Title	Optimization and Visualization Tools for Situational Awareness in Highly Renewable Power Systems
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Publication date	2020-10-01
Publication information	Cuffe, Paul. “Optimization and Visualization Tools for Situational Awareness in Highly Renewable Power Systems.” IEEE, 2020.
Conference details	The 6th IEEE International Energy Conference (EnergyCon 2020), Gammarth, Tunisia (held online due to coronavirus outbreak), 28 September - 1 October 2020
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/11725
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Publisher's version (DOI)	10.1109/energycon48941.2020.9236524

Optimization and Visualization Tools for Situational Awareness in Highly Renewable Power Systems

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***Abstract*—This paper proposes new tools for predicting and visualising the plausible near term shifts in branch loading that may arise due to output fluctuations from renewable generators. These tools are proposed to enhance situational awareness for control room operators, by providing early warnings of where bottlenecks may manifest in a transmission system. For predicting plausible branch loading shifts, a linear optimal power flow formulation is presented which uses a novel objective function to *characterise* the maximum loading a branch could be exposed to in the short term. This analysis therefore identifies which branches could become overloaded due to shifts in output from volatile generators. Equivalently, these branches can be seen as congestion bottlenecks which may cause curtailment of renewable generation. To allow the system operator to maintain awareness of such potentialities, these *congestable* branches are highlighted on a system diagram which is drawn to explicitly portray the electrical distance between components in the network.**

I. Introduction

It can be challenging to operate a power system under the uncertainty that attends high penetration levels of volatile renewables. For instance, fluctuations in wind or solar outputs can have worrisome and hard-to-predict effects on line loadings throughout a system [1]. To help keep control room operators informed amid such uncertainty [2], the present work proposes an online optimal power flow tool that quantifies the worst credible short-term loading shifts that may arise on each transmission branch. The results of this analysis are made tangible via a novel visualisation of a large power system, to form an integrated monitoring dashboard.

A paucity of such *situational awareness* among operators has been identified as a contributing factor to a number of significant system disturbances [3]. New solutions are required: *"Operators should therefore be provided with [...] the information that they need to understand the current state of the system and be able to project its future behavior."* [3]. Portraying flow dispositions in large networks is known to be difficult [4], and in proposing a novel flow field solution to this problem, the authors of [5] point out *"It is crucial to understand how renewable generation sources influence power flow on the existing system so we can determine critical junctions and interactions in the system."* The present work proposes novel optimization and visualisation tools to provide system operators with a overview [6] indication of where congestion issues could materialise in the short term.

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While linear optimal power flow techniques have been applied to a broad range of problems over their long history [7], [8], they have not been used to characterise the maximum active power flow a branch might be exposed to, as is proposed here. A notable precursor to the present work is [9], which used linear programming to calculate the absolute maximum load that could feasibly be met by a combined generation/transmission system. Similarly, work in [10] used optimization to characterise the envelope of available reactive power for groups of distributed generators. Machine learning tools have also been proposed to enhance forward-looking situational awareness for power system operators [11].

II. Methodology

A. Characterising plausible branch loading envelopes

A linear programme (DC-OPF) is sequentially invoked for every branch l in a system, maximising its power flow F in both directions in turn. Considering a flow from bus i to bus j, the objective function is:

$$max(F_{l,i \to j}) \tag{1}$$

This objective function seeks only to *characterise* the envelope of line loadings that could plausibly arise due to short-term generator fluctuations. The optimization here is functioning as a search technique: the generator dispatch that would cause the maximum flow in a line is not desirable in itself, but is only of interest to delineate the worst case loadings that may materialise in the short term. The decision variables are the power outputs P for each online generator g. The optimisation can only control these outputs within a *volatility range*, which defines the envelope of plausible output fluctuations for e.g the renewable generators:

