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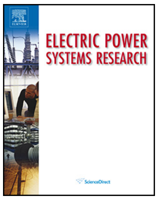

Optimisation of costs and carbon savings in relation to the economic dispatch problem as associated with power system operation

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ABSTRACT

In this paper, the costs and carbon savings in the economic dispatch (ED) problem of the power system operation are optimised. Energy demands and generation are forecast and assimilated using ensemble Kalman filter (EnKF). Optimisation is performed using the ensemble-based closed-loop production optimisation scheme (EnOpt). The real energy parameters of thermal units with green generators (wind farm) are used to test the methodology. The ability of the EnKF to predict, and the robustness of the EnOpt to optimise costs and the resultant carbon emissions are demonstrated. The proposed approach addresses the complexity and diversity of the power system and may be implemented in operational conditions of energy suppliers.

1. Introduction

In a power system, the grid operator aims to appropriately tune power flows with minimal systems losses [1]. However, the tuning of parameters in randomised manner without optimal planned strategy may increase the power operating costs, and also the environmental effects due to unnecessary firing-up of power plants. Instead of randomly tuning the parameters without proper arrangements and strategies, the optimisation of parameters through a selected objective function is required [1,2]. The objective function is formulated to optimise operational strategies such as generating costs, reservoir production level, and system losses. With the increasing need to optimise power generation, the economical dispatch (ED) models were introduced. Due to the environmental concerns the ED problem has been undergoing major enhancement addressing the reduction of carbon emissions. Such enhancement is needed due to the legislation on the 2050 low carbon economy that requires the reduction of emissions by 80% below 1990 levels, with 40% reduced emissions by 2030 and 60% by 2040 [3]. The legislation by D.G. Clima [3] requires the implementable and affordable participation of all sectors in the transition to low-carbon economy.

These legislations have led to implementation of various low carbon energy plans, with rising need to quantify the environmental impacts. One of the earlier modelling frameworks that addresses this is the UK MARKAL-Macro developed by Strachan and Kannan [4]. The model predicts the aggregated energy demand response and technological change through the 2007 UK Energy White Paper policy framework. It provides the quantification of cost-economical implications due to the long-term decarbonisation strategies.

In the present paper, the novel modelling approach focusing on the quantification of costs and carbon emissions is proposed in the electricity generation which optimises costs and carbon savings. The approach is based on the ensemble Kalman filter (EnKF) combined with optimisation using ensemble-based closed-loop production (EnOpt) algorithm. The framework integrates the electrical data from generators (green and non-green energy) predicted and assimilated by EnKF and optimised by EnOpt, with operational constraints in a power system. In principle, this framework may be implemented at the level of the UK National Grid (the transmission operator) in collaboration with energy suppliers and distribution network operators.

The paper is organised as follows. Section 2 outlines modelling of energy systems, reviews the carbon factors, emissions and savings. The later includes the review of uncertainties in the power system and the introduction of the EnKF application. The review of the ED problem is also performed, along with the earlier optimisation technique in the power system and further introduces the

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Nomenclature

Acronyms

BAU	business-as-usual
BMRS	balancing mechanism reporting system
ED	economic dispatch
EnKF	ensemble Kalman filter
EnOpt	ensemble-based closed-loop production optimisation scheme
HH	half hourly

Index

α_{λ}	tuning parameter that determines step size
λ	iteration index
i	generating fuel index
j	ensemble member index
k	index for data times in EnOpt model
t	time step index
t_k	time step at data times k in EnOpt model

Parameter

$\lambda_{\max}$	maximum iteration step
$C_{\max,i}$	maximum fuel cost at ith generating unit
d	model prediction
$E_{\max,i}$	maximum amount of energy generation for ith generating unit
$E_{\min,i}$	minimum amount of energy generation for ith generating unit
$h_{\max,i}$	maximum price penalty factor at ith generating unit
m	real parameters of energy data
N_e	total number of ensemble members
N_i	total number of fuels or generating units
N_k	total number of data times for EnOpt model
N_t	total number of time steps
N_x	total number of control variables
NE	total number of generating units that contribute carbon emissions
NG	total number of thermal units
NW	total number of wind generators
$W_{\max,i}$	maximum amount of generation for ith wind generator
$\mathcal{E}_{\max,i}$	maximum emission cost at ith generating unit

