An Educational Open-Source Market Modeling Toolbox for Future Grid Studies

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***Abstract*—The paper presents an educational open-source Matlab and CPLEX-based market modeling toolbox for future grid studies. The market model is based on a unit commitment problem and is suitable for power system analysis involving renewable energy sources and energy storage.**

The toolbox includes a simple graphical user interface as well as a suite of input data and case studies that can be simulated without requiring additional files. The software is written in Matlab, with CPLEX as a backend solver. The source code is provided for ease of understanding and modification, which makes the tool suitable for research. Six different case studies are presented to demonstrate the capabilities of the toolbox, using wind, solar, and demand traces published by the Australian Energy Market Operator.

***Index Terms*—Electricity market simulation tool, future grids, optimization, unit commitment, renewable energy sources, energy storage, power engineering education.**

I. Introduction

The increasing uptake of variable renewable energy sources (RES) and the emergence of cost-effective demand-side technologies, like rooftop photovoltaic (PV) and battery storage, is driving the transformation of conventional power systems dominated by fossil fuel generation and passive demand into future grids. The uncertainty that comes with that requires a major departure from conventional power system planning. Instead of focusing only on a handful of the critical scenarios, future grid studies use scenario analysis to account for possible evolution pathways [1]–[4]. Existing future grid studies [5]–[8] have so far mostly focused on balancing, where simplified market dispatch and transmission network models (copper plate or network flow) suffice. Future grid studies—like the Future Grid Research Program funded by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO)—that also involve stability assessment, require a more detailed network representation and a market dispatch model that explicitly considers inter-temporal coupling.

Against this backdrop, this paper presents an open-source[1] Matlab and CPLEX-based market modeling tool for future grid studies based on a conventional unit commitment (UC) model. The modeling framework is market structure agnostic and is capable of easy integration of various types and penetrations of RES and storage technologies. The toolbox runs in Matlab and uses the IBM ILOG CPLEX Optimization Studio as the backend solver. Higher educational institutions commonly have Matlab educational licenses available for academic staff and students, and CPLEX provides a free educational license for academics and students, making the tool easily accessible to academia.

The toolbox doesn't require an in-depth understanding of the underlying optimization principles. It comes with an intuitive graphical user interface (GUI) and a number of case studies, along with wind, solar and demand traces provided by Australian Energy Market Operator (AEMO) [9], which sets it apart from Minpower [10], the only other open-source UC model (to the best of the authors' knowledge). The toolbox is not optimized for computational performance, so its primary use is educational. A computationally efficient market model with a planned future open-source release is proposed in [11]. The future release uses AMPL to formulate the UC problem rather than Matlab and has been used to study stability [12], [13], energy storage [14] and demand response [15]. As the UC toolbox presented in this paper is implemented in Matlab, it provides the advantage that the user can clearly see the matrix structure of the problem, making this toolbox suitable for educational purposes.

The rest of the paper is structured as follows. Section II describes the toolbox features. In Section III the UC formulation used in the model is outlined. Section IV gives the case studies, and Section V concludes.

II. Market Modeling Tool Features

A. Graphical User Interface

The toolbox has a simple GUI that allows users to perform complex data processing and mathematical analysis without requiring in-depth knowledge of the underlying algorithms. The GUI provides the option of selecting one of the in-built case studies or defining a new simulation.

