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The challenges of the unit commitment problem for real-life small-scale power systems

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ABSTRACT

Small-scale power systems mainly present two particular problems when it comes to their modeling and solution. Due to their size, it is important to consider and meet various types of reserve requirements in order to have a reliable operation of the power system. It is also important to consider variable start-up costs in order to obtain a more accurate unit commitment. In this paper six different types of reserve requirements are considered for the unit commitment problem: spinning reserve, regulation reserve (AGC per unit), ten-minute reserve, ten-minute non-synchronized reserve, ten-minute operational reserve, and ten-minute distributed reserve. Additionally, a Mixed Integer Programming formulation is introduced to represent variable start-up costs. The model introduced here is currently in use by the Baja California (México) power system operator.

Introduction

Real-life Power Systems present Power System Engineers with various challenges when it comes to their modeling and solution. These challenges are different depending on their size. While large-scale power systems call for simplifications in their modeling in order to obtain fast solutions suitable for the day/week-ahead short-term planning, small-scale power systems call for a higher level of detail in the model in order to obtain good quality solutions suitable for their specific challenges such as reserve requirements and accurate start-up costs. Additionally, some of the simplifications used for the modeling of large-scale power systems are not suitable for small-scale power systems. This is the case of some linearizations of the quadratic cost function used for the unit commitment (UC) problem.

During the past forty years a number of different techniques have been proposed to solve the UC problem: Dynamic Programming [1], pure Lagrangian Relaxation methods [2–5], unit de-commitment, advanced priority listing [6], Benders Decomposition [7], Population-based techniques [8–11], Genetic Algorithms [12,13], and Heuristic Algorithms used to enhance Priority List and Lagrangian Relaxation Methods [14–17]. In the past decade, the trend for modeling real-life power systems has been Mixed Integer Programming (MIP) [18–23]. Recent reports show the ability of commercial optimization software to solve real-life UC problems based on MIP, Mixed Integer Linear Programming (MILP), and Mixed Integer Quadratically Constrained Programming (MIQCP) formulations. In fact, the tendency among power system operators around the world is to migrate from Lagrangian Relaxation (LR) based formulations to MI(L) P based formulations, i.e., PJM, California ISO, ISO New England, MISO, NYISO, and the Southwest Power Pool (SPP) in the USA; Comisión Federal de Electricidad (CFE) in Mexico; and Terna in Italy, to name a few.

The authors present in [23] a working algorithm for real-life large-scale power systems that is currently in use by CFE's Centro Nacional de Contol de Energía (CENACE), Mexico's power system operator, to perform the short-term planning for the Central Interconnected Power System. This Heuristic algorithm makes use of various optimization techniques such as MILP Quadratic Programming (QP), Quadratically Constrained Programming (QCP), and Dynamic Programming (DP). A commercial optimization software, IBM's CPLEX 12.6, is used as the main optimization engine for MILP, QP, and QCP. The DP is an in-house algorithm used to obtain the commitment of Combined Cycle Plants (CCPs) when represented with the component-based model. The Heuristic algorithm combines the global optimality capabilities of MI(L) P formulations with the highly detailed models available for CCPs using LR – DP formulations. The Heuristic algorithm is capable of solving up to 1-week scenarios with a 1-h time window with over 240,000 variables (integer and continuous) and over

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244,000 constraints (quadratic and linear) in under fifteen minutes.

The work presented in this paper was requested by the Baja California (BC) Power System Operator of CFE-CENACE to address five critical needs: consideration of several reserve requirements (spinning reserve, regulation reserve per unit, ten-minute reserve, ten-minute non-synchronized reserve, ten-minute operational reserve, and ten-minute distributed reserve), variable start-up costs, modification of the generators' cost function to better suit the pool of generating units present in their system, inclusion in the model of commercial transaction to buy an sell energy with neighboring power systems, and the consideration of external costs from the environmental impact of power production. The model in [23] is not directly applicable to small-scale power systems like the one in BC since it does not obtain solutions suitable for their specific needs. In this paper, the authors expand and modify the model in [23] to meet the needs of real-life small-scale power systems. The model introduced here has been in use by CFE-CENACE to perform the day/week-ahead short-term planning for the electrically isolated Baja California (BC) power system since July 2014.

A major contribution in the field of modeling the UC problem using MIP is the representation of variable start-up costs. The MIP formulation presented in this paper is far superior in computation time than the one presented in [24]. Even though the formulation in [24] is simple, it adds a considerable number of constraints involving binary variables impacting negatively the computation time. The novel MIP formulation in this paper takes into account the initial conditions of the generating units, availability, commit-ability, and dispatch-ability of the units during the planning horizon, and uses several segments to represent time dependant hot *and* cold start-up costs.

