design, and performance of prototype or actual controllers. In this case, the power system is simulated in a real-time simulator, which is connected to an actual controller device or prototype controller (i.e., an additional independent simulator) through hardware IOs. This technique has been used for decades using analog simulators and over the last ten years using fully digital simulators to test thyristor-based power electronic systems such as high voltage direct current and FACTS. Most developers of fast IGBT systems still use analog simulators to test power electronic controllers since most conventional digital simulators are not able to reach the very low time step required to simulate IGBT-based power electronic systems. However, hybrid automotive manufacturers such as Toyota and manufacturers of fast industrial drives such as Mitsubishi have challenged real-time simulator manufacturers to develop fully digital simulators capable of simulating IGBT-based power electronic systems. Simulators capable of simulating systems with carrier frequencies of up to 10 to 20 kHz have been available for five years and have enabled power-grid equipment manufacturers to take advantage of the HIL tests of IGBT-based controllers.

The IOs are required to have a much higher resolution than the simulation time step due to the following reasons.

1. The hardware output must be able to generate events with a resolution that is better than 500 ns to 5 µs, which is shorter than the typical time steps achievable with the fastest simulators. For example, switching dead time must be set between 1 and 5 µs to prevent short circuits when driving an actual IGBT bridge. Simulation of low-frequency harmonics generated by dead-time effect requires high firing pulse generation accuracy.

2. The hardware input must be able to detect events from an actual controller that occur between time steps. Otherwise, those intrastep events could be missed, which will generate unrealistic and noncharacteristic harmonics.

3. To avoid digital simulation inaccuracy discussed in the previous section.

In the RT-LAB real-time simulator, FPGA-based IO cards are used to reproduce events according to the output RTE signals and to convert detected events to input RTE signals. Since the FPGA operates at a frequency of 100 MHz, the resolution of the event generation and detection is below 0.1 µs when using a fast optocoupler signal conditioning interface. Better accuracies of up to 20 ns can be obtained with a transistor–transistor logic (TTL) interface. In addition, the use of FPGA minimizes the
TABLE I
CHARACTERISTICS OF BATTERY AND SUPERCAPACITOR TECHNOLOGIES

<table>
<thead>
<tr>
<th>STORAGE TECHNOLOGY</th>
<th>LIFE CYCLE</th>
<th>DC-DC EFFICIENCY</th>
<th>TIME SCALE</th>
<th>DYNAMIC RESPONSE</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRB</td>
<td>10,000 cycles</td>
<td>75–80%</td>
<td>Minutes-Hours</td>
<td>Fast</td>
<td>Low</td>
</tr>
<tr>
<td>Supercapacitor</td>
<td>$10^4–10^8$ cycles</td>
<td>86–98%</td>
<td>Seconds-Minutes</td>
<td>Very Fast</td>
<td>Very Low</td>
</tr>
</tbody>
</table>

Fig. 3. VRB battery model.

CPU load for IO management, and therefore increases available processing time for the model.

To simulate or test high-bandwidth converter and drive controllers, models using the Xilinx System Generator (XSG) can be downloaded directly to the FPGA board, and the total latency of the model computation and IO drive can be as low as a few hundred nanoseconds [16].

The two key advantages of the RT-LAB simulator, namely, the switch-event interpolation technology and high-speed FPGA-based IO, make it most suitable for this study. Other merits of the simulator over conventional simulators are the use of standard PC-compatible multicore computers, SIMULINK, and FPGA chips that are programmable by the users.

III. WIND ESS SYSTEM MODELING

Integration of an ESS into wind farms will reduce wind power fluctuations [19], [20]. This paper proposes a flow-battery–supercapacitor hybrid ESS which takes advantage of these two complementary technologies to provide both large power and energy ratings.

The vanadium-redox flow battery (VRB) is an excellent candidate for wind applications with many advantages, including high life cycle and efficiency, a wide range of power outputs, and low maintenance cost. Modeling and design of a VRB was studied in [21] and [22], and applications of VRB in wind farms are explored in [23]–[25]. Supercapacitor modeling and efficiency studies are provided in [26]. An interface converter for a battery–supercapacitor system is proposed in [27]. Supercapacitor storage in wind applications is studied in [20] and [28]. The VRB and supercapacitor characteristics are listed in Table I.