A simulation is defined through the GUI by specifying the name of the Excel workbook containing the network representation, the simulation horizon, details about modifying demand traces to account for residential PV, the load flow model, and the minimum quantity of spinning reserve required. The GUI includes functionality to plot simulation results as aggregated generation over the simulation interval. A simulation is run by

[1] available at: https://github.com/AaronRamsden/UCMatlabToolbox

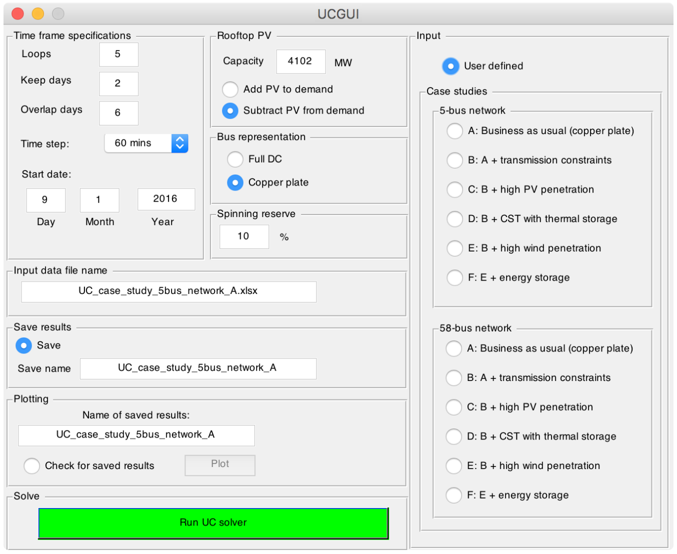

Fig. 1. The graphical user interface.

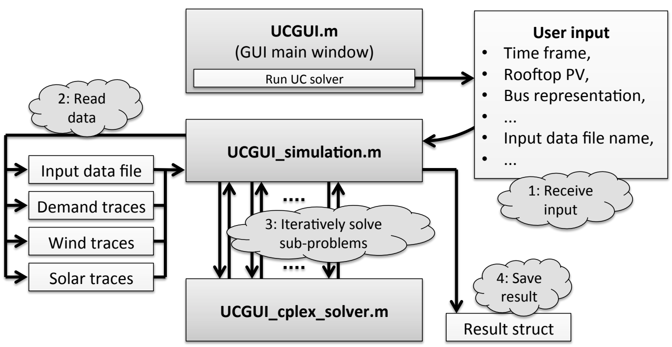

Fig. 2. The toolbox flow chart.

entering `UCGUI` in the Matlab command window, which opens the GUI in Fig. 1. Fig. 2 shows the computation stages of a UC simulation, starting with the GUI.

B. Generation Technologies

The toolbox can model the following technologies: coal, combined cycle and open cycle gas, concentrated solar thermal (CST) with thermal energy storage (TES), wind, solar PV, and generic energy storage (GES). Distributed residential PV is modeled at load centers and does not contribute to transmission network power flows. The toolbox GUI includes the option to modify demand traces to account for distributed residential PV. Additional generation technologies can be included in the model by modifying the source code to implement the specific behavioral characteristics of the new technology.

C. Case Studies

A number of case studies are provided with the toolbox, including a simple 5-bus network based on [16, Example 12.8] and a 58-bus model of the National Electricity Market (NEM) in Australia based on [17], both of which can be easily augmented by the user. The input data used for these case studies, including demand, wind, and solar traces, is based on publicly available data published by AEMO [9]. The case studies are used to demonstrate the capabilities of the toolbox as well as to highlight some potential applications, as discussed in Section IV.

D. User Manual

A user manual is provided with the toolbox, which includes installation instructions, a guide to using the toolbox to perform simulations, a description of the input data, and the required format of the Excel workbook containing the network representation. The user manual also includes a detailed description of the mathematical optimization model including constraint equations in shorthand notation and in standard mixed integer linear programming (MILP) matrix notation.

III. Mathematical Model and Algorithms

The toolbox formulates the input data into a UC problem, modeled as an MILP problem to minimize an objective function, subject to system constraints, network constraints, and generation constraints (including intermittent renewable generators, CST generators with TES, and GES). Due do space limitations, we only provide a high-level description of the proposed UC formulation. The full model is given in the user manual.

A. Objective

The objective of the model is to minimize total generation costs, including maintenance, startup, shutdown and fuel costs, which are assumed constant for computational simplicity. Each generator is modeled as offering energy at the short-run marginal cost of production (SRMC), which is assumed constant. The generators in the case studies represent the registered generators in the NEM [18].

