A Graphic Form with Emergent Properties for Monitoring Renewable Generation Stations

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***Abstract*—Electric transmission grid reliability and resilience are challenged by increased use of intermittent renewable generation. This paper describes a straightforward, short-term approach to support grid operators monitoring fleets of renewable generators: designing displays using emergent visual features to communicate functional properties. An example wind generator graphic form and integrated meteorology display page are described. This graphic design distinguishes four practically significant functional operating modes of most wind turbines using a compact, familiar barchart format that can be implemented in almost any control system.**

Keywords—human factors, interface, design, ecological, monitoring, power grid, renewable, generation

I. Introduction

The renewable share of the electric generation supply mix has been steadily rising over the past two decades, with some jurisdictions occasionally deriving almost half their electricity supply from wind [1]. Wind and solar generation are intermittent sources of energy and challenge reliable transmission operation. Transmission grid control systems have been and must continue to be adapted to maintain resilience while accommodating more renewable generation.

Independent System Operators (ISOs) manage transmission reliability, balancing electricity load and supply in their jurisdiction. This control requires forecasts of estimated wind and solar generation patterns over daily and week-ahead timescales. However, transmission operators must still monitor in real-time for the emergence of physical conditions, such as strong winds or icing, that can make wind generation less predictable. Weather patterns can systematically disrupt renewable generation over wide areas, presenting a threat to transmission grid resilience. Generation equipment vendors have improved automatic control of renewable power systems to reduce adverse events. Still, human-machine interfaces to support renewable energy integration into the power grid remain under development [2,3]. This paper describes a display designed for transmission operators to monitor renewable generation stations for performance and reliability.

II. Motivation and Method

A. Emergent Features in Graphic Forms

In an eight-month research project, we observed and researched transmission system operation at our regional ISO. We found that existing control room displays of wind generation station telemetry used only text and numbers. Renewable summary displays tabulated station power output and circuit breaker status. While legible, the displays supported only serial (one-at-a-time) visual search and separated station power output from contextual measures such as wind speed.

For operators to efficiently maintain awareness of the state of dozens of wind generation stations requires a visual presentation that shows context and that scales up effectively. This is especially pressing as new wind stations come online.

We aimed to create a graphic form to represent wind input and power output, as well as normal/abnormal relationships between them using emergent features [4]. This could support a visual overview of dozens of renewable stations at once.

B. Ecological Interface Design

One well-established interface design method for complex sociotechnical systems is Ecological Interface Design (EID) [5]. Among its principles is to show data in their functional context (e.g. power output in the context of wind input). We based our EID process on a functional analysis of transmission grid operations [6]. A key functional constraint of wind generators is that they react in four different modes to wind speed ranges:

- Below cut-in wind speed, wind turbines do not generate (and may not contribute reactive voltage support)
- Faster than cut-in and below rated wind speed, they generate roughly proportionally
- At or above rated wind speed, they generate constantly
- Above a maximum cut-out speed, they may trigger generator shutdown (depending on wind gust speed and duration)

These important functional distinctions were not represented in the existing transmission operator displays we observed. We set a goal to show this context in a graphic form.

C. Implementation Limitations

We implemented the display in ABB WS500 Network Manager, using existing telemetry data points. We avoided specifying calculations (e.g. power output normalized as a percentage of maximum) to not interfere with time-critical database processes. Available analog graphics features were very limited, the most useful being a bar chart with static high/low limits. In this prototype we reserved space for trend charts using temporary placeholder graphics pending upgrades to system software.

