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FACTS devices and energy storage in unit commitment

Zora Luburić*, Hrvoje Pandžić

Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia

A R T I C L E I N F O

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A B S T R A C T

Both Flexible AC Transmission System (FACTS) devices and energy storage may provide benefits to the power system, e.g. reduced transmission losses, improved system stability, voltage regulation and reduced congestion. As a result, FACTS devices can diminish the value of the installed energy storage and vice versa. In order to assess their impact on each other, this paper formulates a unit commitment model that includes generic energy storage and FACTS devices in order to investigate characteristics of their joint operation assess how they cancel out each other's benefits. The results of four unit commitment models are presented: (i) with no storage or FACTS devices (base case); (ii) with FACTS devices only; (iii) with energy storage only; (iv) with both FACTS devices and energy storage. An analysis of the benefits of both technologies is performed and economic assessment is presented. The simulations are performed on IEEE RTS96 system using CPLEX 12 under GAMS.

1. Introduction

Intermittent power produced by renewable energy sources, especially wind, has introduced many challenges to Transmission System Operators, whose mission is to ensure reliability and stability of the transmission power system. This is a consequence of the reduced controllability, only partial generation predictability and locational dependence of the connected renewable sources [1]. Many countries have introduced measures to improve integration of renewable sources, e.g. feed-in-tariff incentives [2]. However, possible wind curtailment can drastically reduce savings in power system operating costs and reducing greenhouse gas emissions. Therefore, power network needs to be upgraded and new control methods should be included in operating procedures in order to maximize the utilization of renewable power. These include utilization of energy storage units and Flexible AC Transmission System (FACTS) devices, upgrading transmission lines, load management, sufficient provision of ancillary services and others. Power transmission lines are usually congested in areas with high capacity of installed renewable sources, which causes congestion and decreases transmission system adequacy [3]. Besides upgrading the existing or building new transmission lines, this problem can be tackled by using FACTS devices and energy storage. Both FACTS and energy storage can control power system flows in order to optimize the system operating costs. There are three categories of FACTS devices distinguishable by their connection to the grid: (i) series controllers, (ii) shunt controllers and (iii) combined series-shunt controllers. Each category contains several specific technical solutions. This paper is based on series controllers, i.e. Thyristor-Controlled Series Capacitor (TCSC), whose purpose is to modify the reactance of a power line to which it is connected [4]. TCSC consists of controlled reactors in parallel with sections of a capacitor bank, which enables a smooth control of the capacitive reactance. As a result, TCSCs contribute to a better utilization of the existing lines, resulting in increased transmission power capacity due to redistributed power flows from congested lines to non-congested parallel lines in the same direction. Energy storage affects power flows by consuming power at certain time periods and injecting it back into the grid later on. This reduces congestion, and consequently the curtailed wind generation.

1.1. Literature review

1.1.1. Unit commitment

Unit commitment is a well-researched problem in the research community. This is a short-term problem, usually consisted of 24 consecutive hours, comprising one day, whose goal is to determine optimal on/off status and dispatch of thermal generating units in order to minimize operating costs. Unit commitment formulations are constantly being improved. For instance, in [5] the authors propose more accurate thermal units start up and shut down trajectories. Another unit commitment model, which captures variability of wind generation at the sub-hourly level and considers uncertainty of renewable generation via stochastic scenarios, is proposed in [6]. Study on the feasibility of energy delivery in case of a large-scale wind integration is examined in [7]. The numerical results indicate that including a continuous piece-

* Corresponding author.
E-mail addresses: zora.luburic@fer.hr (Z. Luburić), hrvoje.pandzic@fer.hr (H. Pandžić).

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wise sub-hourly linear formulation of power generation would enable effectively meeting the energy delivery requirement. Impact of wind power forecasting uncertainty on unit commitment problem is examined in [8]. This uncertainty is represented by wind scenarios that include cross-temporal dependency. The authors conclude that this type of representation of uncertainty has advantages over traditional deterministic unit commitment approach. Value of forecasting is also investigated in [9], where the authors present an adaptive unit commitment formulation based on rolling horizon approach. A unit commitment model that considers different sources of grid uncertainty, i.e. uncertainty related to the output of renewable generation, load uncertainty, generator contingencies and line outages, is formulated in [10]. This security constrained unit commitment model uses a heuristic genetic algorithm to obtain the optimal commitment schedule. The results indicate that power systems are more prone to contingencies at peak load hours and that the stochastic scheduling model is more robust than deterministic ones.

1.1.2. Energy storage

Energy storage can be operated by a regulated entity, i.e. System Operator, or by an independent owner. As shown in [11], energy storage is operated differently in case of a vertically integrated utility as opposed to an investor-owned energy storage. This is because the investor operates its storage to maximize its profit, while in vertically integrated utility the main goal is to minimize overall operating costs. In [12], a novel model of storage capacity auction is proposed which presents an efficient utilization of priced storage capacity rights, such as power capacity and energy capacity rights, for both competitively priced and unpriced services. In fact, it is shown that a storage owner receives the same revenue through the auction as it could collect through market bids. Operation of energy storage can be divided into few categories, e.g. energy arbitrage, reserve provision, and cooptimization with renewable plants, such as wind farms and photovoltaics, to ensure better position of renewables in the market. The authors in [13] analyse how the operation of strategic energy storage affects conventional generators in the day-ahead electricity market. They show that the energy storage profits are directly related to the electricity price volatility and that they are very low in case of relatively constant market prices throughout the day. A model that includes stochasticity of market prices is shown in [14]. Stochastic model, where an investor-owned independently-operated energy storage offers energy and reserves in the day-ahead market, is proposed in [15]. The authors use many wind generation scenarios to obtain profitability of energy storage. Similarly, the authors in [16] model energy storage in a single-stage transmission expansion planning model in which the line losses are linearized by segments. Their results show that investment in energy storage contributes to a decrease in power system operating costs and improves flexibility of the power system operation. Many papers propose a coordinated operation of renewable plants and energy storage, since energy storage can reduce the negative effects of poor predictability and intermittency of renewable plants. In [17], an energy storage unit is modelled to compensate for forecast errors in wind farm production as determined by the market transactions. The authors showed that large energy storage units contribute in complying delivery requirements in production of wind farms, and from economical point of view, ensure that their operation is more profitable. The authors in [18] formulate a problem for optimal production strategy for joint wind farm and pumped storage hydro unit. The approach is based on energy arbitrage and maximum utilization of wind energy. A thorough review of energy storage technologies for alleviating variability of renewable energy sources is available at [19]. A study on grid-scale energy storage is as an option to reduce wind curtailment in transmission network is presented in [20]. The results indicate that wind spillage can be reduced with energy storage costs as high as \$780/kW and ten hours of storage capacity. Generally, batteries with higher power ratings result in less overall wind curtailment in the system. The sensitivity analysis showed the most sensitive parameters are wind subsidies, cost of transmission expansion, battery degradation and battery life cycle. A heuristic algorithm that solves a unit commitment problem that includes renewable generation and pumped-hydro energy storage is presented in [21]. The results of this paper indicate that higher forecast error of renewable generation increases operating cost of thermal units, which can be effectively counterbalanced with pumped-hydro storage plants. Interval unit commitment formulation that includes pumped-hydro storage units and their hydraulic constraints is proposed in [22]. The authors demonstrate that cost-effective regulating capabilities of the pumped-hydro storage units result in large savings in overall system operating costs. Mathematical formulations of energy storage investment models are much more complex than those of operating models. Minimization of investment costs for new technologies of generators, transmission lines and energy storages is proposed in [23]. This model is tested on the power system of Great Britain and the authors report that energy storage can contribute to the island power system by providing ancillary services, enabling balancing energy in real time, as well as reducing transmission investment in new lines. Modelling of siting and sizing of energy storage is provided in [24,25]. The former is focused on technical and economic aspects of the energy storage investment problem. The objective function of the proposed model minimizes the sum of the generation costs and the investment costs in energy storage reduced on a daily scale. The outcome of the model are optimal locations and capacities of distributed energy storage. Paper [25] formulates a linear programming model, which the authors use to show how the proper sizing of energy storage units can have an important role in providing flexibility in transmission grids. However, they also point out that siting has a minor role in the optimal operation of the power system.

1.1.3. FACTS devices

FACTS devices are commonly used in operations that require both rapid dynamic response and frequent variations in output. The most important role of FACTS devices is to increase utilization of transmission lines. In other words, they are used in areas where bottlenecks and less utilized power lines appear simultaneously. In this paper, the modelling of line's reactance is similar to the model proposed in [26], where the transmission grid is modelled with variable line impedance determined by the operation of FACTS devices. A characteristic of the model presented in [26] is that the same sign of the voltage angle difference in lines equipped with FACTS devices is imposed. The model finds the optimal number of FACTS devices in a power system, which results in maximum cost savings. The authors in [27] contribute with reformulating a non-linear problem into a MILP and optimize the operation of FACTS devices to improve the deliverability of reserves to ensure the day-ahead corrective operation. This approach minimizes the out-of-market corrections, such as re-dispatching units different from deliverable market plan and committing more costly power plants. Another method for converting a non-linear problem into a MILP is proposed in [28]. This method is based on Big M reformulation and applied to the economic dispatch problem. The results of the case study indicate that utilization of FACTS devices improves economics of power system operation. Moreover, in case of low power line capacities, altered line admittances, provided by FACTS devices, can find feasible solution when no such solution exists for fixed line admittances. Operations of both FACTS devices and wind farms are investigated in [29] to minimize wind curtailment. Model has two stages: market stage, which consists of the day-ahead and balancing market, and operational stage, which considers wind scenarios. The authors highlight the possibility of changing the TCSC reactance for each wind scenario to find the optimal solution. In [30], a split TSCS is used to fine tune power flows in order to increase the transmission line capacity. The fine tuning of the lice reactance is performed using the Newton Raphson power flow analysis method in order to compensate for small changes in power demand. Analysis of the impact of TCSC on the available transfer capacity in transmission system with wind and hydro generation is performed in [31]. The authors conclude that wind generation brings more variability to the available transfer capacity and that installation of TCSC generally improves available transfer capacity, especially since it removes the downward peaks upon sudden lack of wind generation. A model for optimal allocation of TCSC and unified power flow controllers is proposed in [32]. The optimization model is based on step-by-step variation of control parameters of these devices. The impact of these devices on LMPs and system voltage is investigated. The case study demonstrates the effectiveness of the proposed TCSC and unified power flow controller placement strategy. Few types of FACTS devices are modelled in the redispatching problem to enhance system security in [33], which uses AC power flow representation. The authors indicate a reduction in redispatching procedures in presence of an appropriate FACTS device. In addition, they show an increase in system stability and security if FACTS devices are installed. Using FACTS devices to improve available transfer capability of interconnecting lines in [34] results in up to 18% improvement in total transfer capability. The optimal multiplier Newton–Raphson method is used to maximize the power flows in the IEEE 118-bus system in [35]. Available Transfer Capacity enhancement of interconnectors was achieved, as well as improved transmission services in market-based power systems by modelling several FACTS devices, such as series, shunt and unified controllers. An investment model of FACTS devices is proposed in [36] by a generic algorithm. It consists of three investment parameters: location, type and value of the FACTS device. The authors model four types of FACTS devices for steady-state analysis of the IEEE 118-bus system and show increase in loadability of the power system. The most efficient solution is achieved by simultaneous use of several kinds of FACTS devices. Furthermore, results show that after a certain number of FACTS devices, the loadability of the system cannot be improved.

