Technical Report

Energy-Plus Roadway/Traffic Signal Lights

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1. **Executive Summary**

The most effective way to reduce net energy consumption of roadway systems is by using the public right-of-way and roadway infrastructure as a source for energy production, storage, and distribution. An innovative energy-plus roadway/traffic signal light (EPRTL) has been developed as the fundamental energy production unit to produce and store green electric power, where energy-plus stands for annual energy consumption that is less than production. The EPRTL contains a grid-connected wind/solar hybrid power system (HPS) installed on the pole of a roadway/traffic signal light to exploit the advantages of both solar and wind energy for clean electric power production. The electric power generated will be consumed locally by the roadway/traffic signal lights; the excess power generated will be stored in an optional battery system attached with the EPRTL or delivered through the roadway microgrid to supply other loads in the roadway microgrid or the utility main grid.

This report provides the details of the topology, configuration, and design of the EPRTL and its components as well as the details of the control and power management system of the EPRTL. Typical simulation evaluation results are also provided to show the effectiveness of the design.

2. **Topology and Configuration of the EPRTL**

The topology of the proposed EPRTL system has been designed based on the existing electrical infrastructure for traffic signals and street lights. Fig. 1 illustrates the typical configuration of four traffic poles at one intersection. The utility power grid supplies single-phase (1-Φ), 120 V, alternating current (AC) electric power to a cabinet, which distributes the 120 V AC power to the four traffic poles through underground cables. Inside the cabinet, the 120 V AC power is converted to 24 V direct current (DC) electric power for sensing, condition monitoring, control, etc., of the traffic signal system. An optional battery is connected to the 24-V DC bus to provide backup power during power outages. Based on the configuration in Figure 1, we designed the topology and configuration of the EPRTL for four traffic poles at one intersection, as shown in Fig. 2.

![Fig. 1. Four traffic poles with wind/solar hybrid systems at one intersection.](image)
As shown in Figure 2, for each traffic pole, the wind turbine generator generates three-phase (3-Φ) AC electric power with variable voltage and frequency due to the variations of wind speed. A 3-Φ rectifier converts AC power generated by the wind turbine generator to DC power. The voltage of this DC power is variable depending on the AC-side voltage of the rectifier. A DC/DC power electronic converter is used to converter the variable DC power to constant-voltage DC power, e.g., 200 V. The photovoltaic (PV) panels convert sunlight into DC electric power using the photoelectric effect. Another DC/DC power electronic converter is used to converter the DC power generated by the PV panels into constant-voltage DC power. The DC power generated by the wind/solar hybrid systems of the four traffic poles is collected to a DC bus. A 1-Φ inverter then converts the DC power into 60 Hz AC power and connects the
wind/solar hybrid systems to the utility power grid. If a battery is used, it is connected to the DC bus through a DC/DC power electronic converter. This converter controls the charge and discharge of the battery. In this configuration, the battery serves as a source or sink of the electric power to control the power delivered to the utility grid from the wind/solar hybrid system.

The topology and configuration of the EPRTL system is shown in Fig. 3. In each EPRTL, the wind turbine generator generates three-phase (3-Φ) AC electric power with variable voltage and frequency due to the variations in wind speed. A 3-Φ rectifier converts AC power generated by the wind turbine generator to DC power. The voltage of this DC power is variable depending on the AC-side voltage of the rectifier and is lower than the required voltage level for operation of the single-phase (1-Φ) grid interface DC/AC inverter. Therefore, a DC/DC boost converter is used to increase and regulate the DC output voltage of the 3-Φ rectifier to a constant DC voltage at a level required by the grid interface inverter. The PV panels convert sunlight into unregulated DC electric power using the photoelectric effect. The variable DC power generated by the wind/solar hybrid system is collected to a constant-voltage DC bus, e.g., 200 V, through DC/DC power electronic converters. A controller has been developed for each DC/DC converter to control the corresponding wind turbine or solar panels to generate the desired amount of power. A typical control strategy is called the maximum power point tracking (MPPT) control, where the wind turbine and PV panels are always controlled to generate maximum power. The 1-Φ DC/AC inverter then converts the DC power into 60 Hz AC power and connects the wind/solar hybrid system to the utility power grid. If a battery is used, it is connected to the DC bus through a DC/DC power electronic converter. This converter controls the charge and discharge of the battery. In this configuration, the battery serves as a source or sink of the

Fig. 3. Topology and configuration of one EPRTL.
electric power to control the power delivered to the utility grid from the wind/solar hybrid system.

