OPTIMAL POWER FLOW CONSIDERING OPERATION OF WIND PARKS AND PUMP STORAGE HYDRO UNITS UNDER INTEGRATION OF RENEWABLE ENERGY SOURCES

Marek Kurajda

ABSTRACT

The purpose of this article is to describe a module that solves the optimal power flow in a power system, which includes wind parks and pump storage hydro units owned by Independent Power Producers (IPP) under large-scale integration of dispatchable renewable energy sources (RES). When IPP are present in the system, the operation of wind parks and pump storage hydro units is based on special contractual agreements for buying or selling energy between each IPP and the power utility, so that additional physical and economic operation constraints must be taken into consideration for the optimal operation of the system. Also the optimal co-ordination of RES units is examined so that the best exploitation of RES is succeeded. A successive linear programming approach is utilized for the solution of the problem.

Index Terms — optimal power flow; dispatchable renewable energy sources; independent power producers

1. INTRODUCTION

The purpose of the Optimal Power Flow (OPF) is to define the power system control variables in order to optimize an objective function while satisfying a set of non-linear equality or inequality constraints expressing the secure operation limits of the power system.

The OPF problem [1] is a large-scale non-linear constrained optimization problem of great complexity and since it's first introduction several modifications, approaches and solution methodologies have been proposed and they are described in the literature [8]. The problem is further complicated when renewable energy sources (RES) and independent power producers (IPP) are present in the system. The purpose of this article is to describe a module that solves the optimal power flow in a power system, which includes wind parks and pump storage hydro units owned by IPP under large-scale integration of dispatchable RES. The module is intended for on line operation and advises the operator for the appropriate resetting of all control parameters so that optimal economic and secure operation is succeeded.

2. THE BASIC OPF FORMULATION

The OPF problem seeks to adjust the control variables available in the system, in order to minimize the cost of power generation. In general, the OPF problem can be stated as:

Find vector u, which:

Min $f(u,x)$

$$\text{s.t } g(u,x) = 0 \qquad (1)$$

$h(u,x) \leq 0$

Where:

u : is the control vector, consisting of all control variables available to the dispatcher such as real power output of conventional thermal units, voltage magnitudes of generators, tap transformers, switched capacitors and reactors and active output of IPPs.

x : is the state vector, consisting of the voltage magnitudes and phase angles of all the buses in the system

f : is the cost function of operation. In general the cost of operation is the sum of the operation cost of the conventional units and the cost imposed by the operation of the independent producers.

g : these include the typical load flow equations, expressing balance of real and reactive power at each bus of the system.

h : these are the system operating limits and they include:

1) Control variable limits: each control variable’s value is restricted by an upper and lower limit.

2) Reactive generation limits: for each conventional unit reactive generation is restricted by an upper and lower limit.

3) Security limits: These include circuits loading and voltage magnitude constraints at load buses.

4) Other operation limits: These include wind power penetration limit.

3. THE RENEWABLE ENERGY PLANTS OPERATION

A . General

The operational cost of a power system depends on the load conditions, type of generating units and fuel used. If RES power units are present in the grid, additional physical and economic operation constraints must be taken into consideration for the optimal operation of the system. The problem’s complexity due to RES units is mostly affected by the existence of IPP, and the economic and physical constraints are related to the contracts between each IPPs and the Power Utility. The additional difficulties to the OPF problem imposed by the presence of RES units can be described as follows:

1) The objective function accounts not only for the operation cost of the conventional units but also for the operation cost of wind parks and pump storage hydro units owned by IPPs operating in the system.

2) The real power generated from the wind parks is a function of the wind velocity. The dispatcher can control the generated power output of a wind park by switching on or off units of the wind park.

3) The reactive power, required for the operation of the wind park, is a function of the generated real power produced.

4) A pump storage hydro unit may operate either producing energy injected to the power system using the water stored or consuming energy from the power system in order to pump water into the reservoir.

5) A total penetration limit, or local penetration limits restrict the total real power generated from all the wind parks of the system or wind parks of particular areas respectively.

6) Special contractual agreements determine the operation limits of each RES unit owned by an IPP.

B. The Wind Park’s Model

The operation of a wind park depends on the following parameters:

1) The purchase price (Sk/kWh) of power produced.

2) The minimum - maximum power accepted from the utility (according to the contract between the IPP and the utility).

3) The reactive power needed for the wind plant to operate.