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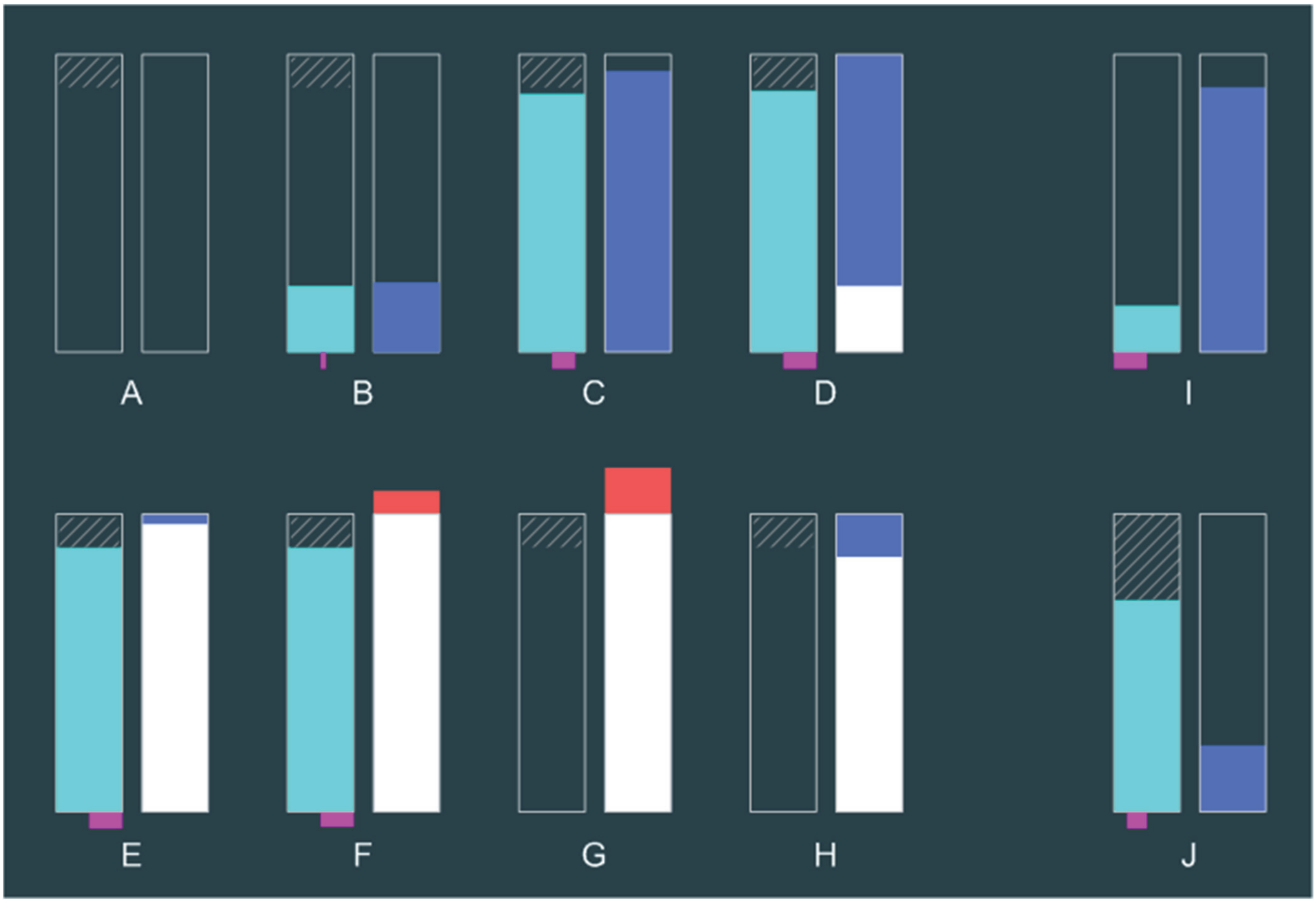
Fig. 1. Ten scenarios A-J from TABLE I. illustrated in distinct barchart representations of power (left) and wind (right). Scenarios A-F illustrate typical effects of increasing wind speed across four functional ranges. Scenario G shows overspeed wind tripping turbines (in H). Scenarios I and J show inconsistent data.



III. Design Case Study: Output/Input Barcharts

In this paper, we describe the most important display feature, renewable output/input bar charts (Fig. 1 and Fig. 2). Bar chart high/low scales are pre-configured with parameters specific to each generator, then animated by station telemetry.

A. *Description of Graphic Elements*

The left (cyan) bars in Fig. 1 indicate MW output relative to nameplate maximum and in-service available power (less crosshatch). Available power is often less than nameplate due to day-to-day maintenance, for example. The right (blue/white/red) bars indicate wind input (described next). Power and input bars are placed side-by-side because comparing them indicates how effectively a wind generator is converting renewable inputs to electric output. To illustrate how practically different operating situations are distinguished by emergent combinations of bar charts, ten scenarios are outlined in TABLE I. and illustrated in Fig. 1.