A. VRB Module

The model of a VRB module, given in [29], is illustrated in Fig. 3. This VRB module has 500 series cell stacks, a nominal output voltage of 700 V at 50% state of charge (SOC) and zero current, and a minimum voltage of 525 V. The current rating is 800 A, and the power rating is 420 kW (525 V × 800 A).

The VRB has approximately 79% efficiency, i.e., 15% internal and 6% parasitic losses, at the operating point of 20% SOC and rated discharging current. The model parameters are listed in the Appendix.

B. Supercapacitor Module

The first-order supercapacitor model is a series $RLC$ circuit, which is frequency, temperature, and voltage dependent in very accurate models [30]. In wind applications, the supercapacitor operates in a frequency range well below its self-resonant frequency. Therefore, the inductance is ignored. A constant capacitance and equivalent series resistance (ESR) model gives enough accuracy and is adopted in this study. The model is based on a 0.58-F 400-V supercapacitor module. The ESR is 0.6 $\Omega$, as specified by the manufacturer and verified in [26]. The supercapacitor works in the 10% to 100% SOC range, i.e., 0.3 to 1 per unit (p.u.) voltage. The effective energy capacity of each supercapacitor module is 42.2 kJ (0.5 × 0.58 F × 400 V$^2$ × 0.9) or 0.0117 kW·h.

C. Integrated WTG and ESS System

A permanent-magnet synchronous machine (PMSM) WTG integrated with a VRB supercapacitor hybrid ESS is modeled, as shown in Fig. 4. The PMSM WTG power rating is 2 MW, the dc bus voltage is 1400 V, and the grid-side ac voltage is 690 V. The rectifier and inverter are three-level converters.

The VRB and the supercapacitor are connected to the dc bus through two bidirectional dc/dc choppers. Sizing of the storage is determined by the choice of the energy management algorithm. As a filtering algorithm is used in this paper, the energy capacities of the VRB and the supercapacitor are selected so that their discharge duration is on the order of magnitude of the filter time constant, with a margin. The VRB storage has two VRB modules in parallel. The total power rating is 840 kW, and the discharge duration is 120 s, i.e., an energy capacity of 28 kW·h (840 kW × 120 s). The supercapacitor storage has
400 0.58-F modules, two modules per stack, and 200 parallel stacks. The ratings of the total supercapacitor storage are 4.7 kW·h and 800 V. The power rating of the supercapacitor is limited by its converter and determined by its power peak in the application, which is same as the WTG (2 MW).

D. WTG and ESS Control

To maximize the wind power, the rectifier controller regulates the WTG speed according to the maximum power point tracking control scheme. The controller inputs are wind turbine speed and angle, and PMSM current and voltage. The controller outputs are the 12-IGBT gating signals of the three-level rectifier. The inverter controller regulates the dc bus voltage and the reactive power in the grid side.

The ESS power and energy are regulated by the ESS management algorithm, whose major task is to regulate the output wind power according to certain specifications. A simple filtering algorithm is used since this is not the focus of this paper. The total ESS power $P_{ESS}$ is regulated as the wind power $P_w$ filtered by a high-pass filter (1). Wind-power fluctuations faster than the cutoff frequency (0.003 Hz) are reduced by the ESS. The supercapacitor is designed to absorb high-frequency power surges. Therefore, its power is controlled as in (2) with a smaller time constant. The VRB power is the power difference between the total ESS and the supercapacitor, (3)

$$P_{ESS} = \frac{50s}{1+50s} P_w$$  \hspace{1cm} (1)

$$P_{cap} = \frac{10s}{1+10s} P_w$$  \hspace{1cm} (2)

$$P_{VRB} = P_{ESS} - P_{cap}.$$  \hspace{1cm} (3)

This ESS management algorithm does not account for the effect of power losses inside the ESS, which gradually decreases the ESS SOC over time. In practice, the algorithm has to compensate for power losses to prevent complete discharge of the storage.

