Applied Energy 189 (2017) 395–402

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Demand side management of an urban water supply using wholesale electricity price

R. Kernan *, X. Liu, S. McLoone, B. Fox

School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, United Kingdom

HIGHLIGHTS

- The proposed method provides a realistic method of cost minimisation in a water supply system.
- Optimisation was carried out on the basis of wholesale electricity cost.
- This method encourages wind power utilisation without explicit operator intervention.
- The method was demonstrated on a benchmark simulation system as well as a real water supply network.
- Water utility costs decreased significantly while wind power utilisation increased.

ARTICLE INFO

Article history:
Received 20 October 2016
Received in revised form 12 December 2016
Accepted 15 December 2016

Keywords:
Demand side management
Real time pricing
Genetic algorithms
Wind energy
Renewable energy
Optimisation
Water pumping

ABSTRACT

Municipal water supply consumes large quantities of electrical energy to move water from catchment areas to service reservoirs near centres of population. Pumping does not necessarily occur round the clock, but rather when necessary to uphold constraints relating to reservoir levels and system pressure. There is a degree of flexibility in the timing of pumping that makes it an excellent candidate for Demand Side Management, meaning that it can provide opportunities for improving power system operation and reducing electricity costs for the water utility. The extent of this flexibility depends on a number of factors. This study examines the optimisation of two water supply systems - the 'Van Zyl' benchmark system and a representation of the supply for the city of Belfast, Northern Ireland. The potential to employ intelligent operation of pumps to help bolster uptake of variable wind generation is assessed, as is quantification of the potential savings for a water utility. The results show significant potential savings for the water utility as well as a substantial increase in the utilisation of wind power.

1. Introduction

The drive to phase out fossil-fired generation has increased investment in renewable generation. In Northwest Europe, wind is an abundant renewable resource [1], and, as such, significant efforts have been made to increase the penetration of wind generation in power systems.

Ireland, although composed of two political jurisdictions (the Republic of Ireland and Northern Ireland), has one synchronised power system and Single Electricity Market (SEM). The Irish power system supports a relatively small population of 6.5 million people and has 750 MW of HVDC interconnection with Britain [2]. A target of 40% of all electricity is to come from renewable sources by 2020, predominantly from wind power [3]. This target causes some issues for the Irish system, some of which are unique due to its relative isolation and limited available interconnection.

Modern wind turbines, unlike traditional synchronous generators, do not provide inertia to the power system as their rotating masses are connected to the grid through power electronics. Significant power system inertia mitigates frequency transients during system faults and large disturbances [4], and hence it is necessary to maintain a minimum level of system inertia. Unlike other countries with high penetrations of wind power (such as Denmark), Ireland has only limited HVDC interconnection, which provides no inertial support. Because of this constraint, System Non-Synchronous Penetration (SNSP) is currently limited to 55% on the Irish power system [5], with any renewable generation above this level wasted. Due to its variable nature, wind power is non-dispatchable apart from curtailment by a system operator.

In order to meet the high targets for wind power integration, it is estimated that the SNSP limit would have to be raised to 70% to

* Corresponding author.
E-mail address: rkernan01@qub.ac.uk (R. Kernan).

http://dx.doi.org/10.1016/j.apenergy.2016.12.082

Nomenclature

i	time period ($i = 1, 2, \ldots, 24$, 60 min/period)	$F_{p,i}$	pump p flow rate, ith period (l/s)
m	Mourne supply	M_i	energy cost per unit, ith period (£/kW h)
n	Lough Neagh supply	$D_{p,i}$	flow from service reservoir p, ith period (l/s)
d	inside pipe diameter (m)	$P_{p,i}$	pump p energy consumption, ith period (kW h)
h_f	head loss (m)	$R_{p,i}$	service reservoir p water volume, ith period (l)
C	Hazen-Williams pipe roughness coefficient	$R_{p,max}$	maximum water volume, service reservoir p (l)
L	pipe length (m)	$R_{p,min}$	minimum water volume, service reservoir p (l)
Q	volumetric flow rate (m^3/s)		
E_i	electricity cost, ith period (£)		
W_i	wind generation as % of total in ith period		

avoid excessive curtailment [2]. This will be a significant challenge, especially for conventional generators [5], but presupposes that generation must be varied to meet a varying demand beyond the operator's influence. Under this regime, the system operator would have more problems when controlling a power system with high penetrations of wind power than one without. Dispatchable generation would see much greater variation in output in order to address wind variability, which is undesirable as it prevents generators operating at their most efficient settings.