1.2. Contributions

With respect to the literature review above, the contributions of the paper are:

- Formulation of a unit commitment problem with energy storage and continuous variable admittance of power lines to which the FACTS devices are connected.
- A detailed analysis of effects of both the energy storage and the FACTS technologies (individually and combined) on power system economics and utilization of renewable power.
- A sensitivity analysis of the wind power penetration level and level of congestion, i.e. capacity of transmission lines.

2. Model

2.1. Nomenclature

Sets and Indices	
$a \in A$	Index and set of generator cost curve segments
$b \in B$	Index and set of nodes
$i \in I$	Index and set of all transmission lines
$l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}}$	Index and set of transmission lines l^{FACTS} with FACTS devices
$\bar{l} \in L$	Index and set of transmission lines $\bar{l}$ without FACTS devices
$s \in S$	Index and set of energy storage units
$t \in \mathrm{T}$	Index and set of time periods
$w \in W$	Index and set of wind farms
Parameters	
C_i^{fx}	Fixed production cost of generating unit i (\$)
C_i^{start}	Start-up cost of generating unit i (\$)
$ch_s^{\max}$	Maximum charging power of energy storage s (MW)
$D_{t,b}$	Demand at node b (MW) during period t
$dis_s^{\max}$	Maximum discharging power of energy storage s (MW)
g_i^{down}	Minimum down time of generator unit i (h)
$g_i^{\mathrm{down,init}}$	Time that generating unit i has been down at $t = 0$ (h)
g_i^{up}	Minimum up time of generator unit i (h)
$g_i^{\mathrm{up,init}}$	Time that generating unit i has been up at $t = 0$ (h)
$G_{i,a}^{\max}$	Capacity of segment a of the cost curve of generating unit i (MW)
$G_i^{\min}$	Minimum power output of generating unit i (MW)
$G_i^{\max}$	Maximum power output of generating unit i (MW)
M	Large number
$mc_{i,a}$	Generation cost on segment a of generating unit i's cost curve (\$/MW)
p_i^0	Initial power of generating unit i at $t = 0$(MW)
R_i^{down}	Ramp-down limit of generating unit i (MW/h)
R_i^{down}	Ramp-down limit of generating unit i (MW/h)
R_i^{up}	Ramp up limit of generating unit i (MW/h)
$RS_t^{\mathrm{up/down}}$	Minimum required up/down reserve during period t (MW)
$sus_{l^{\mathrm{FACTS}}}^{\max}$	Maximum susceptance of line $l^{\mathrm{FACTS}}$with FACTS devices (S)
$sus_{l^{\mathrm{FACTS}}}^{\min}$	Minimum susceptance of line l^{FACTS} with FACTS devices (S)
$sus_{\bar{l}}$	Susceptance of line l without FACTS devices (S)
$soc_s^{\max}$	Maximum state of charge of energy storage s (MWh)
$soc_s^{\min}$	Minimum state of charge of energy storage s (MWh)
$V_i^{\mathrm{up,min}}$	Time that generating unit i must stay on at the beginning of the operating horizon (h)
$V_i^{\mathrm{down,min}}$	Time that generating unit i must stay off at the beginning of the operating horizon (h)
$Z_{t,w}^{\max}$	Available output of wind farm w (MW)
$\eta_s^{\mathrm{ch/dis}}$	Charging/Discharging efficiency of energy storage s
η_s^{dis}	Discharging efficiency of energy storage s
Variables	
$flow_{t,l}$	Power flow through line $l \in L$ during period t (MW)
$flow_{t,\bar{l}}$	Power flow through line $\bar{l} \in \bar{L}$ during period t (MW)
$flow_{t,l^{\mathrm{FACTS}}}$	Power flow through line $l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}}$ during period t (MW)
$p_{t,s}^{\mathrm{ch}}$	Charging power of energy storage s during period t (MW)
$p_{t,s}^{\mathrm{dis}}$	Discharging power of energy storage s during period t (MW)
$p_{t,i}$	Output of generating unit i during period t (MW)
$p_{t,i,a}$	Output of generating unit i on cost curve segment a during period t (MW)
$p_{t,w}$	Output of wind farm w during period t (MW)
$r_{t,i}^{\mathrm{up/down}}$	Up/Down reserve provided by generating unit i during period t (MW)
$soc_{t,s}$	State of charge of energy storage s during period t (MWh)
$sus_{t,l^{\mathrm{FACTS}}}$	Susceptance of line l^{FACTS} with FACTS devices during period t (S)

$\vartheta_{t,b}$	Voltage angle at node b during period t (rad)
$u_{t,i}$	On/off (1/0) status of generating unit i during period t
$v_{t,i}$	Start up (1/0) of generating unit i during period t
$z_{t,i}$	Shut down (1/0) of generation unit i during period t
$x_{t,s}^{\mathrm{ch}}$	Charging (1/0) of energy storage s during period t
$x_{t,s}^{\mathrm{dis}}$	Discharging (1/0) of energy storage s during period t
$x_{l^{\mathrm{FACTS}}}$	Voltage angle difference; 1 if positive, 0 if negative

2.2. Description

This section formulates a unit commitment model that incorporates both energy storage and FACTS devices. The objective function (1) aims to minimize overall generation cost of all generators. It comprises three terms: fixed operating cost, start up cost and variable cost of each generator. Wind farms are assumed to produce at zero cost.

$$\text{Minimize} \sum_{t=1}^{T} \sum_{i=1}^{I} \left(C_i^{\mathrm{fx}} \cdot u_{t,i} + C_i^{\mathrm{start}} \cdot v_{t,i} + \sum_{a=1}^{A} mc_{i,a} \cdot p_{t,i,a} \right) \tag{1}$$

This objective function is subject to a number of constraints.

Conventional generating unit constraints (2)–(21):

Eq. (2) represents logic constraints in operation of generating units. If generator i is started at time period t, then both $u_{t,i}$ and $v_{t,i}$ are equal to 1. Else, if generator i is shut down at period t, then $z_{t,i}$ is equal to 1, and $u_{t,i}$ is zero. Moreover, (3) imposes that generator i can only start up or shut down at any period of time t.

$$v_{t,i} - z_{t,i} = u_{t,i} - u_{t-1,i} \quad \forall\, i \in I,\, t \in T \tag{2}$$

$$v_{t,i} + z_{t,i} \leqslant 1 \quad \forall\, i \in I,\, t \in T \tag{3}$$

Constraints (4)–(7) ensure that generators operate between their minimum and maximum allowed outputs, while the overall output is comprised of multiple piecewise generation cost curves a.

$$p_{t,i} = \sum_{a=1}^{A} p_{t,i,a} \quad \forall\, a \in A,\, i \in I,\, t \in T \tag{4}$$

$$p_{t,i} - r_{t,i}^{\mathrm{down}} \geqslant G_i^{\min} \cdot u_{t,i} \quad \forall\, i \in I,\, t \in T \tag{5}$$

$$p_{t,i,a} \leqslant G_{i,a}^{\max} \quad \forall\, a \in A,\, i \in I,\, t \in T \tag{6}$$

$$p_{t,i} + r_{t,i}^{\mathrm{up}} \leqslant G_i^{\max} \cdot u_{t,i} \quad \forall\, i \in I,\, t \in T \tag{7}$$

The next block of generator constraints are minimum up and down time constraints (8)–(13), which use different start up states, depending on the time a generator had been on or off before being started. A detailed explanation of these constraints is available in [37].

Minimum up time constraints:

$$\sum_{t=1}^{V_i^{\mathrm{up,min}}} (1-u_{t,i}) = 0 \quad \forall\, i \in I \tag{8}$$

$$\sum_{tt=t}^{t+g_i^{\mathrm{up}}} u_{tt,i} \geqslant g_i^{\mathrm{up}} \cdot v_{t,i} \quad \forall\, i \in I,\, t \in [V_i^{\mathrm{up,min}} + 1,\, T - g_i^{\mathrm{up}} + 1] \tag{9}$$

$$\sum_{tt=t}^{T} (u_{tt,i} - v_{t,i}) \geqslant 0 \;\; \forall\, i \in I,\, t \in [T - g_i^{\mathrm{up}} + 2,\, T] \tag{10}$$

where

$$V_i^{\mathrm{up,min}} = \max\{0,\, \min\{T,\, (g_i^{\mathrm{up}} - g_i^{\mathrm{up,init}}) \cdot g_i^{\mathrm{on-off}}\}\}$$

Minimum down time constraints:

$$\sum_{t=1}^{V_i^{\mathrm{down,min}}} u_{t,i} = 0 \quad \forall\, i \in I \tag{11}$$

$$\sum_{tt=t}^{t+g_i^{\mathrm{down}}-1} (1-u_{tt,i}) \geqslant g_i^{\mathrm{down}} \cdot z_{t,i} \;\; \forall\, i \in I,\, t \in [V_i^{\mathrm{down,min}} + 1,\, T - g_i^{\mathrm{down}} + 1] \tag{12}$$

$$\sum_{tt=t}^{T} (1 - u_{tt,i} - z_{t,i}) \geqslant 0 \quad \forall\, i \in I,\, t \in [T - g_i^{\mathrm{down}} + 2,\, T] \tag{13}$$

where

$$V_i^{\mathrm{down,min}} = \max\{0,\, \min\{T,\, (g_i^{\mathrm{down}} - g_i^{\mathrm{down,init}}) \cdot (1 - g_i^{\mathrm{on-off}})\}\}$$

Constraints (14)–(17) are up and down ramp constraints, which consider both the expected output and the up and down reserve provision of each generating unit. Eqs. 18,19 impose up and down reserve requirements, which need to be fulfilled by all the generating units combined. When defining the minimum level of reserve in the system, we use the well-known 3 + 5% rule proposed by the National Renewable Energy Laboratory [38], which sets the required reserves to 3% of the load and 5% of the available wind power at each time period. This is imposed in (20) and (21).