$$P_v^- \leq P_g \leq P_v^+ \tag{2}$$

A power balance is enforced at every bus, where the vector $P_{d,b}$ describes the power demands and $P_{g,b}$ identifies the generation at bus b. The nodal balance also includes the vector of branch power flow variables, F_l, and the system's incidence matrix, $A_{(l \times b)}$:

$$P_{net,b} = P_{g,b} + P_{d,b} = {F_l}^T A_{(l \times b)} \tag{3}$$

To account for the volatility that can also manifest in system loading, nodal demands are also controlled in a uniform way relative to their parametrised spot maxima, $P_{s,b}$:

$$P_{d,b} = L.P_{s,b} \tag{4}$$

The uniform scalar loading level L is also bound between some volatility limits:

$$L^- \leq L \leq L^+ \quad (5)$$

For a branch connecting bus i to bus j, with reactance X_l, the power flow is determined by the voltage angle, ϕ, difference that prevails.

$$F_{l,i\rightarrow j} = \frac{\phi_i - \phi_j}{X_l} \quad (6)$$

B. Network visualisation

The present work seeks to use the results of the above optimization/characterisation methodology to give control room operators a tangible sense for where congestion may manifest in the system. To this end, a network diagram based on the technique in [12] is used. This technique uses a measure of electrical distance to position nodes in the diagram, to better show [13] the electrical structure of a system rather than its (pseudo)geographic disposition (cf [14]). These diagrams also tend to concentrically separate out the different voltage levels in the system, which may better portray the effect of potential congestion in these sub-networks [15]. Categorical colour encodings from [16] are used to further emphasise the distinction between the different operating voltage levels (transformers are depicted as operating midway between their primary and secondary voltages)

III. Test Platform

The methodology was applied to the large `case2383wp` system [17]. Those generators connecting at less than 150 kV with capacity less than 200 MW were deemed to be wind farms, with potentially volatile outputs. The system was dispatched with these wind generators at 75% output to give a 17.75% overall wind penetration level. The volatility range for these wind generators was set at $\pm 25\%$ of their capacity, so each wind generator's output could vary between $P_v^- = P_g - (0.25 \times P_{rated})$ and $P_v^+ = P_g + (0.25 \times P_{rated})$. The output of the other generators in the system could not be controlled by the optimization, aside from the slack generator. Uniform demand loading levels were bound between $L^- = 0.85$ and $L^+ = 1.15$.

The optimization was implemented using YALMIP [18] with MATPOWER [17]. The raw data and scripts underpinning this research are available at [19].

IV. Results

The optimization technique was applied to the `case2383wp` system. This system contains 2896 branches, and as each flow direction must be considered in turn, this required 5792 invocations of the optimization solver.

A. Plausible branch loading envelopes

The range of loading levels that could arise for each branch is shown in Fig. 1. In this diagram, each thin vertical coloured line corresponds to a particular branch, with its lower extent showing the minimum plausible flow, and its upper the maximum. The raw MW flows found by equation (1) have been normalised here by the thermal capacity of the branch. The branches are coloured and grouped by operating voltage, and secondarily ordered by their currently prevailing power loading, as shown by the dark central trace. Those branches whose loadability extends beyond the $\pm 100\%$ envelope are plotted in red ■ to denote their at-risk status. This boxplot display is proposed to give a high-level indicator of how many, and which, branches in the system could cause congestion problem in the short-term. In an interactive control room dashboard context, hovering ones cursor over particular lines on the boxplot could highlight them on the linked system diagram, and vice versa.

Inspection of Fig. 1 reveals that most of the congestion problem are likely to arise in the lower voltage system, shown in blue ■. There are also some congestable branches amidst the transformers operating at 165 kV, shown in green ■, but only a small number evident at the voltage levels above this. This suggests that short-term fluctuations in outputs from volatile generation are more likely to cause localised congestion at the grid's periphery, rather than in its high voltage core.

The middle of the blue ■ section of Fig. 1 also reveals a number of branches that cannot achieve a nonzero loading under any volatility conditions: these are perhaps radial lines to offline generators or loads.

