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A RECEDING-HORIZON OPF FOR ACTIVE NETWORK MANAGEMENT

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ABSTRACT

To be able to integrate significant levels of dispersed renewable energy generation (DG) into rural distribution networks, the conventional 'fit-and-forget' approach will have to be evolved into a 'connect-and-actively-manage' system using Active Network Management techniques. Coordinated scheduling and control of DG and network assets can avoid having to constrain renewable capacity and significantly increase energy production and economic performance of DG in weak or congested networks. This paper proposes a time-dependent receding-horizon OPF technique for the 'pseudo-real time' scheduling of network control set-points to better integrate DG into previously passive areas of distribution networks. The methodology demonstrates the potential for real time reconfigurable autonomous network control over windows of previously problematic network power flows. Modelling of the real-time controller application is performed through a purpose-built pseudo-real time distribution network simulator.

INTRODUCTION

In a period of strong political support for the progressive increase of generation from sustainable renewable energy sources [1], it is certain that levels of Distributed Generation (DG) will continue to increase rapidly. The intermittent and spatially variable characteristics of these resources, as well as the technical impacts of DG [2], are becoming increasingly problematic for distribution network operators (DNOs). In response there is strong support for the principle of a smarter grid and the adoption of active network management (ANM) practices [3]. The technical and economic advantages from implementing real-time active network control measures and the combination of these through advanced communication systems are strongly supported as a means of better integrating new network participants and exploiting the existing network assets [4-5]. While it is certain that the actual integration of active network management by DNOs will strongly depend on the economic and regulatory framework, the technical feasibility of the network to support high DG penetration levels must first be fully explored. The innovative 'connect and actively manage' approach for connecting new DG can better accommodate more resources into the existing networks. While initial projects focus on independent generator control strategies [6] to retain network regulation, the proposed method creates a mechanism for varying system regulation while retaining system security by scheduling variable network set-points and smoothing the fluctuation of control to retain secure and stable system operation.

In this work, a receding-horizon steady-state Optimal Power Flow (OPF) technique is proposed for minimising the curtailment and hence maximising the energy capture from intermittent DG. Further benefits of optimising system usage are also discussed.

OPF techniques have been successfully utilised in power systems operations for many years [7]. Recent OPF formulations have been applied to better understand the connection capacity of distribution networks [8]. Existing OPF practices are formulated off-line from steady-state network conditions and scenarios of consistent generation and demand levels. In the proposed OPF, time series analysis of intermittent DG is considered in an on-line application with the use of forecast data.

Here, an active network scenario is envisaged where coordinated scheduling of network assets and actively managed DG control set-points are used as a means to allow maximum absorption of renewable energy while respecting physical constraints and statutory limits.

A high voltage distribution network considering varying demand and generation levels is analysed over a window of previously problematic network power flows. Results are presented remarking on the advantages of the online-based OPF and the receding-horizon methodology in allowing improved use of existing system assets, further penetration of sustainable power developments and increased energy capture from renewable energy sources.

METHODOLOGY

The proposed time-dependent OPF technique has been established to operate continually in discrete time, using network sampling and forecasted profiles of generation and demand.

Formulation

In the basic formulation the objective function is a minimisation of the real power curtailment for all time and spatially variable distributed generators (g) in the set of DGs, (G) to maximise the real power output and energy capture across the finite horizon:

$$Min \sum_{g \in G} p_{g}^{curt}(k + j|k)$$

Here, *(k + j|k)* represents a finite control horizon and a projected solution across *j* discrete time steps from current time (*k*), subject to current network conditions at (*k*). The optimisation will be subject to (i) the physical laws governing power flow; (ii) the voltage and thermal limitations of the network plant; and, (iii) the Active Network Management control variables and rate-of-change constraints. The formulation was adapted from a robust multi-period OPF [7], to allow 'real-time' data transfer and continuation of the optimised periods in a finite control horizon. The control variables, parameters and time dependent constraints are critical for proper formulation of the optimisation. The following subsections describe some of the considerations embodied in the work.