Ramp constraints:

$$-p_{t,i} + r_{t,i}^{\mathrm{down}} + p_{t-1,i} + r_{t-1,i}^{\mathrm{up}} \leqslant R_i^{\mathrm{down}} \cdot u_{t,i} + G_i^{\min} \cdot z_{t,i} \quad \forall\, i \in I,\, t \in [2,\, T] \tag{14}$$

$$p_{t,i} + r_{t,i}^{\mathrm{up}} - p_{t-1,i} + r_{t-1,i}^{\mathrm{down}} \leqslant R_i^{\mathrm{up}} \cdot u_{t-1,i} + G_i^{\min} \cdot v_{t,i} \quad \forall\, i \in I,\, t \in [2,\, T] \tag{15}$$

$$-p_{t_1,i} + r_{t_1,i}^{\mathrm{down}} + p_i^0 \leqslant R_i^{\mathrm{down}} \cdot u_{t,i} \quad \forall\, i \in I,\, t \in [1] \tag{16}$$

$$p_{t_1,i} + r_{t_1,i}^{\mathrm{up}} - p_i^0 \leqslant R_i^{\mathrm{up}} \cdot u_{t,i} \quad \forall\, i \in I,\, t \in [1] \tag{17}$$

Ramp requirements:

$$\sum_{i}^{I} r_{t,i}^{\mathrm{up}} = RS_t^{\mathrm{up}} \quad \forall\, t \in T \tag{18}$$

$$\sum_{i}^{I} r_{t,i}^{\mathrm{down}} = RS_t^{\mathrm{down}} \quad \forall\, t \in T \tag{19}$$

$$RS_t^{\mathrm{up}} = 0.03 \cdot \sum_{b}^{B} d_{t,b} + 0.05 \cdot \sum_{w}^{W} Z_{t,w} \quad \forall\, t \in T \tag{20}$$

$$RS_t^{\mathrm{down}} = 0.03 \cdot \sum_{b}^{B} d_{t,b} + 0.05 \cdot \sum_{w}^{W} Z_{t,w} \quad \forall\, t \in T \tag{21}$$

Renewable generation constraints:

Renewable generation output is constrained by its available output at each time period in (22).

$$p_{t,w} \leqslant Z_w^{\max} \quad \forall\, w \in W,\, t \in T \tag{22}$$

Transmission constraints:

Constraints (23)–(35) are transmission constraints. Eq. (23) is the power balance at each bus b and at each time period t. It balances the power generated by generators and wind farms, power discharged by energy storage and power inflows with the demand, power charged by energy storage and power outflows. Eq. (24) computes power flows through lines, while (25) and (26) limit these power flows. Constraints (27) and (28) determine power flows through lines equipped with FACTS devices. However, Eq. (27) is non-linear because the susceptance of FACTS equipped lines is a variable, instead of parameter. As explained in [26], this model assumes that FACTS devices do not change direction of flows through the

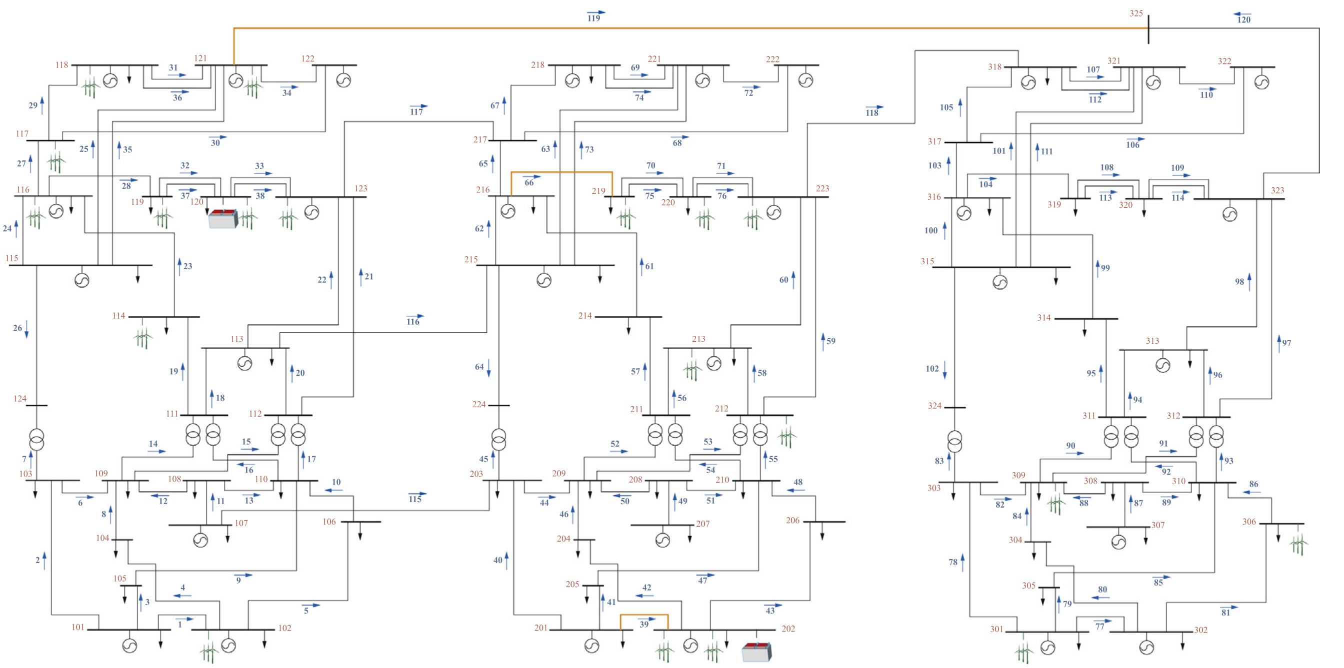

Fig. 1. IEEE RTS96 with 19 wind farms (green symbols), two energy storage units (battery symbols), and three lines with installed FACTS devices (orange color). Blue numbers represent lines, while red numbers represent bus numbers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lines. Constraints (29)–(33) use binary variable $x_{t,l^{\mathrm{FACTS}}}$ to determine when there is a positive angle difference ($x_{t,l^{\mathrm{FACTS}}}$ is 1) and negative angle difference ($x_{t,l^{\mathrm{FACTS}}}$ is zero). Because of this, it is necessary to run the unit commitment without FACTS devices first to determine if there is a positive or a negative angle difference between the buses connected by the lines equipped with FACTS devices. Big M reformulation used to linearize the product of the binary and continuous variables is listed in Appendix A. Finally, constraints (34) and (35) limit voltage angles at each bus and set voltage angle at the reference bus to zero.

$$\sum_{i=1}^{I^b} p_{t,i} + \sum_{w=1}^{W^b} p_{t,w} + \sum_{s=1}^{S^b} p_{t,s}^{\mathrm{dis}} - \sum_{l=1|b(l)}^{L^b} flow_{t,l} + \sum_{l=1|n(l)}^{L^b} flow_{t,l} = D_{t,b} + \sum_{s=1}^{S^b} p_{t,s}^{\mathrm{ch}} \quad \forall\, b \in B,\, t \in T \tag{23}$$

$$flow_{t,\bar{l}} = sus_{\bar{l}} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \quad \forall\, \{b,n\} \in \bar{L},\, t \in T \tag{24}$$

$$flow_{t,\bar{l}} \leqslant flow_{\bar{l}}^{\max} \quad \forall\, \bar{l} \in \bar{L},\, t \in T \tag{25}$$

$$flow_{t,\bar{l}} \geqslant -flow_{\bar{l}}^{\max} \quad \forall\, \bar{l} \in \bar{L},\, t \in T \tag{26}$$

$$flow_{t,l^{\mathrm{FACTS}}} = sus_{t,l^{\mathrm{FACTS}}} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{27}$$

$$sus_{l^{\mathrm{FACTS}}}^{\min} \leqslant sus_{t,l^{\mathrm{FACTS}}} \leqslant sus_{l^{\mathrm{FACTS}}}^{\max} \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{28}$$

$$\text{If } (\vartheta_{t,b} - \vartheta_{t,n}) \geqslant 0: \quad sus_{l^{\mathrm{FACTS}}}^{\min} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \leqslant flow_{t,l^{\mathrm{FACTS}}} \leqslant sus_{l^{\mathrm{FACTS}}}^{\max} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{29}$$

$$\text{If } (\vartheta_b(t) - \vartheta_n(t)) \leqslant 0 \quad sus_{l^{\mathrm{FACTS}}}^{\max} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \leqslant flow_{t,l^{\mathrm{FACTS}}} \leqslant sus_{l^{\mathrm{FACTS}}}^{\min} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{30}$$

$$(1 - x_{t,l^{\mathrm{FACTS}}}) \cdot sus_{l^{\mathrm{FACTS}}}^{\min} + x_{t,l^{\mathrm{FACTS}}} \cdot sus_{l^{\mathrm{FACTS}}}^{\max} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \geqslant flow_{t,l^{\mathrm{FACTS}}} \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{31}$$

Table 1
Modified IEEE-RTS 96 power system.

Type	Capacity (MW)	# devices	Buses/lines
Wind farms	150	4	buses: 202,219,301,309
	300	9	buses: 102,114,118,121,123,202,212,213
	600	6	buses: 116,117,119,120,220,223
Energy Storage	150	2	buses: 120,202
FACTS	50 % X_l	3	lines: 39, 66, 119

$$(1 - x_{t,l^{\mathrm{FACTS}}}) \cdot sus_{l^{\mathrm{FACTS}}}^{\max} + x_{t,l^{\mathrm{FACTS}}} \cdot sus_{l^{\mathrm{FACTS}}}^{\min} \cdot (\vartheta_{t,b} - \vartheta_{t,n}) \leqslant flow_{t,l^{\mathrm{FACTS}}} \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}} \tag{32}$$

$$(1 - x_{t,l^{\mathrm{FACTS}}}) \cdot \vartheta_{t,n} + x_{t,l^{\mathrm{FACTS}}} \cdot \vartheta_{t,b} \geqslant (1 - x_{t,l^{\mathrm{FACTS}}}) \cdot \vartheta_{t,b} + x_{t,l^{\mathrm{FACTS}}} \cdot \vartheta_{t,n} \quad \forall\, l^{\mathrm{FACTS}} \in L^{\mathrm{FACTS}},\, t \in T \tag{33}$$

$$-\pi \leqslant \vartheta_{t,b} \leqslant \pi \quad \forall\, b \in B \backslash\, b\text{: ref. bus},\, t \in T \tag{34}$$

$$\vartheta_{t,s} = 0 \quad s\text{: ref. bus},\, \forall\, t \in T \tag{35}$$

Energy storage constraints:

The last block of constraints are energy storage constraints. Eq. (36) calculates the state of charge of each energy storage unit s at time period t, which consists of state of charge from the previous time period and charging and discharging powers at the current time period. Storage state of charge is constrained from the lower and upper side in (37). Maximum charging and discharging powers are imposed by (38) and (39), while constraint (40) disables simultaneous charging and

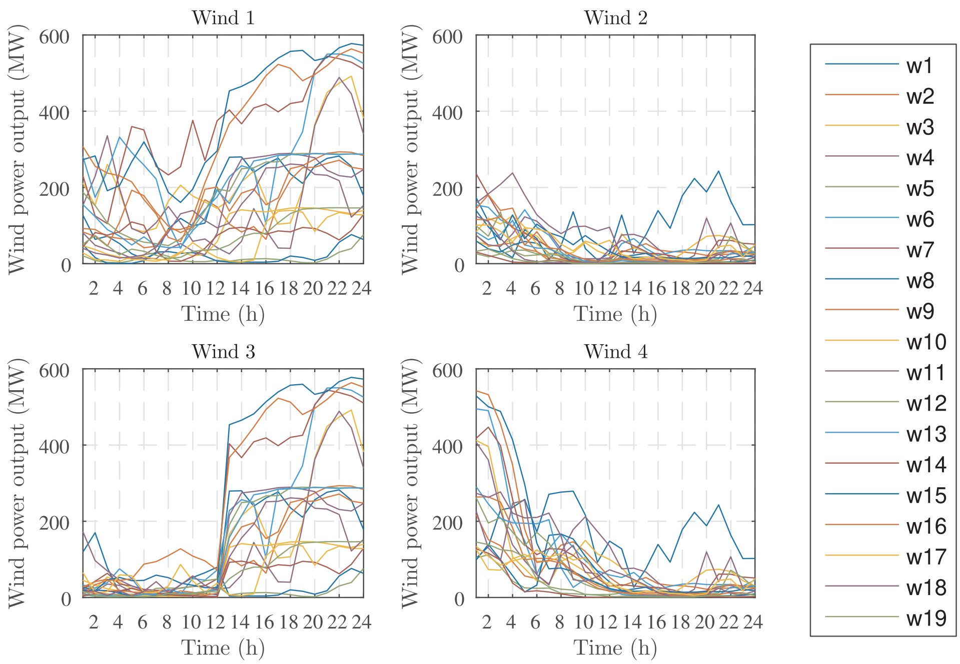

Fig. 2. Generation of 19 wind farms for all four wind scenarios.

