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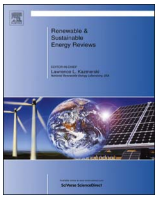

Recent approaches of unit commitment in the presence of intermittent renewable energy resources: A review

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ABSTRACT

Unit Commitment (UC) is an optimization problem used to determine the operation schedule of the generating units at every hour interval with varying loads and generations under different generational, environmental and technical constraints. With the significant increase of Renewable Energy Sources (RES) integration into the power networks, effects posed by these system changes to the UC are actively being studied and investigated by global researchers and operation engineers. To this end, this paper firstly provides a literature survey of UC concept, objectives and constraints. Different UC models developed for addressing RES impacts are also reviewed. Moreover, many algorithms have been proposed in the past few decades to optimize the UC problem. This work explores the necessity for alternative optimization approaches for UC solution. In doing that, the work uncovers the advantages and disadvantages of the existing methodologies so that future algorithms could be designed in retaining the advantages of the existing methodologies while avoiding the presented weaknesses. In addition, installation of energy storage devices to balance the fluctuation in power generation and their associated impacts on UC models are reviewed. The contents of this paper provide ready-to-refer and ready-to-use information for the researchers working in the field of UC.

1. Introduction

With increasing concerns about climate change and the need for a more sustainable grid, power systems have seen a fast expansion of Renewable Energy Sources (RES) in recent years. The economic and environmental benefits that arise from the integration of these resources into the power system lead to increased levels of system variability and uncertainty because of their intermittent nature. With high levels of RES penetrations in future power systems, there has been a growing need to study their impact on power system operations planning [1,2]. Complexities in balancing load with generation have introduced new challenges in regards to maintaining system reliability, while obeying system constraints at the least production cost [3–5].

With RES in the generation mix portfolio, the concept of “net load” arises because of the merit-order preference given to the RES units. The net load represents the demand that must be supplied by the conventional generation fleet if all of the Renewable Energy (RE) is to be utilized. The output level of the remaining generators must change more quickly and be set to a lower level with RES in the system [6]. As a result, more flexible resources are needed to meet the increasingly substantial ramping requirements in the system [7]. The ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons is described as the power system flexibility [8]. To keep the development of RE sustainable and to realize its full potential, the flexibility challenge to the operation of electric power system need to be solved [9].

Legacy operation and planning practices are gradually seen as becoming inadequate or ill-adapted in addressing this flexibility challenge. System operators need to evaluate and plan-ahead flexibility adequacy for their power systems in order to ensure feasible and economical operation under high RES penetration. Likewise, asset owners need to integrate the notion of asset flexibility as part of their investment and operations decisions [10].

In flexibility studies, variability and constraints are typically captured using Unit Commitment (UC) models [11,12]. UC is one of the key and a high priority sub-problem of generation and production scheduling problems. UC can be defined as the determination of generating units to be committed, during each interval of a short-term scheduling period (hours, a day or a week). The UC needs to meet and satisfy system demand, reserve requirements and electricity market context in an optimal, cost-efficient manner for the total scheduling period. It is also subject to system reliability, system capacity, transmission, and environmental constraints [13–15]. The electricity

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demand is varying constantly, causing variability and uncertainty to the electric system. Due to this inherent characteristic of the demand, the UC is employed to ensure that appropriate resources are available to meet demand and to maintain reliability through the expected range of system operating conditions. For this reason, UC is one of the most important critical decision processes performed by the system operator [16].

Recently, higher penetration of intermittent RES and more price-responsive demand participation have posed new challenges to the UC process [17]. It became important to have an effective methodology that produces robust UC decisions and ensures the system reliability in the presence of the increasing real-time uncertainty [18].

Following the described research trend, this paper aims to revisit the UC problem formulation and attempt to review the latest models of UC proposed in the context of high penetration of RES. Within this framework, the paper also provides a survey of optimization techniques used to solve the UC problem. Lastly, the impacts of specific RE and energy storage technologies to the UC computational tools are reviewed.

To achieve the above objectives, the paper is organized as follows; Section 2 presents the UC problem with problem formulation, objectives and constraints. Additionally, the evolution of RES-based UC models is reviewed within the Section 2.4. Section 3 provides a comprehensive survey of the optimization techniques employed in solving the UC optimization problems. Section 4 surveys the impact of intermittent renewables on UC problem formulations. Impact of energy storage is addressed at Section 5. Lastly, Section 6 provides the conclusion of the paper.

