Stability-constrained Unit Commitment with Water Network Loads

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***Abstract*—The paper presents an analysis of the economical and technical impact of Water Network Loads (WNLs) on the operation of power systems. The paper also proposes an iterative technique to solve both a unit commitment problem with the inclusion of conventional power generation, wind power and WNLs and a N-1 contingency analysis based on time-domain simulations. At each iteration, if the WNLs schedule in a given period is not acceptable for some of the considered contingencies, the unit commitment problem is solved again constraining the amount of dispatchable WNLs. The proposed technique is tested using the New England 39-bus 10-machine system adapted to include wind generation and WNLs.**

I. Introduction

A. Motivation

This paper originates from the observation that water systems are, at least in developed countries, among the largest electricity consumers [1]. Moreover, water network loads (WNLs) can be considered, from the viewpoint of the power system, as deferrable and flexible loads. Their operation, in fact, can be shifted depending on the generation cost. However, the operation of water loads is often not optimal. For example, in Ireland, the scheduling of WNLs is not widely coordinated. There is thus a clear economical opportunity for both the power system and the water network. On the other hand, in Ireland, WNLs are generally asynchronous machines, which are known to be a possible threat for power system stability when coupled with low inertia systems (see, for example, [2]–[6]). This is, again, the case for Ireland, where non-synchronous generation can be up to 55% of the total power supply [7]. Since it is expected that solving an economic dispatch would cluster WNLs in hours with low energy prices, which generally correspond to hours with high wind power penetration, the coordination of WNLs with the electricity market is a possible threat for the stability of the power system. In this paper, we present an appraisal of the economic and technical impact of WNLs on power system operation and we propose a stability-constrained economic dispatch model.

B. Literature Review

System operators generally solve a Unit Commitment (UC) problem based on a mixed integer linear programming (MILP) model on a *day-ahead* basis [8]. These UC models may contain hundreds of generators, sets of generator constraints, estimated hourly demand data and renewable generation profiles, and additional operational constraints. Subsequent *in-day* schedules may require modifications to the day-ahead schedule in real time based on actual demand, available generation capacity and unforeseen events.

A MILP model is described in [9], whereby the branch-and-bound search space is reduced by making certain assumptions about cycling of units in the planning horizon. Cycling issues include the turning on and off of units, and ramping units at their maximum ramp rates which leads to increased wear-and-tear. However, no data or computational results are given.

A more detailed MILP formulation is given in [10]. Computational results for the MILP model are presented using test data from [11]. Setting a 0.5% optimality gap, an integer solution is reported, which is an improvement on the results given in [11], [12]. A common approach is used, similar to [11], whereby shut down costs are ignored. Ramping constraints are described but no ramp limits are given. Reserve is assumed to be 5% of demand.

Some more recent work has focused on selecting strong MILP formulations [8], [13]–[18]. An analysis of valid inequalities is given in [8], [13], [14], with a focus on the start-up and shut-down ramp rates in [15], and combined cycle gas turbines in [16]. The minimum-up/down polytope associated with UC models is characterized in [17] with a focus on the start-up costs in [18]. An accurate modeling of unit cycling and operational costs is given in [19] and a proposal of sub-hourly UC is found in [20].

C. Contributions

The contributions of the paper are twofold, as follows.

- An economic dispatch based on the unit commitment problem suitably modified to account for WNL operating constraints. The proposed model, while approximation, clearly shows the opportunity to coordinate water networks with power system operation.
- An iterative technique, based on the UC problem above, to obtain a balance between the economic benefits and the stability of the power system. This is achieved through a stability analysis, based on time domain simulation, and by suitably constraining WNL power consumption in the UC model.

D. Organization

The remainder of the paper is organized as follows. Section II presents the economic dispatch problem with the inclusion of system and WNLs operating constraints. Section III describes the stability constraint included in the economic dispatch problem to prevent instabilities caused by WNLs and the proposed iterative technique. Section IV presents a case study based on the New England 39-bus system. Finally, in Section V, conclusions are duly drawn.

II. Unit Commitment Model

System Operators typically rely on mixed integer linear programming (MILP) approaches compared to traditional Lagrangian relaxation due to its ability to find the global optimal solution supported by an increase in computational power available [21]. A MILP implementation based on [10], [22], is utilized for this work.