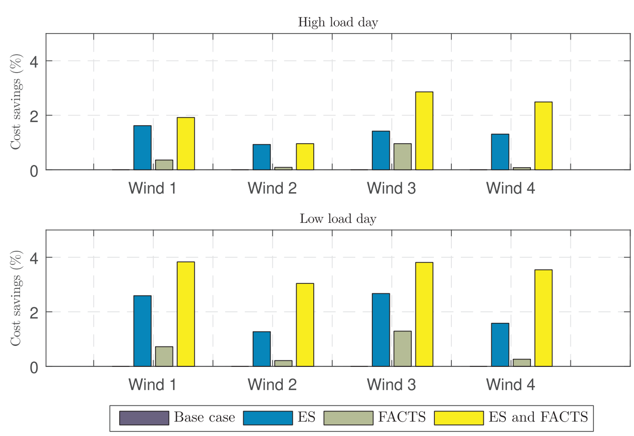

Fig. 3. Operating cost savings in all four cases for all four wind scenarios.

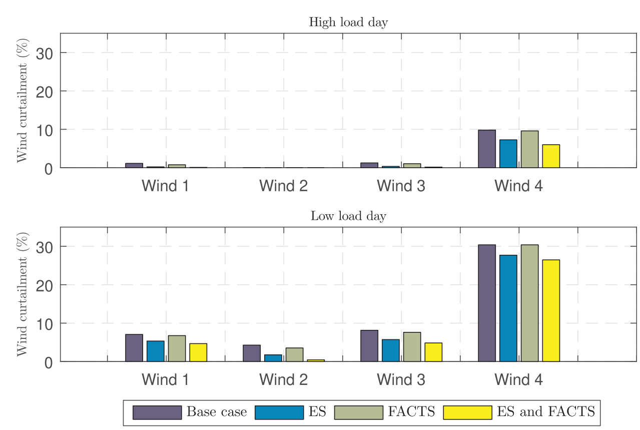

Fig. 4. Wind curtailment as a percentage of the available wind in all four cases for all four wind scenarios.

Table 2
System operating costs and wind curtailment for the high-load day.

		Wind 1	Wind 2	Wind 3	Wind 4
Case 1	Costs ($)	2,048,149	3,436,256	2,493,440	3,154,300
	Wind curtailment (MWh)	888	5	754	3,637
Case 2	Costs ($)	2,015,035	3,404,278	2,457,942	3,113,146
	Wind curtailment (MWh)	183	0	210	2,698
Case 3	Costs ($)	2,040,872	3,433,198	2,469,432	3,151,808
	Wind curtailment (MWh)	598	0	632	3,559
Case 4	Costs ($)	2,008,959	3,403,268	2,422,005	3,075,550
	Wind curtailment (MWh)	70	0	106	2,229

discharging.

$$soc_{t,s} = soc_{t-1,s} + p_{t,s}^{\text{ch}} \cdot \eta_s^{\text{ch}} - \frac{p_{t,s}^{\text{dis}}}{\eta_s^{\text{dis}}} \quad \forall\, s \in S, t \in T \tag{36}$$

$$soc_s^{\min} \leqslant soc_{t,s} \leqslant soc_s^{\max} \quad \forall\, s \in S, t \in T \tag{37}$$

$$p_{t,s}^{\text{ch}} \leqslant ch_s^{\max} \cdot x_{t,s}^{\text{ch}} \quad \forall\, s \in S, t \in T \tag{38}$$

$$p_{t,s}^{\text{dis}} \leqslant dis_s^{\max} \cdot x_{t,s}^{\text{dis}} \quad \forall\, s \in S, t \in T \tag{39}$$

$$x_{t,s}^{\text{ch}} + x_{t,s}^{\text{dis}} \leqslant 1 \quad \forall\, s \in S, t \in T \tag{40}$$

It is worth noting that, in most cases, constraint (40), as well as binary variables $x_{t,s}^{\text{ch}}$ and $x_{t,s}^{\text{dis}}$ in (38) and (39), can be omitted because it is not beneficial for the model to charge and discharge energy storage simultaneously. However, this can happen if the charging/discharging cycle efficiency is close to 100% and if the set optimality gap is not small enough.

Some of the energy storage devices, such as batteries, may have variable charging power limit instead of the constant one imposed by constraint (38). Also charging/discharging cycle efficiency might depend on the charging and discharging currents. However, this paper considers general energy storage constraints, which is common in power system economics studies, see [20–25].

Variable definition:

Continuous variables are defined in (41) and (42), and binary variables in (43):

$$p_{t,s}^{\text{ch}},\, p_{t,s}^{\text{dis}},\, p_{t,i,a},\, p_{t,i},\, p_{t,w},\, r_{t,i}^{\text{down}},\, r_{t,i}^{\text{up}},\, soc_{t,s} \geqslant 0 \tag{41}$$

Table 3
Number of committed generating units for all cases under the Wind 1 scenario and high-load day.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Case 1	60	45	30	21	22	36	47	48	48	48	47	44	39	37	33	33	33	33	33	32	26	26	25	22
Case 2	60	45	31	21	23	33	45	46	46	46	45	42	39	36	32	31	31	31	31	30	25	25	25	23
Case 3	60	45	29	21	23	34	48	48	48	48	48	43	40	37	33	33	33	33	32	31	27	25	23	21
Case 4	60	45	31	21	21	33	45	46	46	46	45	42	38	37	33	32	32	32	32	29	25	25	25	23

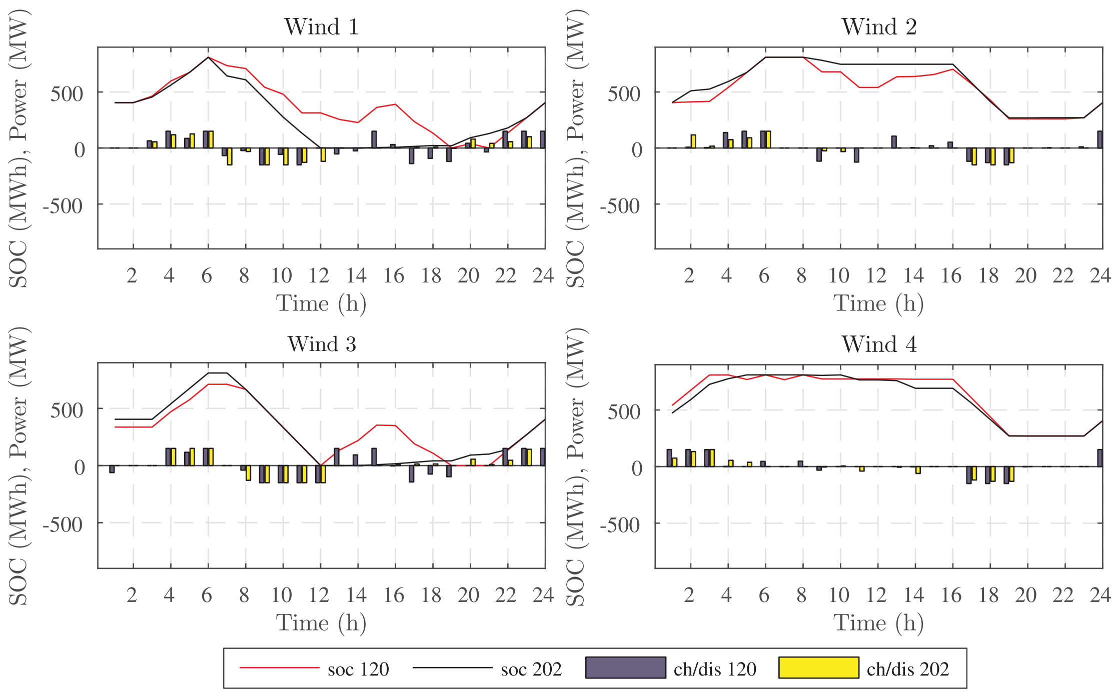

Fig. 5. Energy storage charging and discharging schedules for the high-load day – Case 2.

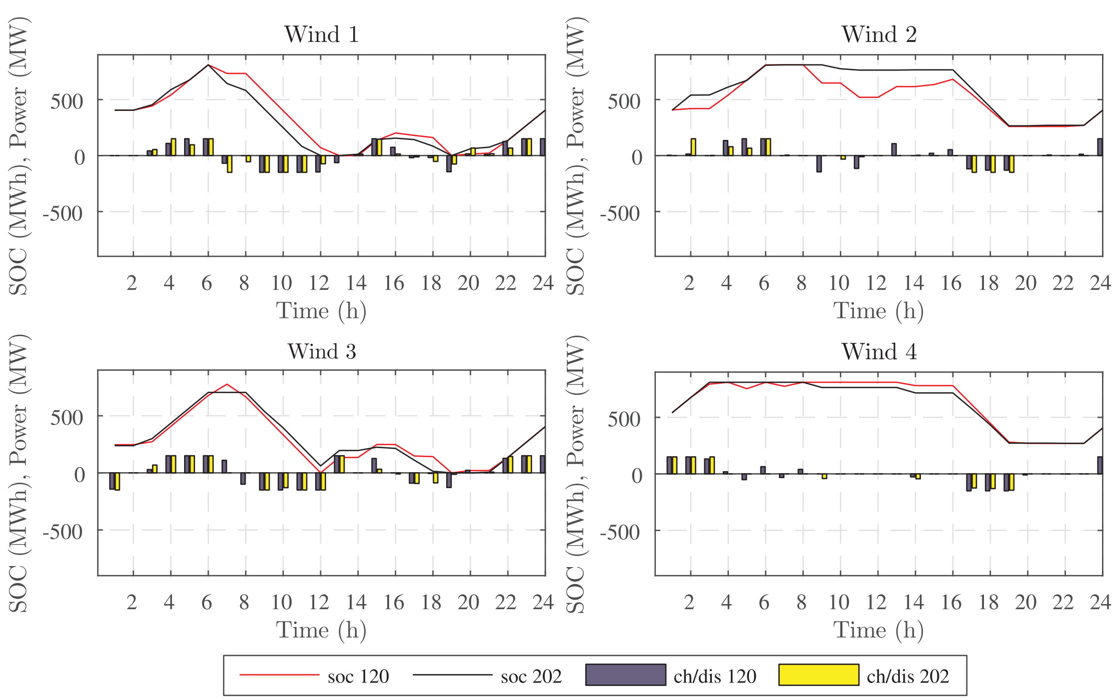

Fig. 6. Energy storage charging and discharging schedules for the high-load day – Case 4.