Variables

$\bar{\mathbf{x}}_{\lambda}$	mean value of control vector $\mathbf{x}$ at iteration λ
$\mathcal{C}(\bar{\mathbf{x}}_{\lambda}, Y^{u})$	mean value of objective function $\mathcal{C}(\mathbf{x}_{\lambda,j}, y_j^{u})$
$\mathbf{x}$	vector of control variables
$\mathbf{x}_{\lambda}$	control vector $\mathbf{x}$ at λth iteration
$\mathbf{x}_{\lambda+1}$	updated control vector $\mathbf{x}$ at iteration $\lambda + 1$
$\mathbf{x}_{\lambda,j}$	realisation of control vector at iteration λ and ensemble j
$d_{i,t}^{G}$	fuel cost coefficient for ith generating unit at time step t
$d_{i,t}^{W}$	wind cost coefficient for ith generating unit at time step t
$d_{i,t}^{\mathcal{E}}$	emission cost coefficient for ith generating unit at time step t
$d_{obs,j}$	perturbed observations at jth ensemble member
E_i	energy generation at ith thermal generating unit (MWh)
W_i	energy generation at ith wind generating unit (MWh)
x_i	control variable for ith generating unit
Y	ensemble of state vector y in matrix form
y	state vector
Y^{p}	*priori* ensemble of state vector y in matrix form
Y^{u}	*posteriori* ensemble of state vector y in matrix form
Y_{G}^{u}	*posteriori* ensemble estimates of thermal units
Y_{W}^{u}	*posteriori* ensemble estimates of wind generators
y_j^{p}	*priori* jth ensemble member of state vector y
y_j^{u}	*posteriori* jth ensemble member of state vector y
$\mathcal{C}(\mathbf{x}, Y_{G}^{u})$	objective function for EnOpt model. It is the function of control vector x and *posteriori* ensemble estimates Y_{G}^{u} of thermal units
$\mathcal{C}(\mathbf{x}_j, y_j^{u})$	objective function for EnOpt model. It is the function of realisation of control vector $\mathbf{x}_j$ at ensemble j, and *posteriori* y_j^{u} at jth ensemble member
$\mathcal{C}_{O}$	optimised cost function
$\mathcal{C}_{S}$	cost savings
$\mathcal{C}_{Y}(\mathbf{x})$	objective function for costs with control vector $\mathbf{x}$
$\mathcal{C}_{BAU}$	BAU cost function
$\mathcal{E}_i$	emission function for ith generating unit
$\mathcal{E}_{O}$	optimised carbon emissions ($ktCO_2$)
$\mathcal{E}_{S}$	carbon savings ($ktCO_2$)
$\mathcal{E}_{BAU}$	BAU carbon emissions ($ktCO_2$)
$\mathcal{C}_{Y}(\mathbf{x})$	objective function for costs with control vector $\mathbf{x}$
$\mathcal{C}(\mathbf{x}_{\lambda,j}, y_j^{u})$	objective function for EnOpt model. It is the function of realisation of control vector $\mathbf{x}_{\lambda,j}$ at iteration λ and ensemble j, and *posteriori* y_j^{u} at jth ensemble member

EnOpt application. Section 3 presents the methodology for the ensemble assimilation and optimisation of costs and carbon savings. Section 4 presents the case study of the ED problem using the formulated EnKF and EnOpt algorithm. Section 5 discusses the numerical simulation results. Section 6 concludes.

2. Modelling of power systems

2.1. General modelling approaches in power system

The power system modelling is expanded substantially in order to mitigate the negative impact towards the environment, where the modelling includes the optimisation of the power system in the area of linear and nonlinear problems [1,5]. The general power system modelling approaches include the economic dispatch (ED), optimal power flow, unit commitment, and optimal load shedding [2,5]. In this paper, the ED problem is applied to optimise the costs and carbon savings of the renewable and non-renewable energy.

2.2. Environmental impact of power generation

The UK carbon factors (also known as carbon footprints) are calculated by the company Ricardo-AEA [6], with quality assurance performed by the Department for Environment, Food and Rural Affairs (DEFRA) [7] and the Department of Energy and Climate Change (DECC) [8]. The results are reported annually by DEFRA. The latest data are available in the form of Microsoft Excel spreadsheets on the website [9], where statistics are currently stored for the years 2002–2015.

Carbon factors for fuel type with uncertainty ranges are reported in the post-notes of the Parliamentary Office of Science and Technology [10,11] and Carbon Trust [12], in grams (or kilograms) of carbon dioxide (CO_2) equivalent per unit of energy (kWh). Since generated energy is given in kWh and carbon factors in $kgCO_2/kWh$,

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