A local power management controller (LPMC) coordinates the operation of different components of the EPRTL for both grid-connected and island operating modes. In the grid-connected mode, the wind turbine generator and PV panels will mostly be operated in the MPPT mode to generate maximum power used by the local loads and delivered to the main power grid. In the island operating mode in which the roadway microgrid is disconnected from the utility main grid, the LPMC will generate reference signals for the PV panels and battery to maintain desired levels of voltage and frequency at the AC terminals of the grid interface inverter. In this operating mode, the PV panels may not be operated in the MPPT mode. The action of the LPMC is subject to the regulation requirements from the upper-layer supervisory power management controller (SPMC) of the roadway microgrid.

3. Sizing of the EPRTL Components

The power capacities of the wind turbines and PV panels are determined based on the wind and solar resources and the structural characteristics of the poles of the traffic-signals and street lights. For traffic poles, the power capacities of the wind turbines and PV panels are in the ranges of 500-3000 W and 100-400 W, respectively. For the street light poles, the power capacities of the wind turbines and PV panels are in the range of 200-500 W and 80-200 W, respectively. The size of the battery can be determined by the worst scenario—when a power outage occurs in the utility main grid or in the microgrid while no power can be generated from the wind/solar hybrid systems, the traffic signal system should operate in required modes for required durations. For example, batteries used at some critical intersections in Lincoln, Nebraska, are required to supply power to allow the traffic signal system to operate in the normal mode for two hours and then in the flashing mode for another two hours. The traffic signal system at a typical intersection consumes 0.7 kWh per hour in the normal mode and 0.35 kWh per hour in the flashing mode. Therefore, the capacity of the battery should be at least 2.1 kWh. However, with the availability of the wind/solar hybrid generation systems and the roadway microgrid, the size of the battery can be reduced.

4. Power Electronic and Control for the Wind Turbine Generator

Fig. 4 shows the detailed topology of the power electronic converters for the wind turbine generator, where the AC/DC and DC/DC converters are implemented by a 3-Φ diode rectifier and a DC/DC boost converter [1], respectively. Due to the variations of wind sources, the magnitude and frequency of the output voltage of the wind turbine generator are variable. Consequently, the voltage at the DC terminal of the 3-Φ diode rectifier is variable, whose magnitude is lower than that of the DC-bus voltage required for the operation of the grid interface inverter. Therefore, a DC/DC boost converter is used to boost the DC-terminal voltage of the 3-Φ diode rectifier to a constant value at the required level.

Fig. 4 also illustrates the control scheme for the wind turbine DC/DC converter. The input voltage and inductor current of the converter are sensed to calculate the power delivered by the converter. The calculated power, the input voltage, and the inductor current are used by a MPPT
algorithm to determine the optimal voltage reference of the DC/DC converter. The MPPT algorithm checks the power against the previous step to adjust the voltage reference of the DC/DC converter with a certain step that will cause the wind turbine to output a current and voltage so as to be operating at the maximum power under the particular conditions at that time. The reference voltage is compared with the measured voltage, and the error is passed through a proportional-integral (PI) voltage regulator to generate the current reference signal. The current reference is used by the inner-loop PI current regulator to generate a control signal, \( v_c \), which is then used to generated the appropriate duty cycle for pulsewidth modulated (PWM) switching of the semiconductor switch, \( S \).