Table 4
System operating costs and wind curtailment for the low-load day.

		Wind 1	Wind 2	Wind 3	Wind 4
Case 1	Costs ($)	1,150,114	2,015,189	1,444,068	1,864,291
	Wind curtailment (MWh)	5,478	769	4,872	11,275
Case 2	Costs ($)	1,120,327	1,989,688	1,405,556	1,834,817
	Wind curtailment (MWh)	4,144	315	3,420	10,272
Case 3	Costs ($)	1,141,785	2,010,896	1,425,393	1,859,505
	Wind curtailment (MWh)	5,234	637	4,555	11,275
Case 4	Costs ($)	1,106,108	1,953,844	1,388,999	1,798,342
	Wind curtailment (MWh)	3,623	80	2,900	9,819

$$flow_{t,l},\ \vartheta_{t,b} \quad \text{free variable} \tag{42}$$

$$x^{\text{ch}}_{t,s},\ x^{\text{dis}}_{t,s},\ x_{t,l^{\text{FACTS}}},\ u_{t,i},\ v_{t,i},\ z_{t,i} \in \{0,\ 1\} \tag{43}$$

3. Case study

3.1. Input data

The model presented in the previous section is tested on the three-area IEEE-RTS 96 system shown in Fig. 1. Wind farm and energy storage locations and capacity, as well as FACTS data are shown in Table 1. The detailed data on lines, load and generating units are available in [37]. All the simulations are performed at 80% of the original line capacity in order to incur congestion. The test system contains 19 wind farms with capacities 150 MW, 300 MW or 600 MW, resulting in 6,900 MW of overall capacity [24]. Both energy storage capacities are 150 MW and they are located at buses 120 and 202, as per findings of [24]. They are assumed to be of NaS type [39] with charging duration of 8 h and discharging duration of 6 h. Both the charging and the discharging efficiencies are 0.9.

Capacity of the FACTS devices is assumed to be 50% of the line reactance, which means that the reactance of these lines can be changed up to 50% in both directions. This percentage is considered to best balance between the investment cost and the achieved operating cost savings (see Fig. 3 in [26]). FACTS devices, namely the series controllers, such as TCSC, are particularly appropriate for very long power lines which are frequently congested. Therefore, it is reasonable to locate these FACTS devices at congested power lines, which are either the interconnecting lines or heavily loaded lines within one of the areas. Having this in mind, FACTS devices are assigned to lines 39, 66 and 119. Line 119 is an interconnection line between the first and the third area. First area has much more wind power than the third area, so this line is heavily loaded. The other two lines equipped with FACTS devices are within the second area, connecting buses 201 and 202 (exports abundant wind power available at bus 202) and buses 2016 and 219 (bus 219 contains a wind farm and is further connected to buses 220 and 223, both containing wind generation).

All simulations include four wind scenarios, as shown in Fig. 2. Overall available wind generation per wind scenario is as follows: 77,496 MWh in wind scenario 1, 17,960 MWh in wind scenario 2, 59,796 MWh in wind scenario 3, and 37,102 MWh in wind scenario 4. These are applied to two specific days: high load (the day with the highest daily consumption throughout the year) and low load (the day with the lowest daily consumption). The high-load day is a winter day with 187,347 MWh overall consumption, while the low-load day is an autumn day with 130,207 MWh overall consumption.

The results of four unit commitment models are represented as follows: Case (1) without energy storage or FACTS devices (base case); Case (2) with energy storage only; Case (3) with FACTS devices only; Case (4) with both FACTS devices and energy storage.

In the entire case study, it is assumed that all generators except the nuclear ones can provide reserve.

3.2. Simulation results

3.2.1. High-load day

This section analyses simulation results of the unit commitment models for the high-load day (overall consumption 187,347 MWh). Table 2 shows operating costs and wind curtailment for all four wind scenarios. Wind 1 scenario has the lowest operating costs in each case due to high available wind production, overall 77,496 MWh. On the other hand, Wind 2 scenario incurs the highest operating costs due to the low available wind generation, overall only 17,959 MWh. Operating cost savings are visualized in Fig. 3(top) with respect to the base case without energy storage and FACTS devices (Case 1). The highest savings (up to 2.86%) are achieved in Case 4 with both energy storage and FACTS devices in operation. Energy storage contributes more to these savings in all the cases. It is interesting to note that operation of only FACTS devices does not reduce operating costs significantly (only 0.08%) in Wind 2 scenario. This is the result of high production of thermal generators and low production of wind farms, which diminishes the impact of FACTS devices located in vicinity of the wind power plants.

Fig. 4(top) shows overall system wind curtailment for all four cases as a percentage of the available wind. The highest wind curtailment occurs for Wind 4 scenario due to high wind output during the first six hours, i.e. the low load time periods. The installed storage capacity is insufficient to store all the excess wind generation for later use. However, energy storage is more successful at reducing wind curtailment than the FACTS devices. Wind 1 and Wind 3 scenarios have similar wind curtailment levels because Wind 3 scenario coincides with the evening peak load, although the overall available wind generation is lower than in the Wind 1 scenario. In all four cases, the lowest levels of wind curtailment are achieved in Case 4 (combination of energy storage and FACTS devices).

Table 3 shows the number of committed thermal generating units under the Wind 1 scenario in all four Cases. Green numbers indicate less and red numbers more online generating units as compared to the base case (Case 1). In most hours, Cases 1, 2 and 3 result in the same number or fewer online generating units. Case 3 has one committed generating unit more than Case 1 in hours 5, 7, 11, 13, and 21, but in hours 3, 6, 12, 19–20, and 22–24 it commits one or two generating units less. This is because FACTS devices relieve congestion, resulting in a more efficient commitment schedule. Case 2 also commits less generating units in most time periods, but in hours 3, 5 and 24 this number is increased. To better understand this phenomenon, results from Table 3 should be compared with energy storage charging/discharging schedules in Fig. 5 (top left graph). The increase in the number of committed generator at hours 3 and 5 is the result of storage charging process at these hours.

Table 5
Number of committed generating units for all cases under the Wind 1 scenario and low-load day

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Case 1	59	37	23	25	25	18	29	31	31	31	28	28	24	20	21	23	23	23	24	22	22	21	20	19
Case 2	59	39	23	23	24	17	25	27	27	27	25	25	20	20	22	23	22	22	24	23	23	22	20	20
Case 3	59	37	23	25	25	17	28	32	32	31	29	27	24	21	21	23	22	23	24	23	23	21	20	19
Case 4	59	39	23	23	25	17	25	27	27	26	26	25	20	20	21	22	21	22	23	22	22	21	20	19

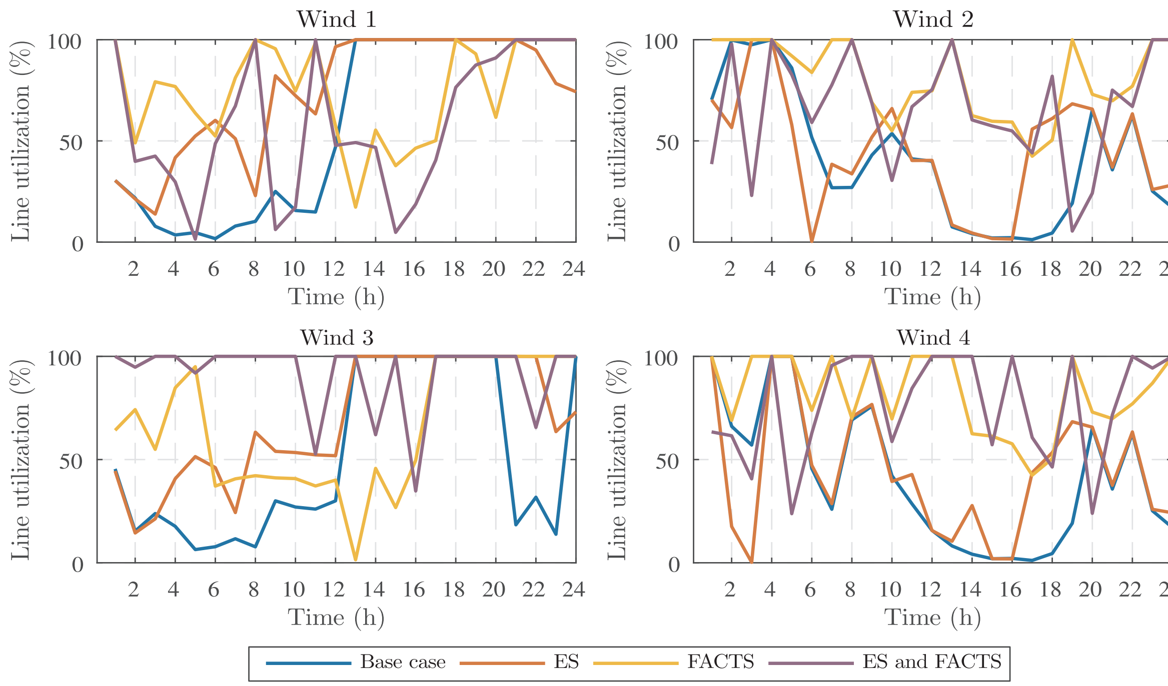

Fig. 7. Utilization of line 39 during the high-load day.

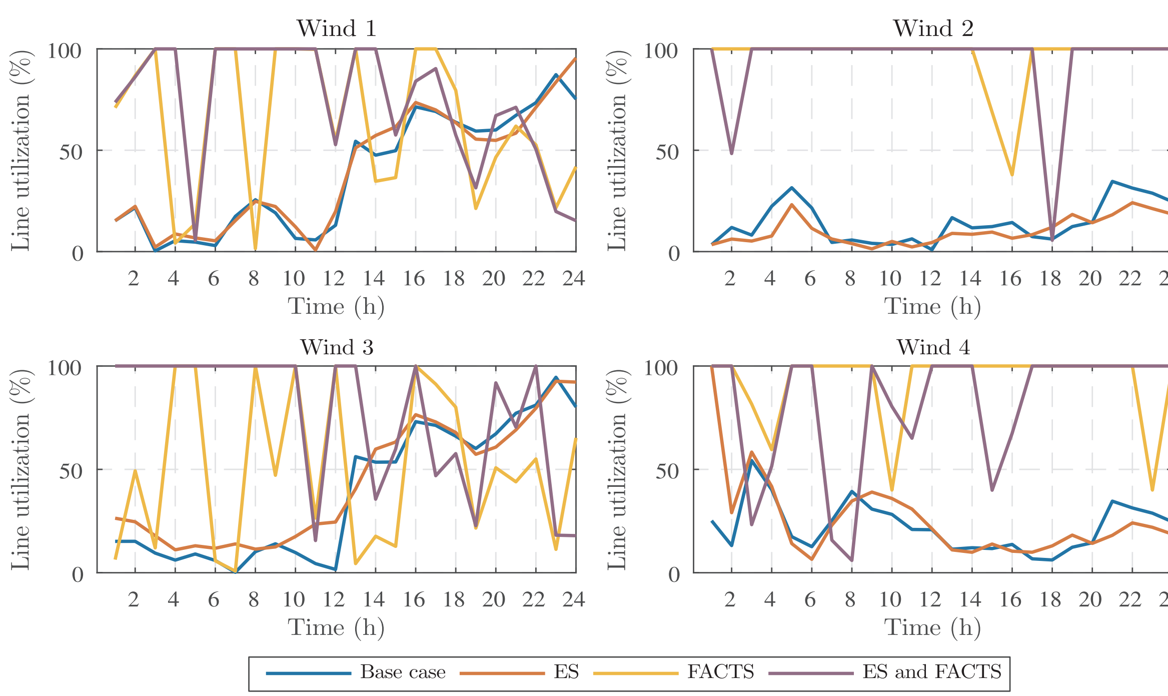

Fig. 8. Utilization of line 66 during the high-load day.