4) The number and type of the wind generators installed in each wind park.

In this article it is assumed that a wind park can operate in one of the following operating modes:

a) Wind park under fixed schedule. In this case the output of the park is fixed and is decided by the system operator on the basis of contractual agreements. The remaining control variables are determined so that they minimize the operation cost all other production units and plants.

b) Wind park under economic schedule. In this case the output of the park is included in the control variables and is constrained by an upper and lower predetermined limit, decided by the system operator on the basis of contractual agreements. The power output of the park and other control variables are determined so that they minimize the operation cost of the system.

A description of the model used in this article to simulate the production of a wind park follows. In a wind park several wind turbine generators (WTG) are installed and they are available to operate. It is assumed that the WTGs are asynchronous generators, requiring reactive power to operate. At each time interval each WTG can provide a specific active output, calculated by the turbine's Power-Velocity curve. The reactive power consumed by each WTG depends on the type of the generator and it is modeled through a P-Q curve; through this curve constant power factor can be also simulated.

The total active output of the wind plant is the sum of the WTG in operation. By switching on or off a number of wind turbines of the park, a different active power output can be obtained. In this way at each time interval a wind park's possible active output can achieve discrete values. The total reactive power needed for the wind park operation, assumes also a discrete value and is modeled through one of the following ways:

a) The reactive power of the park follows the reactive power of each wind turbine or

b) The reactive power of the park follows a constant power factor (due to additional control equipment -converters, or capacitor banks connected at the output of the park).

In summary for each wind park a discrete values array of its total output active power can be constructed. Since the reactive power is dependent on the active power, at each active output discrete value corresponds a reactive discrete value.

C. The Pump-Storage Hydro Unit's Model

The operation of pump storage hydro unit depends on the following parameters:

a) The status of the unit: producing energy using the water stored or absorbing energy to pump water into the reservoir. This status is input to the OPF problem.

b) The selling or purchase price (Sk/kWh) of power produced or consumed respectively.

c) The minimum - maximum power accepted or contributed respectively from the utility (according to the contract between the IPP and the utility).

The operation mode of a pump storage hydro unit may be one of the following:

a) Pump storage hydro unit under fixed schedule. In this case the output, or respectively the load, of the unit is fixed and is decided by the system operator on the basis of contractual agreements.

b) Pump storage hydro unit under economic schedule.

In this case the output, or respectively the consumption, of the unit is included in the control variables and is constrained by an upper and lower predetermined limit, decided by the system operator on the basis of contractual agreements.

In this article it is assumed that all pump storage hydro units use synchronous machines, providing a constant voltage output, and reactive power varying between an upper and lower limit.

4. PROPOSED METHODOLOGY

The proposed methodology to solve the OPF problem presented, is an iterative algorithm, which utilizes a Linear Programming (LP) approach [3,4]. Each iteration involves the following major steps:

A. Identification and linearization of failed operating constraints.

In this step circuit flows, bus voltage magnitudes, and reactive power outputs are computed and the violations or near violations are identified and stored. These form a subset h_f of the system operating limits h. Linearization of operating constraints requires the computation of sensitivities with respect to the control variables [1,7], i.e. the computation of

$[dh_f(x,u)/du]=[\partial h_f(x,u)/\partial u] - X \,.\, [\partial g(x,u)/\partial u]$ (2)

where,

$X=[\partial h_f(x,u)/\partial x] \,.\, [\partial g(x,u)/\partial x]^{-1}$ (3)

We define the wind parks active output control variables vector as u_w, and all the other control variables vector as u_m.

During the linearization procedure the i-th wind park's active output control variable $u_{w,i}$ is handled as a continuous variable.

A. fit function $Q_{w,i}=f_{w,i}(u_{w,i})$ is applied on the wind park's P-Q discrete curve, expressing the relationship between the active power produced by the wind park and the reactive power required to operate. The computation of sensitivities in (2) takes in consideration the relationship between the active and the reactive power [7].

B. Analysis of coherent operating constraints:

For large power systems, the set of failed constraints may be large. However, the number of failed operating constraints, which dictate the control resetting actions may be small. These constraints are called active or effective. If correction to a constraint leads to correction of other constraints then these constraints are labeled "coherent". From the efficiency point of view, it is important to include in the model only a reduced subset h_f, of all failed operating constraints h_f.