![Fig. 4. The power electronic converters and control for the wind turbine generator.](image)

5. Power Electronic and Control for the PV Panels

The power generated by the PV panels is fed to the common DC bus by a DC/DC converter. A characteristic of the PV system is that the voltage of the PV panels is relatively low (e.g., a few tens of volts) while the voltage of the common DC bus is relatively high (e.g., 200 V). Therefore, a quasi-double-boost DC/DC converter [2], as shown in Fig. 5, is used. Compared to the standard DC/DC boost converter, the benefit of using the double-boost DC/DC converter is that at the same duty ratio and input voltage, \( V_{in} \), the output voltage, \( V_{out} \), is doubled. Therefore, the converter can be operated close to its optimal duty ratio where the optimal efficiency can be achieved.

![Fig. 5. Control scheme for the PV panel DC/DC converter](image)

Fig. 5 also illustrates the control scheme for the PV panel DC/DC converter. The control scheme enables the PV panels to work in two modes: MPPT and constant power. The input voltage and current of the converter are sensed to calculate the power delivered by the converter. The measured power is compared with the power reference generated by the LPMC in Fig. 3. The sign of the power error determines whether the PV panels work in the MPPT mode or the constant power mode. In practice, the LPMC can set the power reference at the rated power of the PV panels to make them continuously operate in the MPPT mode. The MPPT algorithm
checks the power against the previous step to adjust the duty cycle of the two switches, $S_1$ and $S_2$, with a certain step that will cause the PV panels to output a current and voltage so as to be operating at maximum power under the particular conditions at that time. Once the maximum PV output is reached, the controller will hold right around that point until the conditions change. If the constant power mode is used, the duty cycle of the two switches is decreased incrementally until the PV panels output a current and voltage so as to be operating at the reference power.

Fig. 5. The power electronic converter and control for the PV panels.

6. Power Electronic and Control for the Battery

Fig. 6 shows the topology of the DC/DC converter [3] for the battery, which can deliver power in two directions, i.e., from the battery to the 200 V DC bus or the reverse. The bidirectional DC/DC converter consists of an inductor ($L_{dc}$) on the battery side and two half-bridge converters placed on each side of the main transformer, $T_r$. A small capacitor ($C_{r1}-C_{r4}$) across each of the four switches provides a lossless snubber for soft switching. The use of soft switching reduces the switching losses and stresses of the semiconductor switches of the circuit. The transformer is used to provide isolation and voltage matching between its two terminals. When power flows from the low-voltage battery side to the high-voltage (200 V) DC-bus side, the DC/DC converter works in the boost mode to boost the battery voltage (e.g., 24 V) to a desired voltage level (200 V DC). In the other power flow direction, the DC/DC converter works in the buck mode to transfer power from the DC-bus side to the battery side to charge the battery. This bidirectional DC/DC converter has distinct advantages for applications that require high power density and low cost. The soft switching is achieved in either direction of the power flow without the need for any additional components.

Fig. 6 also illustrates the control scheme for the bidirectional DC/DC converter in the battery system. The input of this control scheme is the power reference generated by the LPMC in Fig.3.
and the sensed battery output voltage and current; the output is the phase shift angle $\Theta$ of the converter, which is generated by a PI power regulator and is used for generating the PWM signals for the four semiconductor switches, $S_1$-$S_4$, of the bidirectional DC/DC converter. If the reference power is positive, then the converter makes the battery work in discharge mode; otherwise, the converter makes the battery work in charge mode.