The remaining sections of this paper are as follows: Section 'The Mexican Power System: A bird's-eye view' presents an overview of the Mexican Power System (MPS). In Section 'Reserve requirements', the definition, along with the mathematical formulation, of the six different reserve requirements is presented. Section 'Variable start-up costs' presents a MIP based formulation for variable start-up costs. A linearization that takes advantage of the data of the generators in the BC power system is presented in Section 'Better linearization of the objective function'. Section 'Numerical examples' shows some numerical results that highlight the strengths of the model. Finally, Section 'Conclusion' closes the paper with relevant conclusion.

Throughout this paper, several references to the model in [23] are made. Due to space limitations, only the modifications and additions made to the model are explicitly stated. For the full detail of the heuristic model please refer to [23].

The Mexican Power System: A bird's-eye view

The Mexican Power System is divided into three electrically isolated areas, BC, Baja California Sur (BCS), and the Central Interconnected System (CIS). This is show in Fig. 1.

The elements modeled in each one of the electrically isolated power systems is outlined next:

- **Central Interconnected System:** The generation mix includes 215 Thermal Conventional Units (TCUs), 9 Combined Cycle Plants (CCPs), and 1 Hybrid Combined Cycle Plant (HCCP). CCPs range from two, three, and four Combustion Turbine (CT) generators and one Steam Turbine (ST) generator. The HCCP has three CT generators and one ST generator. All of them have a Heat Recovery Steam Generator (HRSG) per CT generator. The transmission system considers an electric network of 1563 nodes and 1479 transmission lines. The power demand covered with thermal dispatch-able units for any given one-week planning scenario ranges from 22400.00 to 30400.00 MW.
- **Baja California:** The generation mix includes 16 TCUs. The transmission system considers an electric network of 160 nodes and 99 transmission lines. The power demand covered with thermal dispatch-able units for any given one-week planning scenario ranges from 600.00 to 1600.00 MW.
- **Baja California Sur:** The generation mix includes 20 TCUs. The transmission system considers an electric network of 55 nodes and 34 transmission lines. The power demand covered with thermal dispatch-able units for any given one-week planning scenario ranges from 160.00 to 280.00 MW.

Reserve requirements

As stated before, small-scale power system operators are more concerned with the accurate modeling of several types of reserve requirements than those who operate large-scale power systems since they have at their disposal a wide range of generation resources. The different types of reserve requirements, along with their mathematical formulation, are outlined next. The notation used here is consistent with the one used in [23].

- **Spinning Reserve (SR):** This reserve requirement is met by all the thermal units that are synchronized (committed) to the system and that are able to increase their generation (dispatch-able) within the hour from their current dispatch level to their maximum output level. The spinning reserve requirement is set per region of the system. The SR requirement can be modeled as in Eq. (1). The first summation corresponds to the contribution that TCUs and CCPs make to the SR requirement while the second summation corresponds to the contribution that HCCPs[1] make to the SR requirement.

$$\sum_{u\in\mathcal{Z}_r}((\hat{\bar{g}}_{u,i}+\bar{l}^{AGC}_{u,i})\beta_{u,i}-g_{u,i}) + \sum_{ch\in\mathcal{CH}_r}\sum_{vh\in\mathcal{VH}_r}\left(\beta_{vh,i}\hat{\bar{g}}_{vh,i}-\sum_{u\in\mathcal{GH}_{ch_r}}\beta_{u,i}\hat{\bar{g}}_{u,i}\frac{\sigma_{u,i}}{1+\sigma_{u,i}}-g_{vh,i}\right) \geqslant l_{r,i}, \quad \forall\, r\in\mathcal{R},\ i\in\mathcal{I}. \tag{1}$$

- **Regulation Reserve (RR):** This reserve requirement is met by a pre-selected set of thermal units that are scheduled as must run units and whose minimum and maximum power limits are modified in order to provide AGC within two operating bands: maximum AGC limit, $\bar{l}^{AGC}_{u,i}$, and minimum AGC limit, $\underline{l}^{AGC}_{u,i}$. The maximum AGC limit is related to the SR. When the maximum generation limit of a TCU[2] is redefined as $\hat{\bar{g}}_{u,i}=\bar{g}_{u,i}-\bar{l}^{AGC}_{u,i}$, the amount that the TCU contributes to the SR would be *at least* $\bar{l}^{AGC}_{u,i}$. The maximum AGC limit contributes to the SR requirement as well as to the Ten-minute Spinning Reserve requirement. The minimum AGC limit has the purpose of preventing the generation of a TCU to drop below $\underline{g}_{u,i}+\underline{l}^{AGC}_{u,i}$. The minimum generation limit for a TCU is therefore redefined as $\hat{\underline{g}}_{u,i}=\underline{g}_{u,i}+\underline{l}^{AGC}_{u,i}$. These concepts are shown in Fig. 2.

  The minimum and maximum generation limits for TCUs, and CT units pertaining to CCPs and HCCPs are re-defined in order to consider the RR requirement as shown next:

[1] For a detailed discussion on CCPs and HCCPs, refer to [25,26]. For a detailed explanation on how CCPs and HCCPs contribute to the SR refer to [22].

[2] The contribution factor σ equals zero for TCUs and is grater than zero for CCPs and HCCPs.