Storage unit at bus 202 completely discharges by hour 12, while the storage at bus 120 discharges at slower pace until hour 14, after which it slightly charges and then fully discharges at hour 19. These discharging actions result in a reduced number of committed generating units in the afternoon and evening hours. The increased number of committed generating units in hour 24 is because energy storage units are charging in order to meet their initial state of charge. It is important to notice that the number of committed units is not strictly proportional to storage actions, e.g. in hour 6 the storage units are being charged, but the number of committed generating units is lower than in the base case. This is due to inter-temporal constraints on generators, i.e. minimum up and down times, ramp up and down constraints, and start-up costs. Case 4, i.e. coordination of FACTS devices and energy storage, results in the least committed generating units throughout the day. The only two hours with more committed units are 3, when storage units are being charged to meet the morning peak load, and 24, when they are charged to meet the initial state of charge level.

Fig. 5 also shows energy storage scheduling for all four wind scenarios. Storage operation schedules are very similar for Wind 1 and Wind 3 (both with abundant wind levels later in the day, providing the opportunity to charge to the initial state of charge level), as well as for Wind 2 and Wind 4 (both with low wind at the end of the day, resulting in fewer charging/discharging actions). As a result, energy storage is more utilized in Wind 1 and Wind 3 scenarios. Energy storage is never

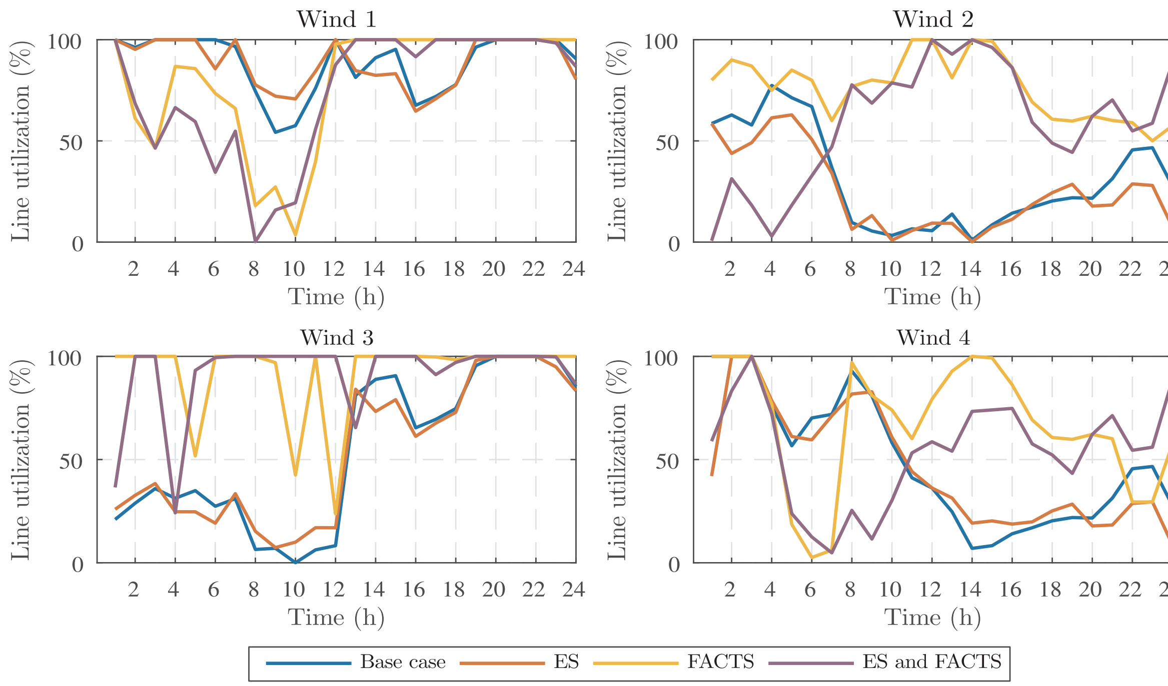

Fig. 9. Utilization of line 119 during the high-load day.

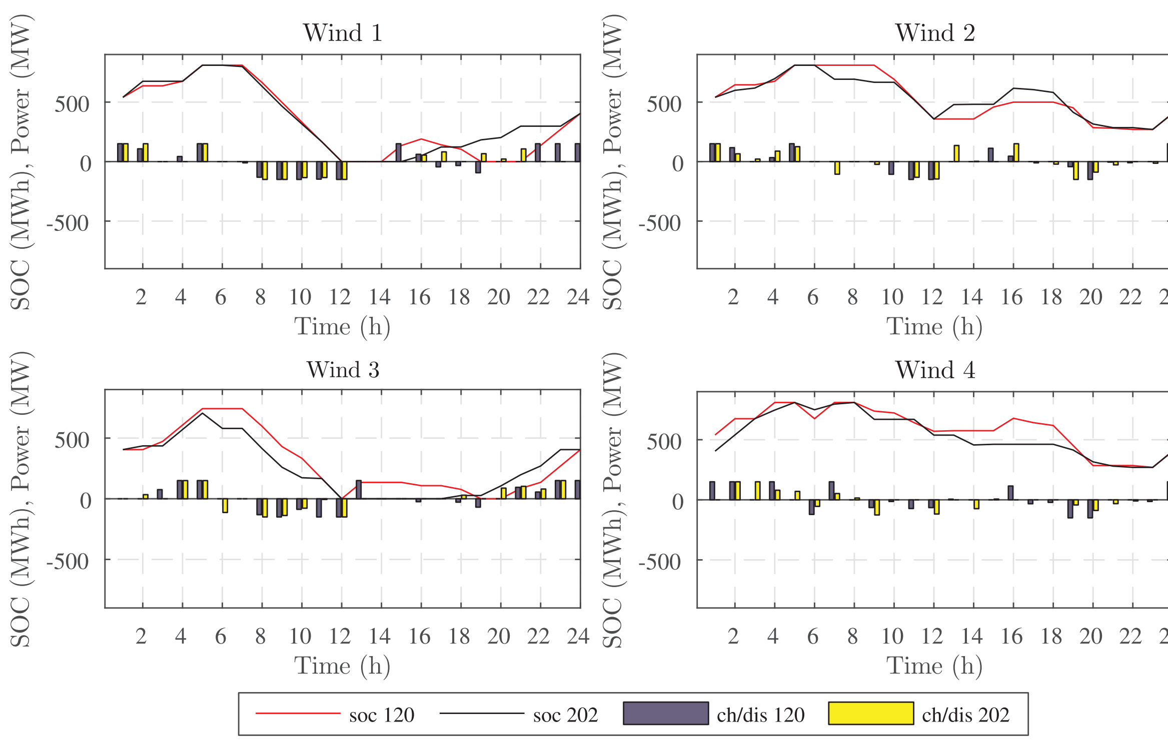

Fig. 10. Energy storage charging and discharging schedules for the low-load day – Case 2.

fully discharged in Wind 2 and Wind 4 scenarios. This is because of low wind power in the other half o the day in those two scenarios. Therefore, the stored energy is discharged during the peak-load hours 17–19.

Fig. 6 shows energy storage operation for Case 4. The charging/discharging schedules are only slightly altered by the presence of FACTS devices. The biggest difference if observed for Wind 1 scenario, where energy storage at bus 120 is fully discharged at hour 13 (there is no full discharge at hour 13 in Case 2). Also, there is a difference in Wind 3 scenario, where energy storage at bus 202 is more active in the afternoon hours instead of energy storage at bus 120, which is the opposite as in Case 2 (compare lower left graphs in Fig. 5 and 6).

To analyze power flows through lines equipped with FACTS devices, Fig. 7–9 show utilization of lines 39, 66 and 119 in all four cases and for all four wind scenarios. Line 39 for Wind 1 scenario, is more utilized in the first half of the day, as compared to the base case, and is relieved in the second half of the day. This relief is mostly caused by FACTS devices, as Case 2 keeps this line congested in hours 13–21. In Wind 2 and Wind 4 scenarios, line 39 is more utilized throughout the day, also

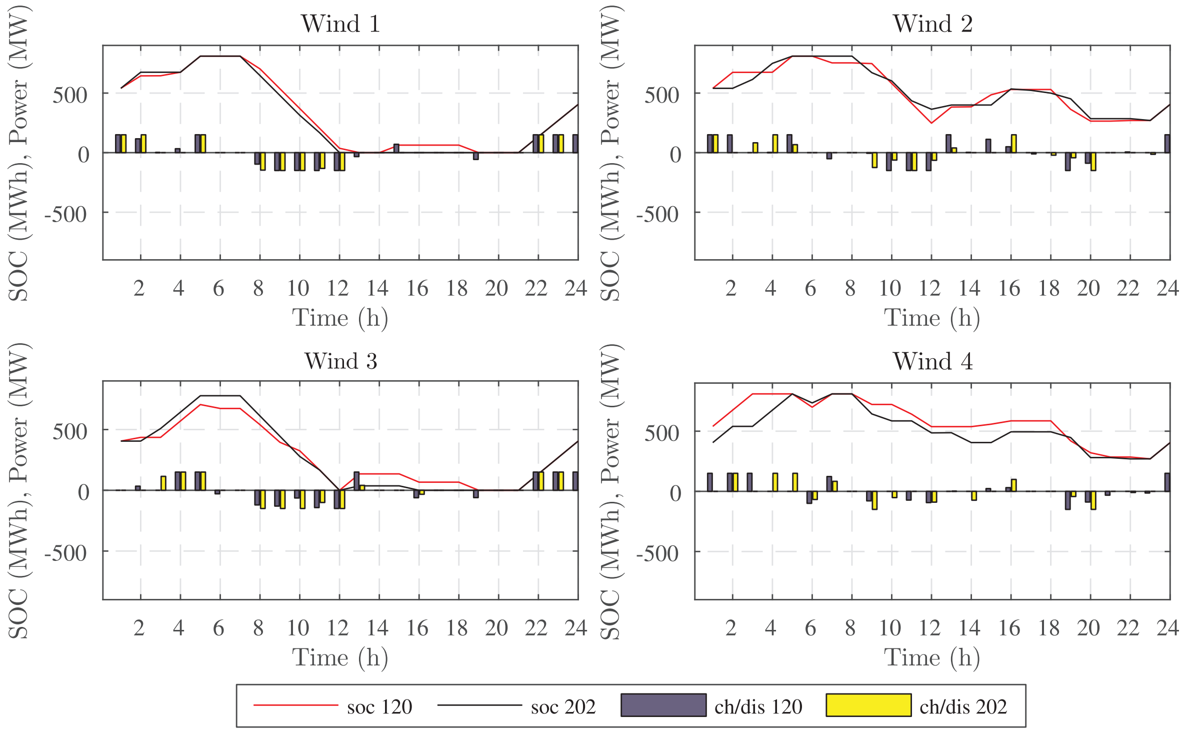

Fig. 11. Energy storage charging and discharging schedules for the low-load day – Case 4.