A. Objective

The objective of Unit Commitment (UC) is to minimize the operating costs of the system over a planning horizon, traditionally minimizing power production, start-up and shut-down costs from each generator:

$$\min \sum_{k\in K} \left[\sum_{g\in G} \left[c_g^p(k) + c_g^{su}(k) + c_g^{sd}(k) \right] + \sum_{i\in I} \left[c_i^{su}(k) + c_i^{sd}(k) \right] \right], \tag{1}$$

where $k \in K$ is the index of time-steps, $g \in G$ is the index of thermal generators, $i \in I$ is the index of WNLs units and $c^p(k), c^{su}(k), c^{sd}(k)$ are the power production, start-up and shut-down costs for the respective units.

B. System Constraints

The primary UC constraint is the production constraint (2). The total production of the units at a given time must equal the system demand including losses. An approach to integrating renewable sources, such as wind generation, is to reduce the demand by the amount of renewable capacity available to give the net demand:

$$\sum_{g\in G} p_g(k) - \sum_{i\in I} d_i(k) = D(k) - W(k) + L(k), \quad \forall k \in K, \tag{2}$$

where p_g is a generator's production; d_i is the WNL power; and D, W and L are the system demand, available wind power and network power losses.

The reserve constraint (3) ensures that the maximum production available in a given time frame is greater than or equal to the demand plus a given reserve target. For this formulation, the reserve does not influence the operational cost directly and is held constant at 5% of the demand.

$$\sum_{g\in G} \overline{P}_g(k) + \sum_{i\in I} \left[e_i(k) - d_i(k) \right] \geq R(k) + D(k) - W(k) + L(k), \quad \forall k \in K, \tag{3}$$

where $\overline{P}_g$ is the generation capacity of a generating unit, e_i is the energy stored in the reservoir of a WNL, and R is the required reserve for the system.

The production cost for a thermal generator is typically modeled as a quadratic expression: $c^p = a + b \cdot p + c \cdot p^2$. Since MIPs require linear constraints, the production cost is modeled using a piecewise linear representation. A more detailed examination of the production cost constraints and thermal generator limits can be found in [10].

C. WNLs Operating Constraints

The electrical pumping limits of WNLs are:

$$\underline{D}_i \cdot u_i^d(k) \leq d_i(k) \leq \overline{D}_i \cdot u_i^d(k), \quad \forall i \in I, k \in K, \tag{4}$$

where $\underline{D}_i, \overline{D}_i$ are the WNL minimum and maximum pumping power limits, respectively, and u_i^d are binary variables representing a WNL on-off status. and the maximum and current storage capacity are constrained as follows:

$$0 \leq e_i(k) \leq \overline{E}_i, \tag{5}$$

$$e_i(k) = E_i(k-1) + d_i(k), \quad \forall i \in I, k \in K, \tag{6}$$

where $\overline{E}_i$ is the WNL capacity. The current capacity of a WNL relies upon its capacity from the previous time-step as well as its current state.

The start-up and shut-down pumping cost constraints for the WNLs are:

$$c_i^{su}(k) \geq C_i^{su} \cdot \left[u_i^d(k) - u_i^d(k-1) \right], \quad \forall i \in I, k \in K \tag{7}$$

$$c_i^{sd}(k) \geq C_i^{sd} \cdot \left[u_i^d(k-1) - u_i^d(k) \right], \quad \forall i \in I, k \in K \tag{8}$$

where C_i^{su} and C_i^{sd} are the fixed start-up and shut-down costs of a WNL.

Note that, for simplicity, in this paper we do not model the water consumption, which would affect the amount of stored capacity of WNLs.

III. WNL Stability Constraint

As discussed in the motivations of this paper, in [4], the authors demonstrate how the inclusion of induction machines in a power system with reduced inertia can lead to undamped oscillations and instability. Therefore, when defining the operation of WNLs, it is necessary to limit the loading level of WNL devices, which, in the Irish system, are pumps driven by induction motors. Moreover, the effect of wind power uncertainty should be considered, specially if the wind penetration in the system is high.

If only economical constraints are considered, it would be expected that WNL devices will preferably consume energy during periods of power surplus in the system, or during high wind periods due to the low marginal price, and vice versa. In this way, however, the stability of the power system can be compromised at peak times of wind penetration.

In this paper we propose to mitigate the negative effects of WNLs on system stability through a simple, yet effective approach, which consists of including an additional limitation on the power consumed by WNLs at a given time step, as follows:

$$\frac{\sum_{i\in I} d_i(k)}{D(k)} \leq r(k) \tag{9}$$

where $\sum_{i\in I} d_i(k)$ and $D(k)$ are the total pumping load of the WNLs and system load at period k, respectively; and r is the maximum pumping power to demand ratio that can ensure system stability while optimizing economical profit.