IV. SYSTEM REAL-TIME SIMULATION

A. HIL Simulation

The WTG ESS system is simulated in real-time on the RT-LAB platform at a time step of 50 μs since the PWM carrier frequency used is rather low (1260 Hz for the WTG rectifier and inverter, and 2000 Hz for the ESS converters). The controllers of the rectifier and the two dc/dc converters are loaded in one standalone simulator. Once this simulator powers up, it automatically loads the controller model, acting as an embedded hardware controller. The rest of the system, decoupled onto two subsystems as shown in Fig. 4, is loaded onto another independent simulator and simulated on two processors. The two simulators are connected via the hardware I/Os. The system measurements are sent from the plant simulator to the controller simulator, and the converter gating signals are sent in the opposite direction.

In this model, the interpolation technology is used, and the converter controllers generate RTE gating signals to drive the IGBT bridges with time-stamp functionality. For example, the ESS chopper controller in Simulator 2 gives RTE signals, which are converted to digital output with a high resolution of less than 0.1 μs by its FPGA-based IO card. Those high-resolution digital signals are wired to the FPGA-based IO card in Simulator 1 and converted back to RTE signals to drive the choppers simulated in Simulator 1.

The external prototype controller is model-based, and its code is generated automatically from SIMULINK and the RTW code generator. The controller can be easily modified during development. Once fully developed and tested under all normal and abnormal operating conditions, the same code could then be downloaded to a production controller. In some cases, the generated code could be further optimized using a production-level code generator such as eCODER.

Model-based design methods using automatic code generation have been used by automotive and aircraft manufacturers for several years. Several leading electrical system manufacturers start to use this technique to reduce the design-to-market cycle, to specify and document their design, and to facilitate maintenance and system upgrades.

B. Hardware Setup and IO Waveforms

The setup of the hardware part of the RT-LAB simulation platform is shown in Fig. 5. It includes four 8-processor simulators (only two are used for these tests), which can simulate complex models in parallel when interconnected by FireWire or fast 10-Gb/s real-time links. In this study, the two simulators are independent of each other, and the only communications between the two are the signals sent via the hardware I/Os. Each simulator is equipped with fast FPGs to manage all IO converters. Models could also be implemented directly on FPGA chips using XSGs and RT-LAB XSG.

The plant model uses only two processors out of the eight available in one simulator. The complexity of the system could be increased to simulate several wind turbines to analyze the interactions between the controllers and the power grid. Several simulators can also be interconnected with high-speed 10-Gb/s links to simulate large wind farms, micro grids, and very large power grids.
Hardware IO signals communicating between the two simulators can be monitored by an oscilloscope. Figs. 6 and 7 show the captured waveforms of the WTG currents from the plant simulator and the gating signals from the controller simulator, respectively. Due to malfunctions with the oscilloscope’s channel four, only the signals of Switches 1 to 3 of the inverter arm-A are recorded and shown in Fig. 7(a). A dead time of 3 $\mu$s, which is less than the 50-$\mu$s simulation time step, is applied to all the converter controllers in this model. A zoom in view in Fig. 7(b) clearly shows the 3-$\mu$s dead time between the two complementary signals of Switches 1 and 3, where one horizontal division is 5 $\mu$s.

C. Practical Implementation Issues on HIL Simulation

Even when the system model works well on one simulator, implementing HIL tests with the controller and plant loaded onto two independent simulators (or one simulator and one controller device) is not a straightforward exercise. This is because the two simulators are not synchronized, and noise is introduced into the hardware IO signals. Special considerations relating to HIL simulation are as follows.

1) The controller is not initialized only at time zero. Initialization should occur when start-up of the plant simulator is detected.

2) Input signals may unexpectedly become zero, due to loss of IO link or shutdown of the other simulator. This should not cause model divergence (e.g., zero in the denominator).

3) An input integer signal, such as mode selection or ON/OFF states, may become a real number when noise is added. It must be rounded to an integer to be used further.

4) Amplifying an input signal will also amplify noise. The amplification can be applied to the signal before it passes through the IO link.

5) Integration of specific input signals should be avoided when an accumulated error caused by biased noise cannot be corrected by closed-loop control.