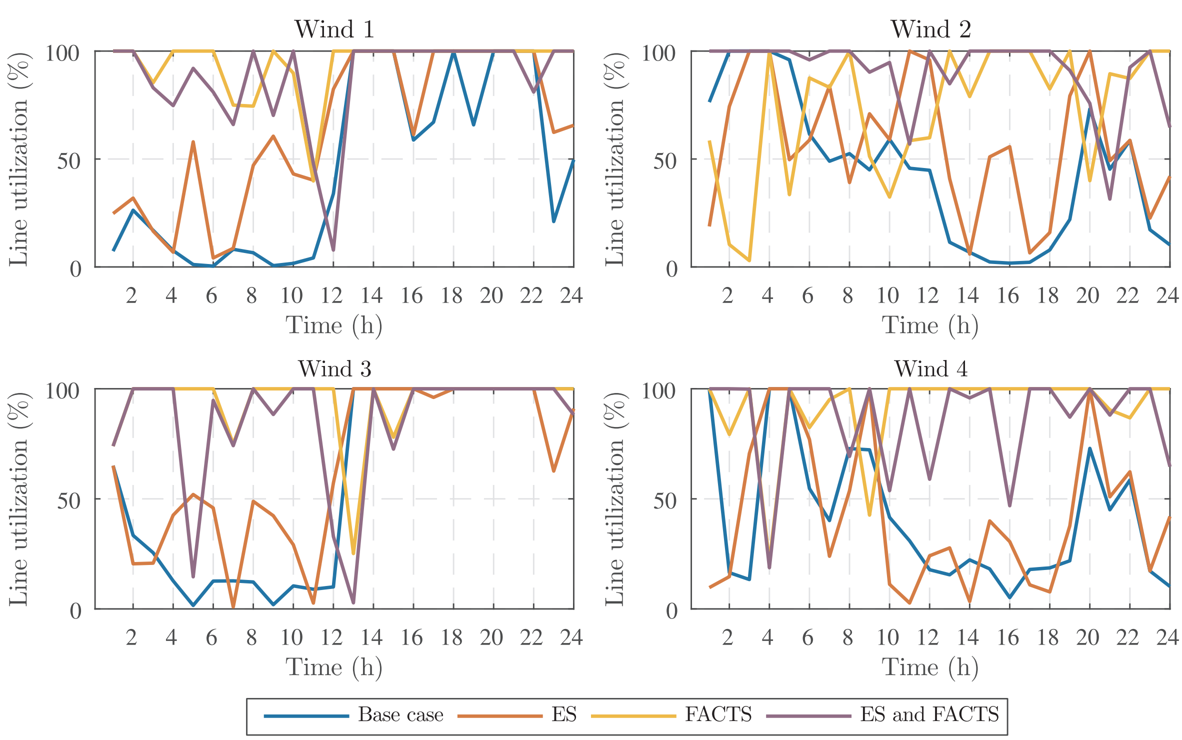

Fig. 12. Utilization of line 39 on the low-load day.

mostly as a result of optimal operation of FACTS devices. Optimal operation of FACTS device at line 66 significantly increases its loading as compared to the Cases 1 and 2, allowing higher power flows and evacuation of cheap wind power from buses 219, 220, and 223. In Fig. 9, Case 2 improves the utilization of line 119 by charging and discharging energy storage units, but this utilization is even more increased in Cases 3 and 4, where FACTS devices rearrange power flows in a more cost effective way.

3.2.2. The low-load day

Table 4 shows operating costs and wind curtailment for all cases and wind scenarios of the low-load day, whose daily consumption is 130,206 MWh. Generally, operating costs are lower and wind curtailment higher than on the high-load day (compare to Table 2). Again, Wind 2 scenario incurs the highest, while Wind 1 scenario incurs the lowest operating costs. Introduction of FACTS devices and energy storage reduces operating costs and wind curtailment. Cost savings

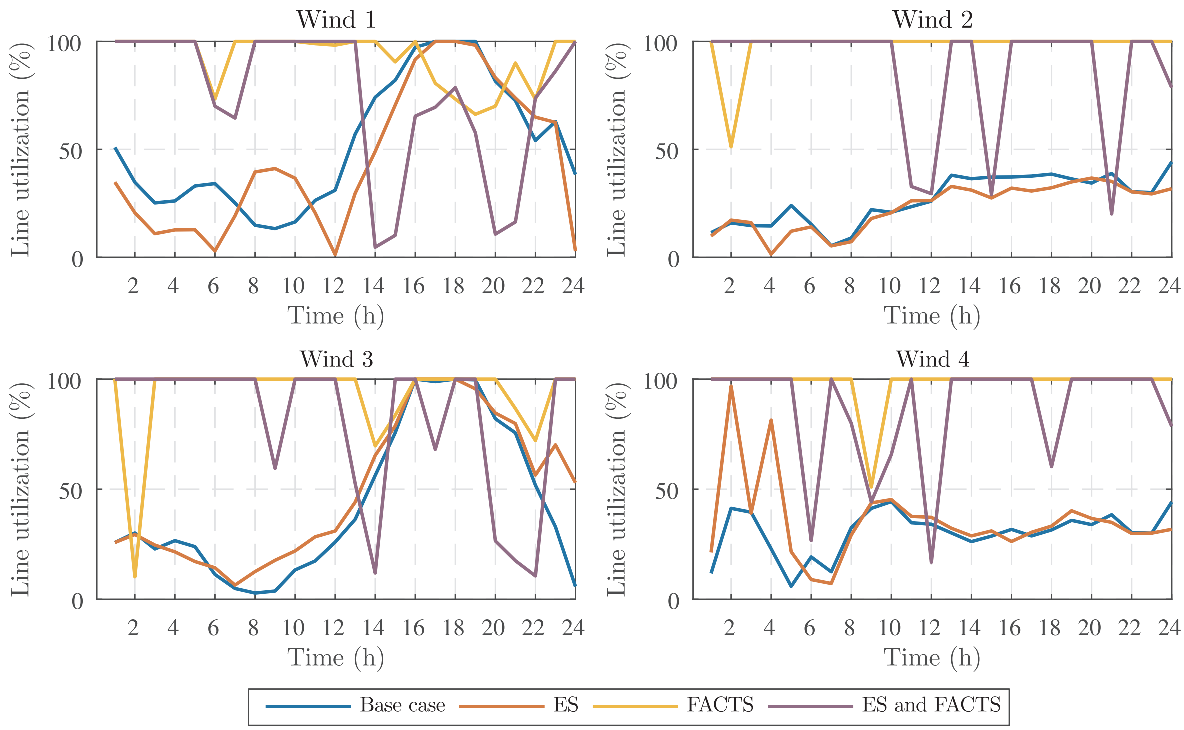

Fig. 13. Utilization of line 66 on the low-load day.

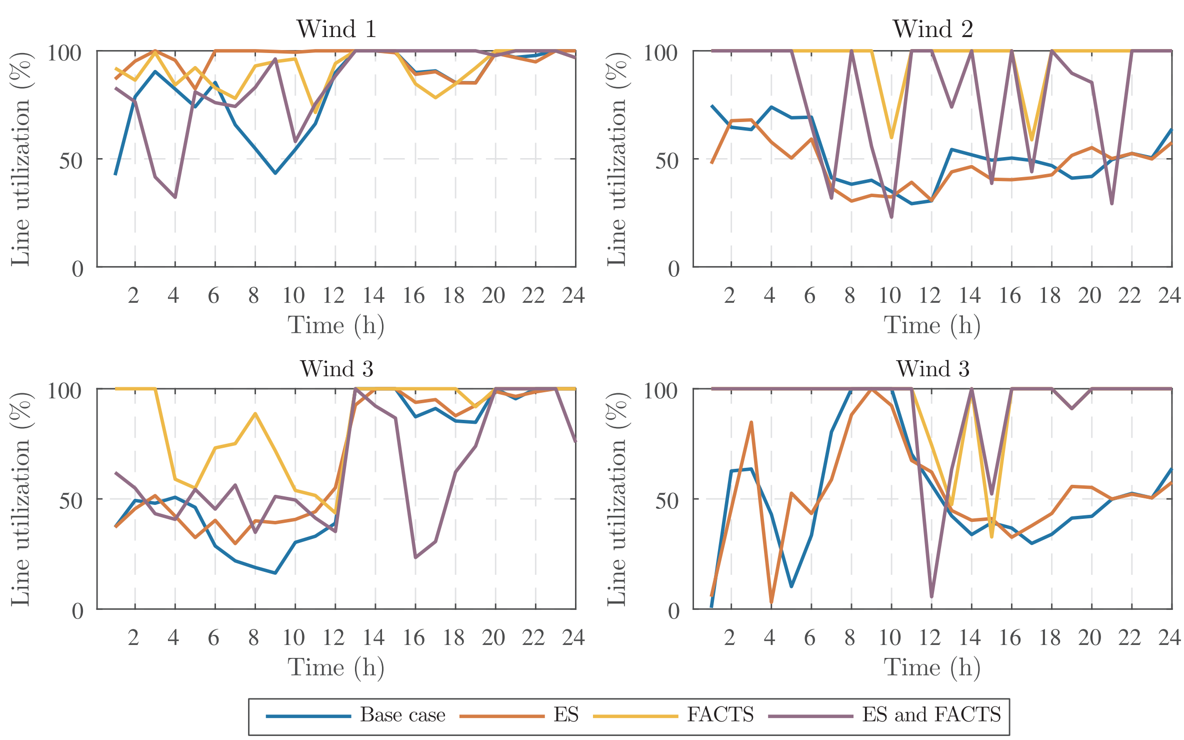

Fig. 14. Utilization of line 119 on the low-load day.

compared to Case 1 are visualized in the lower graph of Fig. 3. Maximum cost savings are 3.83% in Case 4 for the Wind 1 scenario. Similarly as in the high-load day, energy storage contributes more to cost savings, which are percentually higher than for the high-load day.

Impact of energy storage and FACTS devices on wind curtailment for the low-load day is shown in the lower graph of Fig. 4. Energy storage reduces wind curtailment much more than FACTS devices in all the cases. They are very similar to the high-load day, but with higher amounts due to a lower demand. Wind 1 and Wind 3 scenarios have similar wind curtailment level because of the similar wind production in the second part of the day (after hour 12). In Wind 4 scenario, energy storage is better at reducing wind curtailment as it takes advantage of the early morning high wind production that can be stored for later use.