Figure 1 shows the flowchart of the proposed iterative technique to indirectly include a WNL-based stability constraint into the UC problem. The algorithm starts with $r = 1$, i.e., no limit is imposed on the amount of WNLs that can be allocated in the system. After solving the UC problem, a power flow analysis is solved to confirm that the economic solution is feasible in steady-state. If not, the UC problem is solved again with the inclusion of adjusted values for the system losses L. Once the UC and power flow analysis converge to a feasible solution, r is calculated and the dynamic analysis is solved. This involves a set of small-signal stability as well as time-domain simulations for most credible contingencies (e.g., N-1 contingency analysis). If any contingency leads to instability, r is reduced and the UC problem is solved again. The amount with which r is reduced can be defined based on experience. Note that the smaller the reduction, the higher the number of iterations of the algorithm but, likely, the more economic the final solution. In the case study, r is decreased in steps of 0.01. The process continues until both the power flow and dynamic stability analysis converge successfully.

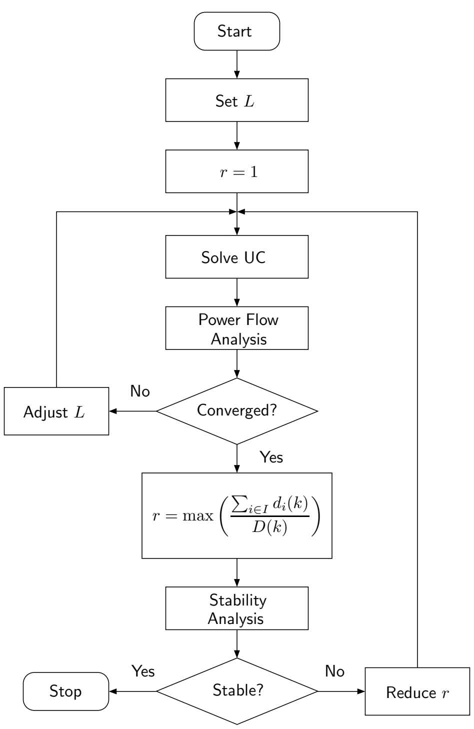

Fig. 1: Flow chart of the proposed strategy.

IV. Case Study

The effectiveness of the proposed approach is tested based on the New England 39-bus 10-machine test system which is used for all simulations (see Fig. 2). The system model includes both primary voltage (AVR and PSS) and frequency (turbine governor) regulation. All dynamic data of the New England 39-bus, 10-machine system can be found in [23].

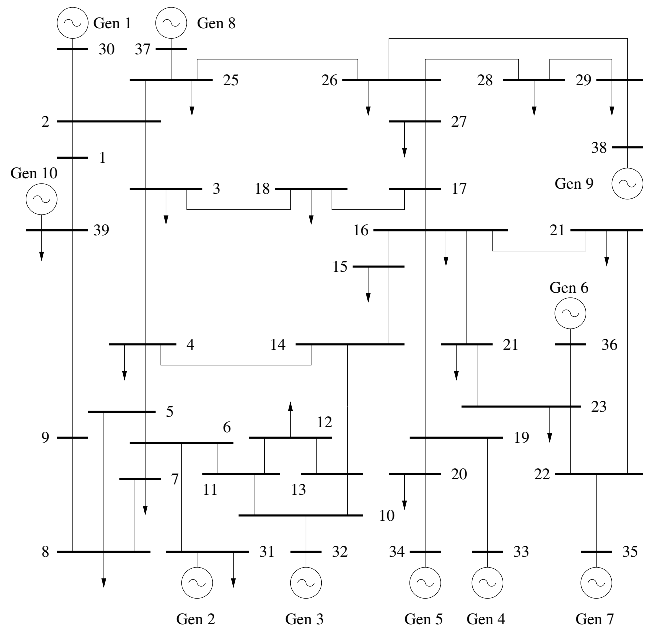

Fig. 2: New England 39-bus, 10-machine system.

The following modifications and remarks on the 39-bus system are relevant:

- Synchronous generators at buses 30, 32 and 38 are replaced by wind power plants with the same capacity as the original machines, totaling 40.4% of the total generation. Wind generators are modeled as 5th order doubly-fed induction generators (DFIGs) [24]. Turbine governors and AVRs are also included in the wind plants.
- For the dynamic analysis, a deterministic Mexican Hat Wavelet model is used to describe the wind for the plants at buses 32 and 39 (W_1 and W_2, respectively), while the wind of the plant at bus 38 (W_3) follows a Weibull distribution. Detailed models of these wind distributions can be found in [24]
- Four WNL units are connected to buses 7 (WNL_1), 18 (WNL_2), 25 (WNL_3) and 26 (WNL_4). The WNLs are described by a third order, single-cage induction motor model [24]. The maximum active power that these units can consume is 384.5, 395.0, 560.0 and 347.5 MW, respectively.
- Constant power load models are considered for the dynamic analysis.