Demand Side Management (DSM) provides a means of mitigating the regulation duty of conventional generation. DSM has traditionally been seen as a method whereby a system operator or utility would exert direct control over load [6]. The main contribution of this work is in investigating whether market-driven DSM can provide improvements in wind power utilisation to the power system without explicit system operator intervention, but rather by the load responding to changes in system price. This is the first study to optimise a water network on the basis of Real-Time Pricing (RTP) and quantify both the energy cost savings and wind power utilisation.

2. Scope for optimising water supply

2.1. Demand side management

With DSM, supply of managed load is encouraged when net demand (consumer demand less renewable generation) is low. The incentive is the lower cost of electricity at such times. Conversely, the supply of managed load is discouraged when net demand, and electricity price, are high. The boost to net demand when renewable generation is plentiful eases the SNSP constraint.

DSM is regarded as an important part of the future operation of power networks and as such has been the focus of a number of studies. Where DSM has been carried out based on energy cost, it has primarily been on the basis of Time of Use (ToU) pricing [7–9]. These are multi-rate tariffs which change several times a day. Although promoting energy use during off-peak times, ToU tariffs do not track the actual market price of electricity and thus do not provide an incentive for consumers to respond to specific events, such as generator outages or high-wind scenarios. ToU tariffs reflect only the general trends of electricity cost and usually have no more than four changes per day. Increased penetrations of variable generation such as wind generation mean that price peaks do not always occur at the same time of day, as high penetrations of low marginal cost generation during peak times reduce the need for low merit generation, thus reducing market prices. ToU tariffs do not reflect these day-to-day variations. An RTP tariff, based on the wholesale cost of electricity, offers a realistic means of tracking the variation in system price.

RTP-based DSM has been implemented in [10–13] with significant savings in energy cost. Finn et al. in [12] optimised residential load on the basis of RTP and saw increases in wind power utilisation of up to 23.3%, while in [13], RTP-based optimisation of industrial loads saw wind power utilisation increase by 5.8% while also reducing energy cost.

A common theme is the aggregation of flexible residential loads through the use of smart meters and a central controller in order to minimise decision making and maximise savings [14,7,8]. Such schemes have the disadvantage of involving a large number of stakeholders (residential consumers) who must voluntarily submit to having their energy consumption controlled externally. However, the potential has been shown for significant savings in energy costs for consumers. Vanthournout et al. in [15] found that it was difficult to maintain involvement of residential consumers in RTP schemes due to response fatigue - automation was required in order to make it viable.

DSM has also been demonstrated as being viable for provision of balancing reserve for wind generation [8].

Industrial loads frequently have a higher degree of operational flexibility than residential loads [11,13]. Industrial consumers represent 42% of global electrical consumption. Industrial units are large compared to residential or commercial loads and are centrally controlled and owned, reducing the complexity of co-ordination and thus making them very attractive for DSM [16]. In [11], DSM of aggregated residential load was compared with that of representative commercial demand and a number of typical industrial processes. A 10% saving in energy costs was seen with the industrial DSM, compared to 5.8% for commercial and 5% for residential. Similarly high savings were also seen in [10].

2.2. Public water supply

Public water supply is an excellent candidate for the application of DSM due its significant potential for a large number of operating modes. Water networks are centrally owned and controlled and would require minimal modification to allow optimised operation.

Water pumping can be classed broadly as an interruptible load. In [16], a steel mill was optimised on the basis of several smart pricing scenarios. Under each pricing model, optimal scheduling resulted in higher profit, although higher profits were seen with ToU pricing compared to RTP - the steel mill which was modelled operated on a batch cycle, meaning that once a batch started it could not be interrupted - making it less suitable for taking advantage of the higher level of variability of RTP compared to ToU pricing. Water pumping can be interrupted, provided reservoir level constraints are maintained and wear from pump switching is considered. The basic layout of a water supply system can be seen in Fig. 1. Large, centrally controlled pumps are used to move water from catchment areas to service reservoirs (SRs) near centres of population, from which water flows to consumers. The hydrostatic head of these SRs is used to maintain system pressure and, as long as SR water levels are maintained between minimum and