B. Constraints

The optimization problem is subject to the following constraints.

1) System Constraints: link dispatch decisions of different generation plants, including power balance constraints and spinning reserve requirements.

2) Network Constraints: include dc power flow constraints and thermal line limits. A dc load flow model is used for computational simplicity. Active power transfer limits are imposed on each bus connection (transmission line or transformer) as a maximum voltage angle difference between the voltage angles at the two buses. These limits are ignored when a copper plate model is specified.

3) Generation Unit Constraints: include physical limits of individual generation units. They include maximum and minimum stable limits for conventional fossil fuel generation, maximum generation limits for RES—limited by the availability of the corresponding renewable resource (wind or sun), on/off restrictions, number of online units, ramp rates, and minimum up and down times. The formulation requires three binary variables per time slot (on/off status, startup, shutdown) to model an individual unit.

4) Energy Storage Unit Constraints: include TES and GES constraints. These constraints enforce energy storage behavior, maximum and minimum charge rates, and charging ramp rates. A charging and generating mutually exclusive enforcement is applied to GES units. One binary variable per time slot is introduced per individual unit to represent the charging status.

C. Rolling Horizon

To ensure computational efficiency, the UC problem is divided into sub-problems that are solved using a rolling horizon technique. This allows a solution of year-long horizons on a home computer. When combining sub-problems, a portion of each solution is discarded to ensure that there is an overlap between consecutive sub-problems. Initial conditions are set for each consecutive sub-problem based on the state of the previous sub-problem. This method of overlapping sub-problems is used to ensure that solutions to each sub-problem are found that do not provide an infeasible scenario for the following sub-problem, if a feasible scenario exists.

IV. Case Studies

The toolbox provides a generic modeling platform that can be used to model any power system. Six case studies are provided with the source code to illustrate some of the capabilities of the toolbox, and provide an example of the required formatting and layout of the input data. The case study input files can easily be modified or used as a reference when modeling a new case.

The case studies are presented in this paper using the 5-bus network in Fig. 3 to clearly illustrate interdependencies of the system. This 5-bus network is based on an educational example by Glover et al. [16, Example 12.8]. Demand from regions of the NEM are used so that the network model represents a modified NEM with interconnections from Queensland to South Australia and New South Wales to South Australia.

The case studies are examined over the 10-day interval of January 9–18, 2016. For the hourly demand traces used in these studies, the maximum demand for the year of July 2015 to June 2016 is 30 601 MW, which occurs on Monday, January 11 from 3–4 p.m.

The toolbox includes a full set of input files where each of the six case studies is extended to a more complex 58-bus model. The 58-bus transmission network model is a simplified representation of the NEM and is based on a 14-generator test system originally developed for small-signal stability studies [17]. The user manual provided with the toolbox includes explanations and results for the case studies applied to the 58-bus network.

A. Business As Usual with Copper Plate Model

The "business as usual" scenario includes coal and gas generators only. This case study assumes a copper plate model, which ignores bus interconnections and transmission network power limits. The results show that the coal generator serves full demand, or is dispatched at maximum capacity of 20 000 MW when demand exceeds 20 000 MW. Gas generation is used to supply daily peaks in demand that exceed the coal generator's capacity. Gas is also dispatched due to the spinning reserve requirement, where demand approaches the maximum capacity of the coal generator.