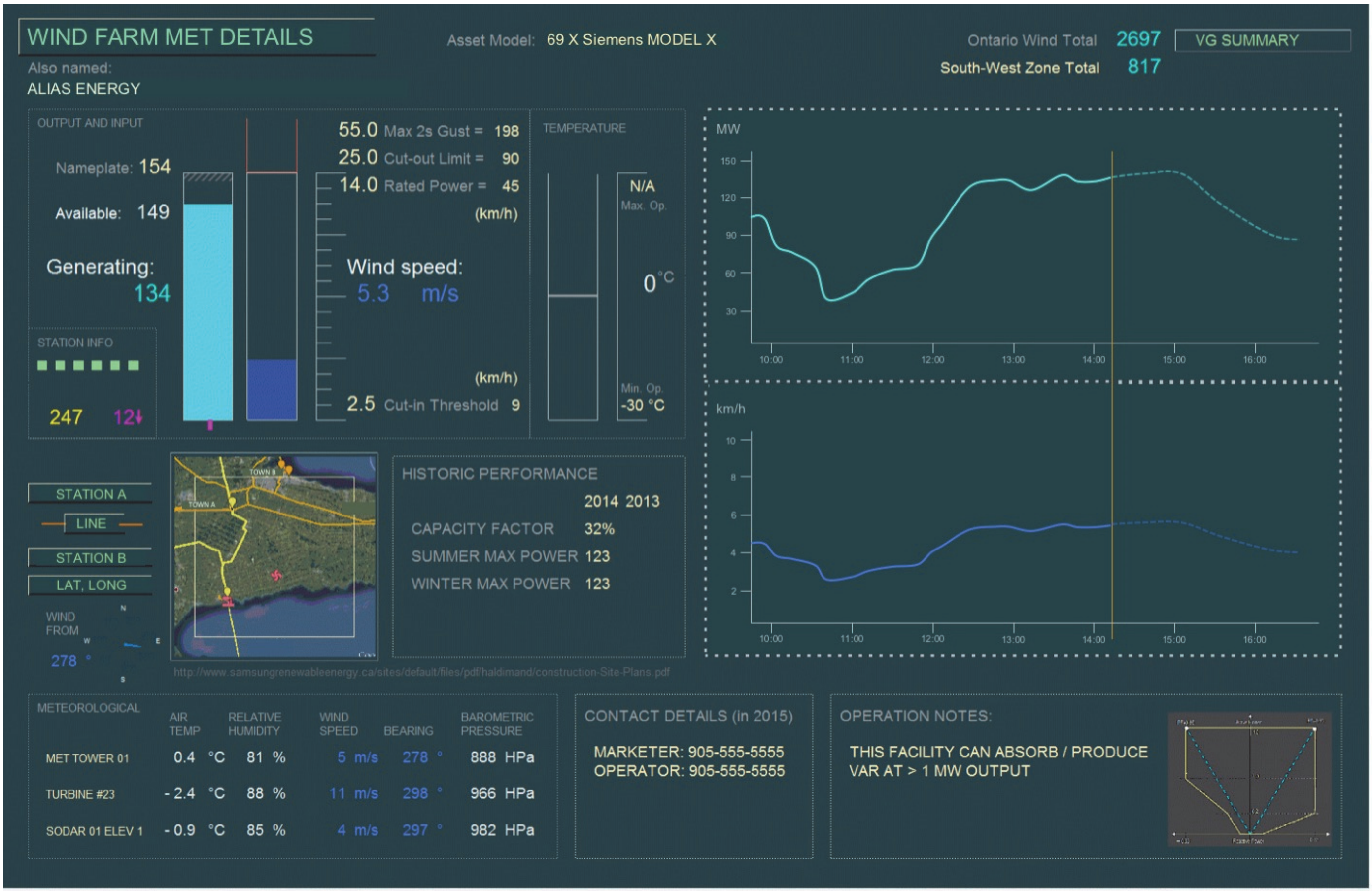
B. *Renewable Configural Form*

As shown in Fig. 1, wind speed is shown by overlapping blue and white bars plus an extra red bar. This captures the different practical meaning of wind speeds below-rated-power, in-power band, and beyond-maximum respectively.

TABLE I. Example Scenarios Illustrated in Fig. 1

Scenario	Wind Generator State				Description
	Power (MW)	*Wind (m/s)*	*Reactive (MVAR)*	*Available (MW)*	
A	0	3.5	0	125	Wind less than cut-in
B	35	10.0	+10	125	Normal ramping
C	122	13.5	+40	125	Normal near rated
D	124	16.5	+75	125	Normal in rated band
E	124	24.5	+75	125	Approaching cut-out
F	124	35.0	+75	125	Exceeding cut-out
G	0	42.0	0	125	All turbines cut-out
H	0	23.5	0	125	Wind reduced
I	25	12.5	-75	154	Strangely low output
J	111	5.0	-35	110	Impossibly high out

Fig. 2. Example wind generation station page, including output-input bar charts (top-left and Fig. 1), annotated with maximum/minimum scales. Other data included, counterclockwise from top-left: grid and geographic connections (including wind direction), raw meteorological data, notes, and power and wind trend charts. Coincidentally, wind speed at the primary measuring point was measuring low when this figure was captured, perhaps due to snow and ice accumulation.



As wind speed increases beyond rated power output, the blue bar is overlaid with a distinct and higher-contrast white (Scenario D in Fig. 1). As wind speed increases through the rated power band to near cut-out limits, the white bar eclipses the blue bar (Scenario E). Wind gusts above the turbine's continuous cut-out limit are shown beyond the barchart in bright red (Scenarios F and G).