The UC model is implemented in GAMS [25] and solved using CPLEX, which is a MILP solver with an optimality gap of zero. Small-signal and time domain simulations are obtained using Dome, a Python-based power system software tool [26]. The Dome version utilized in this case study is based on Python 3.4.0; ATLAS 3.10.1 for dense vector and matrix operations; CVXOPT 1.1.8 for sparse matrix operations; and KLU 1.3.2 for sparse matrix factorization. All simulations were executed on a 64-bit Linux Ubuntu 14.04 operating system running on a 8 core 3.60 GHz Intel Xeon with 12 GB of RAM.

A. Solution of the initial Unit Commitment Problem

The total period of the considered UC problem is six hours, split into 6 intervals of 1 hour. These hours span from midnight to 6 am. This period is chosen for two reasons: (i) the loading level is low and, hence, the percentages of wind power generation and WNL demand with respect to the total load can be high, thus possibly triggering instability; and (ii) the consumption of water during this period is negligible, which makes it unnecessary to model the reduction of energy stored in the WNL reservoirs. The output power of the wind power plants is considered to be fixed for each hour. Different loading levels with respect to the 39-bus system base case for each hour are considered. Hourly data of the load and wind power are provided in Table I.

TABLE I: Hourly UC data.

Hour	**1**	**2**	**3**	**4**	**5**	**6**
Loading level % of Base Case	90	94	82	86	98	103
Power from W_1 [MW]	587	613	804	635	484	252
Power from W_2 [MW]	382	398	524	413	314	164
Power from W_3 [MW]	487	509	669	527	401	209
Wind Penetration (%)	24	24	40	30	20	10

The wind penetration in Table I is defined as the ratio of the total wind power over the total power generation at the same hour. With the aim of simplifying the analysis, the seven synchronous machines are operating every hour. Ideal, lossless WNLs are considered, and energy stored in the reservoirs can be regarded as a system reserve. Transmission lines and transformer limits are not considered in this study.

B. Iterations

For the base case, i.e. with no limits on the WNLs, the objective function is found to be €1,805,862. The costs related to each generating unit are listed in Appendix A. Note that wind and hydro power production costs are considered zero in this study. The WNL pumping schedule is shown in Table II.

TABLE II: WNL pumping schedule

Hour	**1**	**2**	**3**	**4**	**5**	**6**
$\sum_{i\in I} d_i(k)/D(k)$	0	0	0.163	0.034	0	0

According to Tables I and II, the third hour has the highest wind and induction motor penetrations. Therefore, stability analysis is conducted based on the data for hour 3. For this hour, the total power generated by the synchronous machines is 3131 MW, and the pumping power of each WNL is listed in Table III

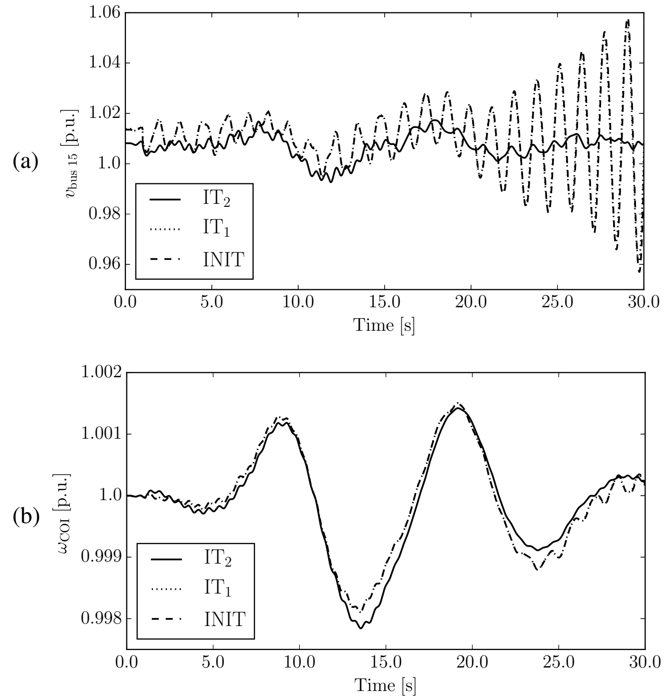

Fig. 3: Dynamic response of the 39-bus system facing a line outage. (a) Voltage of bus 15; (b) Frequency of the Center of Inertia (COI).