Table 5 shows the number of committed generating units at each hour, where red colour presents higher and green colour lower number of committed generating units as compared to Case 1. Case 2 generally results in a lower number of committed generating units, except in hours 2, 15, 20, 22, and 24. At hours 2 and 15, energy storage units are

Table 6
System operating costs for different line rating on the high-load day

Line rating		60%	80%	100%
Wind 1	Case 1	2,078,324 (+1.47%)	2,048,149	2,042,726 (-0.26%)
	Case 2	2,045,735 (+1.52%)	2,015,035	2,040,343 (-0.23%)
	Case 3	2,058,779 (+0.87%)	2,040,872	2,038,821 (-0.10%)
	Case 4	2,027,135 (+0.91%)	2,008,959	2,007,479 (-0.07%)
Wind 2	Case 1	3,442,651 (+0.19%)	3,436,256	3,435,591 (-0.02%)
	Case 2	3,407,346 (+0.09%)	3,404,278	3,404,270 (-0.00%)
	Case 3	3,435,349 (+0.06%)	3,433,198	3,433,182 (-0.00%)
	Case 4	3,405,693 (+0.07%)	3,403,268	3,403,213 (-0.00%)
Wind 3	Case 1	2,527,094 (+1.35%)	2,493,440	2,487,574 (-0.24%)
	Case 2	2,486,793 (+1.17%)	2,457,942	2,454,094 (-0.16%)
	Case 3	2,484,838 (+0.63%)	2,469,432	2,467,586 (-0.07%)
	Case 4	2,438,175 (+0.67%)	2,422,005	2,420,738 (-0.05%)
Wind 4	Case 1	3,161,123 (+0.22%)	3,154,300	3,153,659 (-0.02%)
	Case 2	3,117,410 (+0.14%)	3,113,146	3,112,580 (-0.01%)
	Case 3	3,155,585 (+0.12%)	3,151,808	3,151,577 (-0.00%)
	Case 4	3,079,955 (+0.14%)	3,075,550	3,075,510 (-0.00%)

being charged (upper left graph in Fig. 10), resulting in a higher net load. The charging of energy storage to meet the initial state of charge level results in a higher number of committed generating units at hours 20, 22 and 24. Operation of FACTS devices (Case 3) results with one committed generating unit more than in Case 1 in hours 8, 9 and 11. Combination of FACTS devices and energy storage in Case 4 results in the lowest number of committed generating units throughout the day except in hour 2 due to charging of generating units (upper left graph in Fig. 11).

Figs. 10 and 11 indicate more active storage operation for Wind 1 and Wind 3 scenarios as compared to Wind 2 and Wind 4 scenarios. However, in comparison to the high-load day (Fig. 7 and 8), Wind 2 and Wind 4 scenarios result in more storage charging/discharging actions. Again, because of the significantly lower wind production, energy storage is never fully discharged in these scenarios.

Utilization of lines 39, 66 and 119 are presented in Figs. 12–14. Similarly to the high-load day, energy storage and FACTS devices increase utilization of these lines, thus transferring more electricity from wind farms to load centres and reducing wind curtailment. Lines 39 and 66 are less utilized in the first half of the day in scenarios Wind 1 and Wind 3. Introduction of energy storage (Case 2) slightly increases the loading of these lines in the first half of the day. However, FACTS devices change power flows in a way to significantly increase the loading of these lines (Case 3 and Case 4). Another example how FACTS devices increase loading of transmission lines is the loading of line 66 (Fig. 13) under Wind 2 and Wind 4 scenarios.

3.3. Sensitivity analysis

Sensitivity analysis is performed by three different line capacity cases: 100%, 80% (the one used in the previous subsection) and 60% of original line capacity of IEEE RTS96. Comparison of operating costs is shown in Table 6. The results indicate that line ratings have highest impact on the system operating cost for Wind 1 and Wind 3 scenarios. Reducing line ratings in Wind 1 scenario from 80% to 60% results in 1.47% higher operating costs for the base case (Case 1), while in Case 4 the operating costs are 0.9% higher. On the other hand, increased line rating (80% - > 100%) result in lower savings in operating costs (up to 0.26%). The differences in operating costs for different line ratings in Wind 2 scenario are much more modest (up to 0.19%). Again, they are the highest for Case 1. Results for Wind 3 scenario are very similar to the ones for Wind 1 scenario due to high wind output that cannot reach the load centers due to congestion. Under Wind 4 scenario, the objective function changes only slightly with the change of the line ratings, similarly as under the Wind 2 scenario.

Wind curtailment for different line ratings is shown in Fig. 15. For Wind 1 scenario,and line ratings 60%, combination of FACTS devices and energy storage can reduce wind curtailment from 3.9% to 2.8%. Wind curtailment is much lower for 80% line ratings, while for 100% line ratings energy storage can almost completely eliminate wind curtailment. In Wind 2 scenario, only the base case has a small amount of wind curtailment for line ratings 60% and 80%. Wind curtailment levels in Wind 3 scenario are very similar to the ones in Wind 1 scenario,

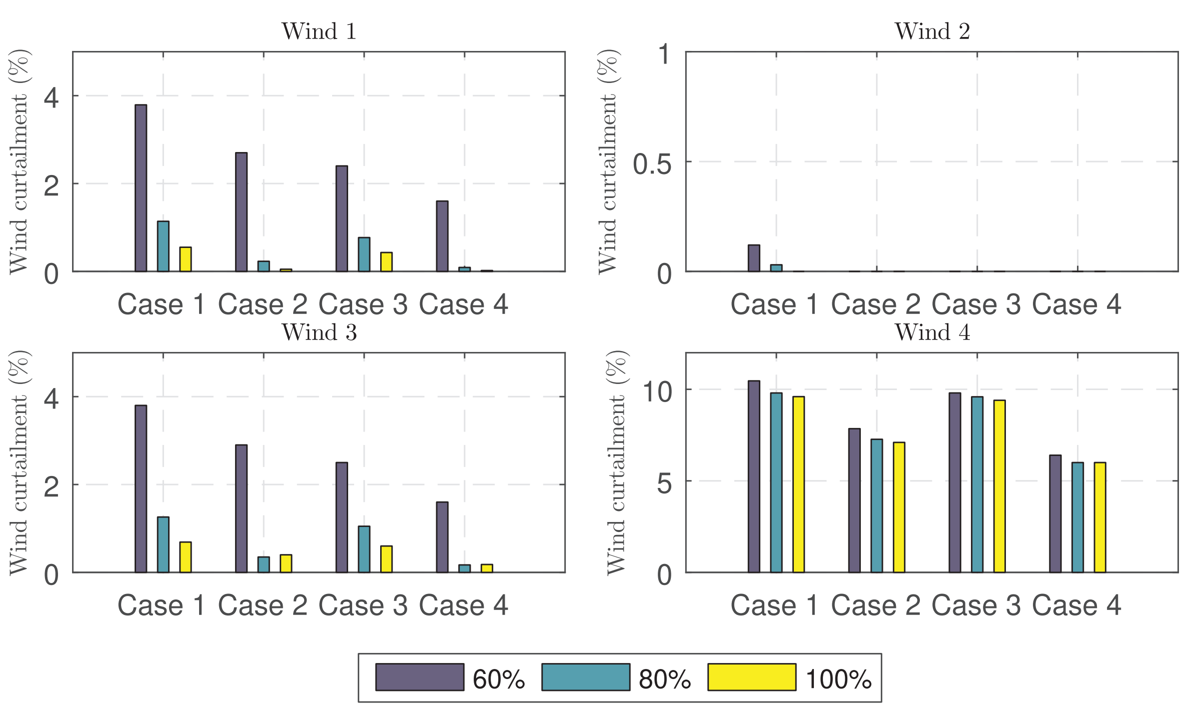

Fig. 15. Sensitivity analysis of wind curtailment in percentage of the available wind for three line ratings on the high-load day.

with the difference that even storage cannot completely eliminate wind curtailment. Wind 4 scenario results in the highest wind curtailment levels, but increased line ratings do not severely reduce them.

4. Conclusions

This paper presented four different unit commitment models considering energy storage and FACTS devices. The following conclusions are derived:

- Energy storage is more efficient at reducing system operating costs than FACTS devices, while the wind curtailment is effectively reduced by both technologies. However, the effectiveness of energy storage at reducing system operating costs and wind curtailment significantly depends on the wind profile.
- FACTS devices can significantly increase line loadings, though a large number of these devices is needed in order to effectively control power flows in the entire system.
- Both energy storage and FACTS devices are efficient at reducing the number of committed generating units. The highest reduction in the number of committed generating units is achieved in the case of their coordinated operation. However, energy storage can increase the number of committed generating units at certain time periods due to charging requirements.
- Although energy storage outperformed FACTS devices in the presented case study, energy storage is a more expensive technology than FACTS. Considering the FACTS prices from [40] and assuming NaS battery cost to be \$450/kWh, the overall installation cost of the FACTS devices in the case study is M\$17.7, while the installation costs of energy storage is over M\$405. This indicates that, at least for the case study at hand, FACTS devices are economically more viable option.

Future work will be focused on implementation of AC power flow model, which will enable to assess the impact of energy storage and FACTS devices on voltage levels and reactive power flows. Also, an important line of research is implementation of a security constrained unit commitment model. Energy storage and FACTS devices could act quickly after a contingency in a corrective manner in order to provide enough time to the system operator to perform re-dispatch of the generators. Another line of research worth pursuing is finding an optimal investment in FACTS devices and energy storage in terms of the locations and capacities.

Acknowledgement

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Appendix A. Big M formulation

In order to linearize the product of binary variable $x_{t,l^{\text{FACTS}}}$ and continuous variable $\vartheta_{t,b}$, the following big M reformulation is used:

$$x_{t,l^{\text{FACTS}}}\cdot sus^{\min}_{l^{\text{FACTS}}}\cdot(\vartheta_{t,b}-\vartheta_{t,n})-(1-x_{t,l^{\text{FACTS}}})\cdot M \leqslant flow_{t,l^{\text{FACTS}}} \quad \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.1}$$

$$(1-x_{t,l^{\text{FACTS}}})\cdot sus^{\max}_{l^{\text{FACTS}}}\cdot(\vartheta_{t,b}-\vartheta_{t,n})-x_{t,l^{\text{FACTS}}}\cdot M \leqslant flow_{t,l^{\text{FACTS}}} \quad \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.2}$$

$$x_{t,l^{\text{FACTS}}}\cdot sus^{\max}_{l^{\text{FACTS}}}\cdot(\vartheta_{t,b}-\vartheta_{t,n}) + (1-x_{t,l^{\text{FACTS}}})\cdot M \geqslant flow_{t,l^{\text{FACTS}}} \quad \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.3}$$

$$(1-x_{t,l^{\text{FACTS}}})\cdot sus^{\min}_{l^{\text{FACTS}}}\cdot(\vartheta_{t,b}-\vartheta_{t,n}) + x_{t,l^{\text{FACTS}}}\cdot M \geqslant flow_{t,l^{\text{FACTS}}} \quad \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.4}$$

$$\vartheta_{t,b} + (1-x_{t,l^{\text{FACTS}}})\cdot M \geqslant \vartheta_{t,n}\ \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.5}$$

$$\vartheta_{t,n} + x_{t,l^{\text{FACTS}}}\cdot M \geqslant \vartheta_{t,b} \quad \forall\ l^{\text{FACTS}} \in L^{\text{FACTS}},\ t \in T \tag{A.6}$$

$$M > \max\{flow_{t,l} + sus_l\cdot(\vartheta_{t,n}-\vartheta_{t,b})\} \tag{A.7}$$

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