2. Unit commitment

Unit commitment problem has, commonly and mathematically, been formulated as a non-convex, large-scale, nonlinear, and mixed-integer combinatorial optimization problem with constraints [2,19,20]. The non-convexity is caused by the binary nature of the on/off decision. Non-linearity occurs due to non-linear generation cost curves and non-linear transmission constraints. The existence of a combination of the binary and non-linear variables necessitates the problem to be formulated as a mixed-integer combinatorial optimization problem. All these increase the difficulty of solving the UC problem. Therefore, researchers have been focusing on the development of an efficient, and near-optimal UC algorithms which can be applied to large-scale power systems [19].

From methodological perspective, two decision-sensitive stages are involved to solve the UC problem. The first is the UC decision and the second is the "economic dispatch" decision. The UC decision includes the determination of the generating units to be synchronizing and running at each hour of the planed horizon, taking in to account the units constraints, the start-up and shutdown, and the system capacity requirements, including reserves. The "economic dispatch" decision includes the allocation of the system demand and the spinning reserve capacity among the operating units during each specific hour of operation [19].

2.1. General problem formulation

The on-off states of the generation units or the "commitment decision" provides the first step toward the optimal solution. It is the discrete variables that determine if a particular unit is on or off at any particular time. U_n^t, the unit n at hour t, is 1, if the unit is "on line" and 0 if the unit is "off line" and is presented by Eq. (1) [21]

$$U_n^t \in \{0,\ 1\}. \tag{1}$$

Thus, the principal objective in UC is to prepare on/off schedule of the generating units in every sub-period (typically 1 h) of the given planning period (typically 1 d or 1 week) in order to serve the load demand and spinning reserve at minimum total production cost (fuel cost, start up cost, shut down cost), while meeting all unit, and system constraints.

In this study, the main objective is to efficiently minimize the total operation cost (*TOC*) over the scheduling period. This *TOC* is due to the fuel cost, start-up cost and shut down cost. The UC problem can be formulated as a mixed integer constrained, in which the overall objective function of the UC problem is described as follows by Eq (2).

$$\min TOC = \sum_{t=1}^{T}\sum_{n=1}^{N} (U_n^t .\ F_n^t(P_n^t) + U_n^t .\ S_n^t\ ). \tag{2}$$

where *TOC* is the total operating cost, *N* is the total generating units, *T* is the time horizon which is 24 h. The fuel cost of *n-th* thermal unit with the generating output *p-th* power at *t-th* hour $F_n^t(P_n^t)$ is expressed as a second order (parabolic) function of every unit output as follows:

$$F_n^t(P_n^t) = a_n(P_n^t)^2 + b_n P_n^t + c_n. \tag{3}$$

where a_n, b_n, c_n are the fuel cost coefficient of *n-th* unit; S_n^t is the generator start-up cost for restarting a de-committed thermal unit, which is related to the temperature of the boiler. The S_n^t depends on the time the unit has been off prior to start-up. By changing the on/off status of the units, the number of the start-up and shut down and their type (hot or cold) will also change [22]. The start-up cost can vary from a maximum "cold-start" value to a much smaller value if the unit was only turned off recently and is still relatively close to operating temperature [23], it is presented by Eq. (4)

$$S_n^t = \begin{cases} HSC_n, & if\ \ MDT_n < T_{off,\,n} \le MDT_n + T_{cc} \\ CSC_n, & if\ \ T_{down} > MDT_n + T_{cold,n} \end{cases} \tag{4}$$

where HSC_n and CSC_n are the hot and cold start-up cost of unit n respectively. The start-up cost and shut down cost values are usually identical and predefined constant values for each unit [24]. The shutdown costs are usually neglected and have been taken to be equal to 0 for all units and are excluded from the objective function.

The economic dispatch solution is the second step in the UC solution. For each UC decision achieved, its economic power generation output P_n^t is visualized as a (H×N) matrix with the real values of dispatch as shown in (5).

$$P_n^t = \begin{bmatrix} P_1^1 & P_1^2 & \cdots & P_1^N \\ P_2^1 & P_2^2 & \cdots & P_2^N \\ \vdots & \vdots & \ddots & \vdots \\ P_H^1 & P_H^2 & \cdots & P_H^N \end{bmatrix} \tag{5}$$

2.2. Variation of UC objectives

In solving the UC problem, a common objective for all power system operators is to ensure that sufficient generation is available for hours and days ahead of the operation time. This helps to ensure that operating reserves are appropriate and to maintain the system balance and meet the reliability standards. In addition to this common objective, further different objectives can be simultaneously considered for the UC problem depending on the operator's need. The following objectives are considered [2,15,25]:

I. Minimization of utility production (start-up, maintenance and fuel) cost.
II. Minimization the thermal power plant emissions.
III. Maximization of security and reliability constrains.

The first objective is the main objective function for UC scheduling is to achieve the most economical generation policy that could satisfy the local demands. Furthermore, the second objective can be consid-