Coherent constraints are identified as follows:

The mathematical analysis theorems of dependent functions are applied on the set h_f of the linearized equations of the failed constraints. In this way the relationships between the equations are detected and groups of dependent constraints are identified. When two or more failed operating constraints belong to the same group are classified as coherent. Among the coherent constraints of each group the appropriate are selected to form the subset h_f, to be included in the model.

C. Formation and solution of the LP model

At each iteration the updated values $u+\Delta u$ are determined by solving the following optimization problem with respect to the variations Δu :

$\min \sum C^T \,.\, \Delta u$, (4)

subject to:

$\Delta h_{min} \leq A \,.\, \Delta u \leq \Delta h_{max}$ (5)

$\Delta u_{min} \leq \Delta u \leq \Delta u_{max}$ (6)

where matrix A includes the sensitivities of the linearized constraint equations subset h_f, the linearized power balance equation and the wind power penetration limits equations with respect to the control variables u; C is the coefficients vector

$[df(u,x)/du]$ of the linearized objective function f with respect to the control variables u.

The LP model is solved via the revised simplex algorithm, using routines provided by the IMSL math library.

D. Convergence testing

After each LP solution, the system control variables are updated and a power flow solution is obtained. Convergence testing is based on the total operating cost change between iterations, tolerance is used to terminate the iterations resulting to the final values for the control variables. After the iterations terminate to a solution, a routine is applied in order to adjust the wind parks active output to the nearest discrete values. To avoid possible changes to the final operating state of the power system, the linear programming module is re-applied, excluding the wind parks control variables from the optimization problem [7].

5. *CONCLUSION*

In this article a methodology to solve the optimal power flow problem in a power system which includes Independent Power Producers under large integration of renewable energy sources was presented.

The methodology developed incorporates 3 additional producers under various contractual agreements.

2) It simulates the operation of pump storage hydro units connected to the system.

3) It simulates the operation of wind parks connected to the grid, taking into consideration the reactive power needed for their operation.

4) It handles the wind power as dispatchable.

Given an initial state of an electric power system, wind power penetration limit, resetting limits of all control variables, the operation mode of each IPP and the characteristics of wind parks and pump storage hydro units, an optimal economic operating state can be found, satisfying the safety operation limits of the system. The model presented provides also the capability to examine the optimal exploitation of the RES in a power system.

A successive linear programming based optimal power flow algorithm was presented, as well as the IPP and wind parks operation models.

6. REFERENCES

[1] Kolcun, M., Griger, V.: Riadenie prevádzky elektrizačných sústav. Mercury-Smékal, Košice, 2003, 288 p., ISBN 80-8906176-1,

[2] Hrubina, K.: Optimálne riadenie I. a II. 1. vyd. Edičné stredisko VŠT v Košiciach, 1987, 367 p.

[3] A. P. Meliopoulos, G. Contaxis, R. Covacs, N.D. Reppen and N. Balu, "Power System Remedial Action Methodology", IEEE Trans. Power System, Vol.PWRS-3, May 1988.

[4] P. Ristanovic: "Successive linear programming based OPF solution", IEEE-PES Tutorial course, 96 TP 11 1-0, pp. 1-9.

[5] Kolcun, M. - Beňa, Ľ. - Duch, M.: Optimálne nasadzovanie elektrární do denného diagramu zaťaženia ES SR. In: ELEKTROENERGETIKA 2003: Symposium Proceedings, Stará Lesná, 16.-18. september, 2003. Košice: Mercury-Smékal, 2003, pp. 212-213. ISBN 80-8906180-X,

[6] Šimůnek, P., Mészáros, A.: Moderné trendy ekonomiky elektroenergetiky. Mercury – Smékal Košice, 2003, 98 p., ISBN 80-89061-73-7,

[7] G. C. Contaxis and A. G. Vlachos, "Consideration of wind parks operation in the optimal power flow problem", Proceedings of the 1999, IEEE Budapest Power Tech Conference, BPT99-211-05.

[8] Trojánek, Z., Tůma, J.: Řízení elektrizačních soustav. Ediční středisko ČVUT Praha, 1990, 306 p.

Author address:
Ing. Marek Kurajda
Department of Electric Power Engineering
Technical University of Košice
Mäsiarska 74
041 20 KOŠICE, Slovak Republic
E-mail: marek.kurajda@tuke.sk
Tel: + 421/55/602 3560
Fax: + 421/55/602 3552