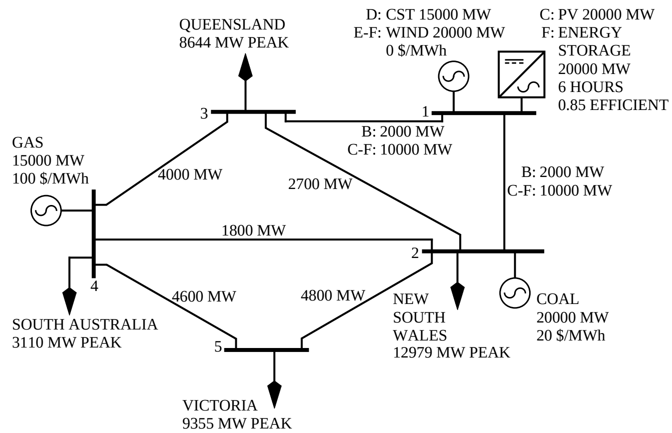

Fig. 3. 5-bus network used for case studies.

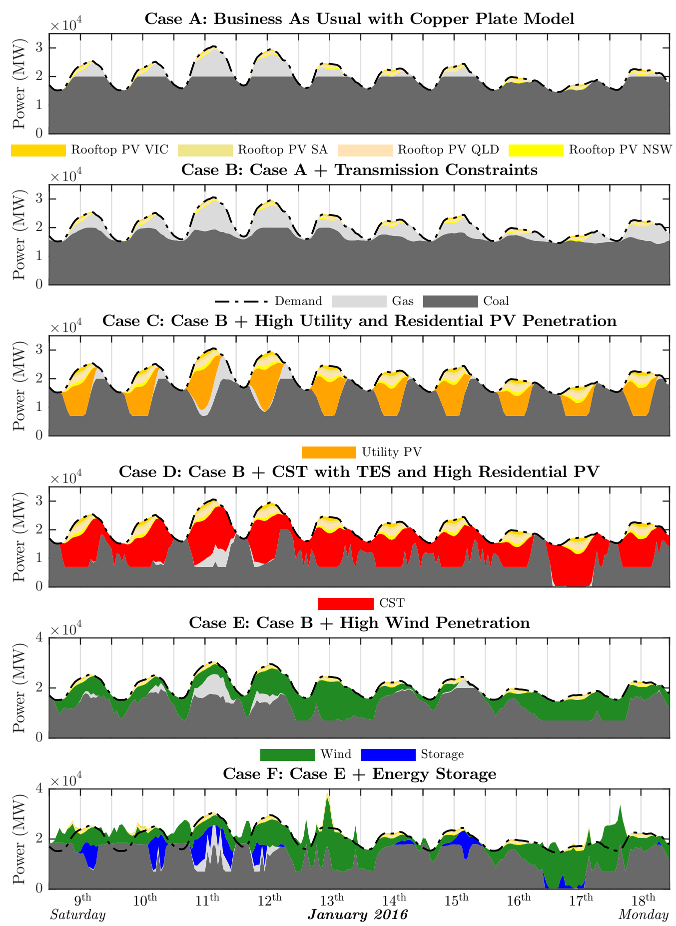

Fig. 4. Case studies A–F results.

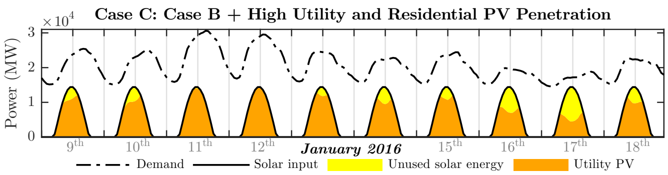

Fig. 5. Case C results.

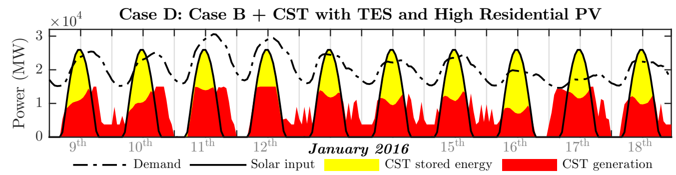

Fig. 6. Case D results.

B. *Business As Usual with Transmission Constraints*

This case study examines the "business as usual" fossil fuel scenario with transmission constraints imposed on all lines between buses. A conventional dc load flow model is used to represent the network.