For example, in this study, the controller needs the WTG electrical angle from the plant for $abc$–$dq$ transform. This can be achieved by using the methods shown in Fig. 8. Each of these methods works well in one-model simulations that do not use hardware IO. In HIL tests, however, the use of methods (1) and (2) may cause the controller to fail due to the reasons listed earlier. The controller will function when using method (3), however, with periodical ripples in the converter currents. This is because when the angle wraps from $2\pi$ back to zero, intermediary values might be captured by the controller, which will cause periodical errors in the angle signal. Errors introduced in method (4) are small and can be corrected through closed loop control. Therefore, method (4) can be used in HIL tests.

D. Simulation Results

The hybrid VRB supercapacitor ESS and a reference ESS of an identical VRB that does not incorporate the supercapacitor are tested in a benchmark of the same wind profile, PMSM WTG, and ESS management algorithm.
The prefiltered WTG power and the filtered power created by the two ESSs are superimposed and shown in Fig. 9. The high-frequency wind power fluctuations are eliminated by the ESS and the two ESSs have the same wind power leveling performance. The performance of the VRB battery in the two ESSs is compared and shown in Fig. 10. The corresponding data are summarized in Table II.

The following differences between the two ESSs are observed.

1) The power peak of the VRB battery in the hybrid ESS (0.267 p.u.) is only about 1/3 of that in the reference VRB ESS (0.803 p.u.). Therefore, the battery power rating and the power/energy ratio in the hybrid ESS can be reduced if the energy rating remains constant. The VRB in the hybrid ESS is more economical.

2) The VRB battery in the hybrid ESS has less loss than that in the reference VRB ESS. Even if combined with supercapacitor loss, the average total loss in the hybrid ESS (0.0241 p.u.) is 62.9% of the VRB ESS (0.0383 p.u.).

3) The hybrid ESS has generally lower battery depth of discharge (about 5 ∼ 9% lower in each charge cycle) and thus, potentially prolonged life span compared with the reference VRB ESS due to two reasons: lower power surges and less power loss.

Note that the ESS loss is a highly nonlinear function of the converter current. Therefore, using the average converter model, which does not take current ripples into account, will introduce significant errors in the ESS loss and efficiency.

V. Conclusion

A real-time simulator, as a complementary tool to conventional offline simulation programs, is an effective tool for wind system studies. Due to its computational power and high-speed IO, the real-time simulator enables detailed modeling of complex wind systems and repetitive simulations of slow phenomena in a short time. It also provides the possibility of HIL simulation, which can accelerate the control prototyping cycle and lower the cost as compared with physical setup or field tests.

As an application, a real-time simulator has been used to study a VRB flow-battery and supercapacitor hybrid ESS for wind-power smoothing. The ESS and WTG interfaces are modeled by detailed IGBT bridges with dead time to accurately simulate the currents, which is important for determining ESS sizing, loss and efficiency, and operational constraints. The integrated wind ESS system is verified by real-time HIL simulation, where the controller is embedded in one real-time simulator and the plant is loaded on a second independent simulator. Simulation results demonstrate the proposed hybrid ESS has advantages of lower battery cost due to its reduced power rating, prolonged battery life due to lower depth of discharge, and higher overall system efficiency.
The prototype controller could be used, when fully tested, as a real production-level controller if the same code is implemented on robust embedded industrial PCs. These model-based design methods using automatic code generation are started to be used by leading electrical system manufacturers.

APPENDIX
PARAMETERS OF VRB Module, FIG. 3

\[
\begin{align*}
\text{SOC}_{t+1} &= \text{SOC}_t + V_{\text{stack}} \cdot I_{\text{stack}} \cdot \Delta t/W_{\text{base}} \\
V_{\text{stack}} &= n \left(1.4 + 0.05136 \ln \left(\frac{\text{SOC}}{1 - \text{SOC}}\right)\right) \\
I_{\text{pump}} &= 1.0126 \left(\frac{I_{\text{stack}}}{\text{SOC}}\right)
\end{align*}
\]


<table>
<thead>
<tr>
<th>n (no. of cells)</th>
<th>(R_{\text{fixed}})</th>
<th>(R_{\text{reaction}})</th>
<th>(R_{\text{resistive}})</th>
<th>(C_{\text{electrodes}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>25.92 Ω</td>
<td>0.07476 Ω</td>
<td>0.04984 Ω</td>
<td>0.012 F</td>
</tr>
</tbody>
</table>

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