B. Overview system diagram

The same branch maximum loading information as in Fig. 1 is also shown as a large system diagram in Fig. 2. Here, the congestible branches are denoted with a red arrow → which shows the problematic flow directionality (note that it is theoretically possible for a branch to be congestable in both directions, however as fig 1 shows this does not arise on this system for the dispatch under consideration) This electrically meaningful system diagram allows the local groupings of at-risk branches to be determined visually.

For instance, a group of congestable branches can be seen at label **A** in Fig. 2. This 'flowgate' arises as power is being served out of the 400 kV network ■ through transformers into the 220 kV ■ and sub-transmission networks ■. A similar grouping of congestion-causing branches can been seen at label **B**. The *coherence* [20] of branch overloading at **A** and **B** is immediately notable: these adjacent branches all overload in the same power flow direction, *outward* from the system's core (as is likewise the case for most of the congestion arrows in Fig. 2). As this diagram exhibits a mostly concentric nesting of the distinct voltage levels, with the highest in the centre, it naturally facilitates such inferences to be drawn.

While **A** and **B.** are congestion flowgates containing many branches, there are various other examples of more localised problems: for instance, **C** shows a transformer overloading issue. Sequential 'corridors' can also be identified in the

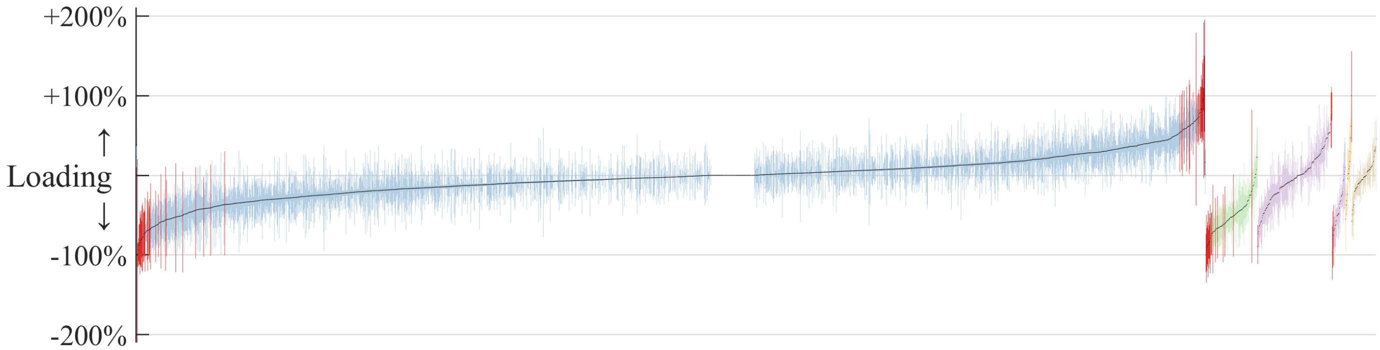

Fig. 1. An example control room dashboard facility showing a boxplot of the loadability envelopes for each branch in the `case2383wp` network. Colours are used to denote operating voltage level, and congestable branches are marked in red