In the unconstrained example in Case A, the coal-fired generator is always fully dispatched at peak times. In Case B, the power flow from Bus 2 to Bus 3 is limited to $4700\,\mathrm{MW}$ through Line 2–3, as well as the parallel path through Line 1–2 and Line 1–3. This constrained connection limits the ability of the coal power station to serve the network demand in Queensland, which cycles between a minimum of $4769\,\mathrm{MW}$ and a maximum of $8448\,\mathrm{MW}$. Line 2–5 is congested on January 11 when the network demand in Victoria exceeds $6000\,\mathrm{MW}$, further limiting the ability of the coal generator to serve remote loads. The effect of network constraints is seen in the energy delivered from the coal generator, which has a 10-day capacity factor reduction from 92% in Case A to 84% in Case B. The gap in energy is filled by the gas generator, as observed in Fig. 4, Case B.

C. *High Penetration of Solar Photovoltaic*

This case study demonstrates the effect of increasing solar PV in a traditional fossil fuel grid. Case B is modified to include a $20\,000\,\mathrm{MW}$ utility PV generator at Bus 1. Distributed residential PV, which is modeled as negative demand, is increased to $12\,000\,\mathrm{MW}$ from $4102\,\mathrm{MW}$ in Case B.

The reduction of demand during daylight hours, coupled with the availability of comparatively low-cost generation from the utility PV generator results in the coal generator following a more exaggerated daily cyclic output pattern than Case B. The coal generator reaches its minimum stable output of $7000\,\mathrm{MW}$ on seven days out of the 10-day interval. The spinning reserve constraint results in the coal generator remaining online while the utility PV does not dispatch available input energy for eight of the ten days. A maximum of $6284\,\mathrm{MW}$ of available solar power not used on January 17, 2016, as seen in Fig. 5. Gas is dispatched on each day from around 4 p.m. as the available solar power reduces to zero, as seen in Fig. 4, Case C. This is due to a combination of transmission constraints, the spinning reserve requirement, and total demand exceeding the maximum capacity of coal.

D. *High Penetration of Concentrated Solar Thermal with Thermal Energy Storage*

This case study explores the dispatchable renewable technology of CST with TES. Case B is modified to include a $15\,000\,\mathrm{MW}$ CST generator at Bus 1, with six hours' energy storage at rated generation capacity. Residential PV capacity is $12\,000\,\mathrm{MW}$ as per Case C.

The CST plant modeled in this study is a central receiver power tower surrounded by a field of heliostats that focus the solar energy onto the tower to heat molten salt. The molten salt provides TES, and is used to drive a conventional synchronous steam turbine generator that is able to provide spinning reserve to the grid. Fig. 4, Case D, shows that the coal generator is operated at its minimum stable output for a greater proportion of the time compared to Case C. The ramping behavior of the coal generator is somewhat improved compared to Case C, however, the coal generator has intermittent ramping behavior at nights and is taken offline on January 17 as the dispatchable CST generator is able to provide a majority of the total demand with minimal support from the gas generator.

The same solar input trace is used at Bus 1 for Case C and Case D, however, the field of heliostats increase the available solar input power above the rated capacity of the CST plant by a factor of 2.3 in this example, resulting in the CST plant receiving a greater energy input compared to the utility PV generator in Case C. Nonetheless, the results in Fig. 6 show that the CST plant shifts the available solar input energy to be dispatched later in the day, compared to the $20\,000\,\mathrm{MW}$ utility PV plant in Case C that is forced to waste energy when the coal generator at Bus 2 reaches its minimum stable output limit of $7000\,\mathrm{MW}$. Fig. 6 demonstrates the relationship between available input energy and CST generation, detailing the shift in available solar energy to be dispatched at different times during the day.

E. *High Penetration of Intermittent Wind Generation*

This case study demonstrates the effect of increasing intermittent wind generation in a traditional fossil fuel grid. Case B is modified to include $20\,000\,\mathrm{MW}$ of wind generation at Bus 1.