This wind speed visual analogy clearly distinguishes three different conditions. As the risk of generator cut-out increases, the colored elements' size, contrast, and finally hue saturation increase. Each makes the graphic increasingly salient (perceptible and attention-grabbing) [5]. Finally, the emergent feature of horizontally aligned bars provides a consistency cue for whether output and input correspond (Scenarios G to J), an indicator of generator or telemetry problems (as in Fig. 2).

C. *Reactive Power Visual Framework*

To know whether a generator cut-out will affect transmission line voltages, operators must know the station's capability to supply or absorb reactive power. Reactive power supply and consumption are shown by the small magenta bar below real power output (Fig. 1). The bar is symmetric to show whether the generator is consuming reactive power (right) or supplying it (left). The reactive bar is rotated 90 degrees from the real power bar to match the graph axes used to plot generator reactive power capability curves (e.g. [7]). The capability curve of each renewable generation station is known to the ISO and could be incorporated in the station display (at bottom-right in Fig. 2).

D. *Temperature Context*

The grey bar to the right of the output-input bars (Fig. 2) indicates the operating temperature of the station relative to maximum or minimum operating temperatures (if any). Future opportunities for a more feature-rich graphing package include more clearly indicating risks to wind generators associated with near-zero (icing) temperatures.

E. *Topological and Geographical Context*

The display provides topological context [6] by showing the nearest connected breakers, transmission line and transmission stations to the generation station (at left). Geographical context, crucial to interpreting wind or solar forecasts, is illustrated by an excerpted satellite overview of the station surrounding area and geographical coordinates.

F. Historic Context and Other Data

At right of Fig. 2, trends of historic power and wind speed transition into short-term forecasts. Trend charts are vertically aligned with a shared X (time) axis to encourage comparing simultaneous changes. Raw telemetry data from redundant measuring stations is available in bottom-left when needed (e.g. to diagnose malfunctioning telemetry like the 'met tower 01' of Fig. 2). Remaining un-used display space can be used for annual average historic performance measures; contact details for the station operator and equipment owner; and finally any custom operation notes applicable to the station.

G. Navigation Links

Light green text in the meteorological display indicates clickable navigation links to the generation station display (showing circuit configuration); the adjoining transmission line and transmission stations, physical location coordinates, and system-wide renewable generation summaries.

IV. Discussion and Conclusions

This brief paper has described the layout and behavior of a wind generation station meteorology display (Fig. 2). This design improves on the existing text-only meteorology displays by contextualizing data in a compact form, freeing space for trends and dedicated notes. However, the station page serves a second purpose [8] as an annotated reference for learning to interpret the power and input bar charts shown compact and un-annotated in Fig. 1. Stripped of clutter-inducing text, these barcharts represent key generator functional states using separable power and wind charts and an emergent 'generation effectiveness' comparison. Compact barcharts could be used for jurisdiction-wide renewable generation station summary overviews.

While a wind generation facility is used as an example in this paper, the barchart and meteorology display design can apply to other types of intermittent renewable stations such as solar and run-of-river generation. We also implemented a display variant for a solar generation station (not shown). Since solar generator power output is roughly proportional to solar irradiation, the input can be depicted more simply as a single bar chart (color-coded gold to be visually distinct).

The display prototype described above was implemented in the non-production (testing) control system, using live telemetry. However, the design has not yet been deployed, in part because of the unresolved labor barrier of maintaining contextual data. Modifying the high and low barchart limits (e.g. if a generator's wind speed limits changed) would need to be done manually in a display editing tool, and repeated for each affected barchart and duplicated location (e.g. on station pages, overview screens, etc.). This would consume configuration labor, introduce the chance of misses, and risk misleading operators. Linking high and low engineering limits to dynamic barchart scale formatting is an opportunity for future extensions of the control system software. Similarly, the prototype display used static mock-ups of trend chart functionality, pending improvements in a soon-to-be-deployed software update.

This design is limited not only by the graphical capabilities of the control software used, but also because our field-study observations were only of dispatchers at one transmission control center. The information required to supervise renewable generators may vary between different ISOs, and will need to be adapted to future market policies, supply mix conditions and control technologies.

We informally sought operator feedback on the prototype renewable meteorology page design, and iterated through six prototypes. A more formal validation process would involve more operators, and use structured questions or exercises to gauge design effectiveness. Evaluation could consider speed and accuracy, and progress from basic interpretation of individual graphics to operational judgments about complex, subtly different simulated scenarios.

Despite its limitations, we propose that designing display graphics to support parallel processing and perceptible, meaningful emergent features is a straightforward opportunity to improve transmission grid monitoring performance. This opportunity can be realized within the constraints of existing reliability-focused enterprise control software. Simply reformatting existing data can contribute to grid resilience if it helps operators more reliably and rapidly diagnose faults such as inconsistent telemetry or anticipate system effects of severe weather disturbances.

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