TABLE III: Hour 3 - WNL pumping power

WNL unit	**1**	**2**	**3**	**4**
Consumed power [MW]	207.1	0	360.0	247.5

The dynamic response of the 39-bus system is studied next. With this aim, the outage of the line connecting buses 4 and 5 at $t = 1$ s is considered. The response of the 39-bus system without constraining WNL power consumption is shown in Fig. 3 as INIT. The voltage at load bus 15 (Fig. 3(a)) shows undamped oscillations after the line outage that are not acceptable for the system. Therefore, the WNL power limit in (9) must be included in the UC model. The transient behavior of the system using the UC solutions of iterations 1 and 2 (IT_1 and IT_2, respectively) of the proposed iterative technique are also shown in Fig. 3. As can be observed, the bus 15 voltage magnitude trajectory, as obtained for IT_2, is stable and well damped.

The maximum pumping power ratio r, the total generation cost z, and the actual active power losses $P^{\mathrm{a}}_{\mathrm{loss}}$ for every iteration are shown in Table IV. Note that the power loss in the UC model is set as 60 MW. Results of this analysis, as well as the dominant eigenvalues for each scenario are also listed in Table IV. Eigenvalues are computed as part of the power flow analysis to make sure that the operating point is stable. It is relevant to observe that, in this case, ensuring stable operation of the system leads to a negligible increase in the total generation cost (only 0.014%).

TABLE IV: Hour 3 - WNL pumping power

Scenario	**INIT**	$\mathbf{IT_1}$	$\mathbf{IT_2}$
r	1.0	0.16	0.15
z [€]	1,805,862	1,805,921	1,806,121
$P_{\rm loss}^{\rm a}$ [MW]	50.92	50.62	54.813
Dominant Eigenvalues	$-0.06 \pm 5.19j$	$-0.07 \pm 5.19j$	$-0.18 \pm 5.08j$

V. Conclusions

The paper focuses on the economical and technical impact of WNLs on power system operation. WNLs are flexible loads as their operation can be shifted depending on the generation cost. Simulation results clearly show that properly coordinating WNL and, hence, the water network, with the electric demand offers an opportunity for both energy systems. On the other hand, results also show that, due to the dynamic behavior of WNLs, which are mostly operated through induction machines, WNLs can significantly reduce the stability of power system. This very likely occurs in systems with low inertia and, in particular, with high penetration of wind power. It is to be expected, in fact, that a high amount of WNLs will be scheduled during wind generation peaks, as energy is cheaper during such periods. The case study demonstrates that the proposed iterative method effectively reduces the destabilizing effect of WNLs without noticeably affecting the market clearing price.

Several improvements of the proposed technique can be implemented, as follows. The major limitation of the proposed approach is that the UC and the dynamic models are solved independently. This clearly leads to suboptimal solutions. Moreover, the power system losses are only indirectly taken into account in the UC problem and this causes an inevitable mismatch between the solutions of the UC problem and the dynamic analysis. A more detailed UC problem, including generation ramp constraints and water consumption would also improve the realizability of the results. The authors are currently working on these improvements and plan to apply the proposed technique to a real-world model of the all-island Irish grid.

Appendix

A. Unit Commitment Data

In Table V, u_0^d is the initial status of the WNL, where $u_0^d = 1$ means that the WNL is in pumping mode, whereas $u_0^d = 0$, the WNL is shut down.

TABLE V: WNLs units data (values in MWh and €).

WNL	$\overline{E}$	$\underline{SG}$	E_0	u_0^d	C^{su}	C^{sd}
1	384.5	116.9	0	0	3000	2000
2	395.0	79.0	0	1	2000	5000
3	560.0	112.0	200.0	0	4000	1000
4	347.5	69.5	100.0	1	3000	1000

TABLE VI: Synchronous generation data.

Gen	$\overline{P}$ [MW]	$\underline{P}$ [MW]	a [€/h]	b [€/MWh]	c [€/MW^{2}h]
2	675	102	57	1.73	0.0031
4	834	126	58	1.63	0.0211
5	670	102	75	1.97	0.0398
6	858	130	67	2.22	0.0712
7	739	112	90	2.78	0.0079
8	713	108	86	2.51	0.0413
10	330	50	90	2.78	0.0173

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