An electrical battery model, as shown in Fig. 7, has been developed to facilitate the design and circuit simulation of the battery and the EPRTL. The model consists of two capacitor and resistor (RC) circuits. The RC circuit on the left models the state of charge (SOC) and operating time of the battery, where the capacitor, $C_{\text{capacity}}$, represents the whole charge stored in the battery; and the self-discharge resistor, $R_{\text{self-discharge}}$, is used to characterize the self-discharge energy loss of the battery. The voltage across $C_{\text{capacity}}$ ($V_{\text{SOC}}$) varies in the range of 0 V (i.e., SOC is 0%) to 1 V (i.e., SOC is 100%). In other words, $V_{\text{SOC}}$ represents the SOC of the battery quantitatively. The RC circuit on the right simulates the voltage-current characteristics of the battery, where the resistors and capacitors are used to characterize the transient response of the battery; and the voltage-controlled voltage source $V_{\text{OC}}(V_{\text{SOC}})$ represents the nonlinear relation between the open-circuit voltage $V_{\text{OC}}$ and SOC. In practice, all of the RC parameters in the model can be obtained from experiments.

![Bidirectional DC-DC Converter](image)

**Fig. 6.** The power electronic converter and control for the battery.
7. Power Electronics and Control for Grid Connection of the EPRTL

The 1-Φ inverter is implemented by a full-bridge, PWM DC/AC inverter [1] for grid connection of the EPRTL, as shown in Fig. 8. The inverter serves as the interface between the wind/solar/battery units, the local AC load, and the roadway microgrid to control the active power exchanged among these elements. In principle, the net active power generated by the wind/solar generation units, consumed by the local load, supplied/stored by the battery, and delivered to or extracted from the microgrid should be zero at any time. This is achieved by controlling the DC-link voltage of the inverter to be constant. In addition to active power control, the inverter can also be arranged to supply/absorb the reactive power to/from the microgrid for voltage regulation of the microgrid.

Fig. 8 also illustrates the control scheme for the grid interface inverter. The control scheme uses the sensed DC-bus voltage and AC-side voltage and current to control the DC-bus voltage at a constant value and the reactive power (optional) exchanged between the EPRTL and the power grid. The reactive power control capability of the inverter could contribute to the voltage stability, power factor control, and power quality improvement of the power grid.
8. Simulation Validation of the EPRTL Design

The proposed EPRTL has been implemented in the MATLAB/Simulink/SimPowerSystems platform to validate the proposed design by computer simulations. All the components of the EPRTL, including the wind turbine generator, PV panels, battery, power electronic converters, load, power grid, control systems, and their connections, have been appropriately modeled or programmed in the simulation platform. Fig. 9 shows the overall EPRTL simulator developed in the simulation platform, where the details of each component and the controllers can be accessed by double clicking the corresponding module of the simulator.

Simulation studies have been carried out to evaluate the performance of the EPRTL at various operating conditions, including various wind flow, solar radiation, and load conditions. Based on the simulation results, the parameters of each controller have been fine-tuned to achieve the best performance. Some typical results are shown as follows.

The solar radiation and temperature data provided by the National Renewable Energy Laboratory (NREL) [4] has been used to validate the proposed current-sensorless MPPT control for the PV system. The data was collected from the South Table Mountain site in Golden, Colorado, on May 31, 2010. Without knowing the information on solar radiation, the proposed MPPT algorithm controls the PV system to track the maximum power points (MPPs). Fig. 10 shows the
operating points, i.e., the real MPPs, of the PV system at various solar radiation conditions (i.e., a larger value of $\lambda$ indicates stronger solar radiation) during the day, which are close to ideal MPPs.

**Fig. 10. MPPT results of the PV system.**

Fig. 12 shows the MPPT results of the simulated wind turbine generator for a wind speed profile of Fig. 11. The results show that the proposed MPPT algorithm controls the wind turbine generator to track the MPPs with good precision.

**Fig. 11. Wind speed profile.**  **Fig. 12. MPPT of the wind turbine generator.**
9. Conclusion

This report has presented the details of the topology, configuration, and design of the EPRTL and its components as well as the details of the control and power management system of the EPRTL. The EPRTL has been optimally designed by taking into account constraints from various factors, such as energy resources, structural stability, driver distraction, economic efficiencies, etc. The EPRTL will provide an energy-efficient new element in transportation systems. Nation-wide deployment of the EPRTLs will significantly change the way future electric power and transportation systems are developed and operated.

References