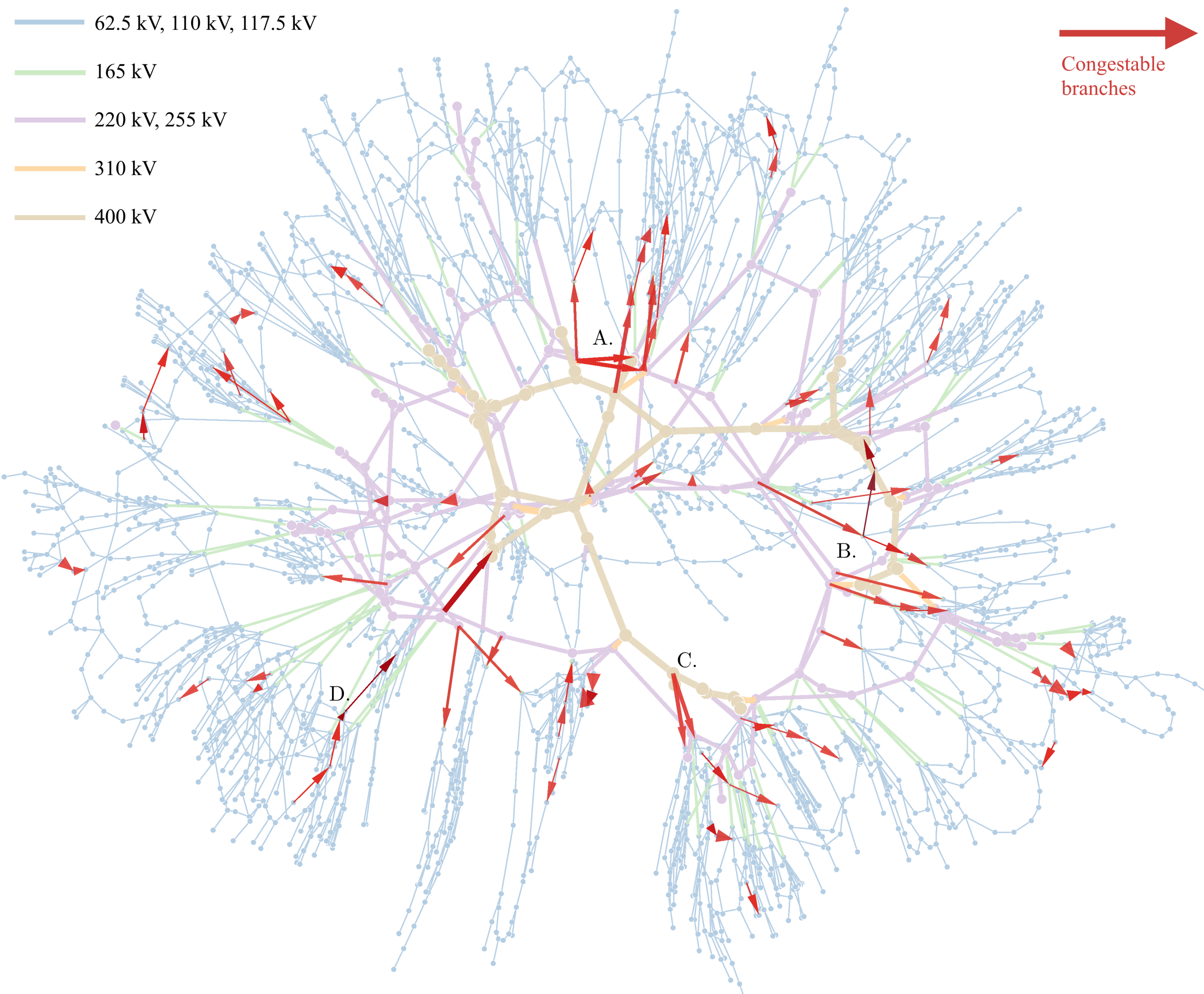

Fig. 2. An example control room display showing potential forthcoming congestion in the `case2383wp` network

diagram: **D** is an interesting case as it portrays overloading associated with transmitting power *towards* the higher voltage levels.

V. Conclusions

This work has proposed a novel objective function to use with linear optimal power flow techniques. This objective function provides a characterisation of the worst-case line loadings a branch could be exposed to due to near term fluctuations in the outputs of renewable generators. By showing these congestable branches on an electrically meaningful diagram of a large system, it is possible to rapidly identify groups of lines that are, collectively, prone to becoming congested, or, equivalently, may necessitate curtailment of renewable generators. This novel combination of the forward-looking optimization and network visualization is proposed to enhance situational awareness for control room operators.

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