Upon increasing intermittent wind generation capacity, gas generation follows less regular patterns of dispatch, and is used to serve peaking loads at times of low wind generation. The system relies on traditional fossil fuel generation on January 11—the day of peak demand—as the available wind power is comparatively low during this period. Wind generation reaches a maximum of $6614\,\mathrm{MW}$ during the peak period of January 11 where the network demand exceeds $20\,000\,\mathrm{MW}$. Coal generation output cycles over greater limits compared to Case B, reaching both its maximum and minimum operating limits, as low-cost intermittent wind generation is dispatched with a

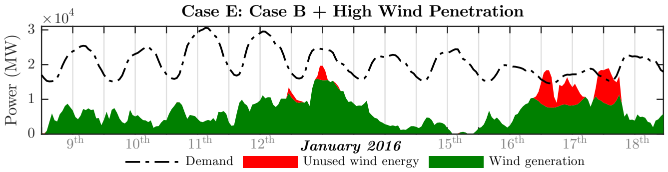

Fig. 7. Case E results.

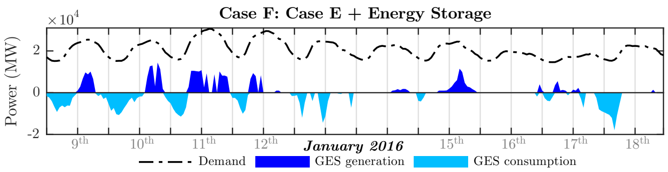

Fig. 8. Case F results.

higher priority than coal. Wind generation is capped during a period of over 24 hours over January 17–18, as shown in Fig. 7, while the coal generator operates at its minimum capacity of 7000 MW, providing spinning reserve to the grid.

F. Energy Storage with High Penetration of Intermittent Wind Generation

This case study examines the effect of including large-scale energy storage near intermittent wind generation. Case E is modified to include a GES plant at Bus 1, which in this case represents a battery storage plant that does not provide spinning reserve to the grid. The energy storage plant has 20 000 MW generation capacity with 120 000 MW h of energy storage capacity, equivalent to six hours' generation at rated capacity.

Results show that the GES plant dispatches at times when gas generation would otherwise be dispatched. Coal and wind generation are utilized for the energy storage plant charging at times of lower network demand on January 9–11 and 17–18, with occasional spikes of the GES plant charging at other times, refer to Fig. 4, Case F. The coal generator is taken offline on January 17 as there is sufficient energy available from wind generation with minimal support from the GES plant. The gas generator remains online at its minimum output of 300 MW to provide the required spinning reserve while the coal generator is offline. The total unused wind energy available to the wind generator over the 10-day simulation interval is 2008 MW h, compared to 198 620 MW h for Case E.

V. Conclusion

This paper describes an educational market modeling toolbox, specifically aimed at future grid studies. It is based on a conventional UC model, typically used in power system operation and planning. The model has assumed startup, shutdown, and production costs are constant for computational simplicity. The UC formulation includes a dc network model, which makes the tool suitable for future grid studies with load flow patterns that are significantly different from those of today.

The toolbox comes with a set of case studies, including a simplified model of the Australian NEM, utilizing wind, solar, and demand traces used by AEMO in their planning studies. This allows the user to generate realistic simulation results without the need for tedious preparation of input data. The toolbox is open-source, so it can be modified to suit other purposes, for example operational market studies.

The tool is primarily intended for educational purposes. It's based in Matlab, a de-facto academic standard for engineering computation, which allows for a steep learning curve. The tool doesn't require an in-depth understanding of the underlying optimization mathematics, so it can be used in courses where optimization is not explicitly taught. For example, this tool has been successfully used in final-year honors projects in Power Engineering at The University of Sydney, without prior formal exposure to applied optimization.

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