Coordinated Voltage Control - In a practice referred to as coordinated voltage control (CVC), on-load tap changing transformers (OLTC) and Voltage Regulators (VR) are allowed to move freely in combination with DG developments performing dynamic control of network voltage.

Adaptive Power Factor Control - Power Factor Control (PFc) varies the voltage level at the point of connection for a DG by actively adjusting the DG power angle variable to absorb/inject reactive power as required to support network operation. Here, all DG plants are assumed to possess the technological capability and are initially installed in the optimisation with the provision to provide network support in the form of reactive power compensation, termed Adaptive PFc.

Energy Curtailment - As a first option to increase the level of DG connection in distribution networks DNOs have permitted the curtailment of DG power output when it will lead to violation of regulation in the network. In the OPF real power curtailment is formulated as negative generation (or positive demand) that opposes each DG output. Control response between discrete time intervals is limited to 5% of rated power output per minute to reflect communication and ramp rate delays.

The Receding Horizon Principle

The receding horizon principle [9] involves solving the finite horizon active network OPF, using forecast data and sampled network measurements as the initial state. With advancement of each discrete time step, initial network control action(s) in a projected network reconfiguration are implemented and optimal network configuration is computed for the next finite control horizon. In this manner, the control horizon is continually receding and the network settings are actively and progressively tracking optimal network configuration.

The advantage of the finite horizon OPF approach means network control decisions can be constructed, not solely on the immediately prevailing network conditions, which may lead to inappropriate and discontinuous control switching, but also on the forecasted nodal power injections. In addition the periodic re-appraisal of system goals applied in the receding-horizon approach better facilitates homeostatic network regulation for systems with highly intermittent participants.

Modelling and Implementation

The solution architecture and a software environment [10] have been developed to perform time-sequential power flow resolution simulating 'real time' network operation across progressive steady state intervals. The system demonstrates an ability to assess the pseudo-real time implications and predict system consequences of varying power flow with active control strategies to manage the overall network response while continually optimising yield, asset and system response. The OPF is formulated externally in the AIMMS optimisation modelling environment [11] using the nonlinear programming solver CONOPT 3.14A. Plug-and-play of the OPF into the software environment via the COM interface allows the OPF to be implemented online. The separation of the OPF from the power flow solver invites the potential to explore how the proposed solution responds to misrepresented, erroneous or missing network and/or forecast data.

CASE STUDY

UKGDS EHV1 – AM Network

The simplified EHV1 Network from the U.K. Generic Distribution System (GDS) [12] was used to demonstrate the potential for real time reconfigurable network control to optimise DG headroom and energy capture. The system is a section of weakly meshed network of parallel feeders supplied by two equivalent 30-MVA 132/33-kV transformers with a voltage regulator between buses 8 and 9 (Figure 1). Reflecting standard U.K. practice the voltage envelope is ± 6% of nominal.

Three DG locations were considered. Two wind farms were connected at buses 7 and 16 and a tidal array at bus 12. A varying demand pattern and annual generation profiles based on 30 minute intervals for two independent wind farms and a modelled generic tidal form were utilised to assess the maximum headroom for new capacity in the network [8]. Results indicated the network could, using ANM, securely accommodate DG developments of 8, 11 and 9MW at buses 7, 12 and 16 respectively.

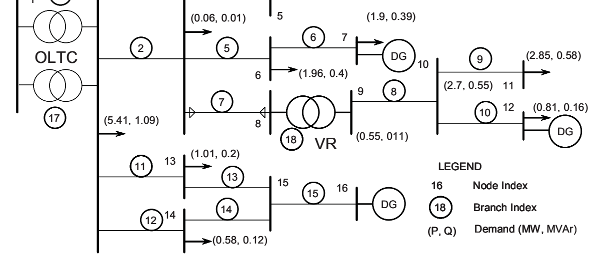

Figure 1: UKGDS EHV1 - Active Management Network [12]

Pseudo-Real Time Evaluation

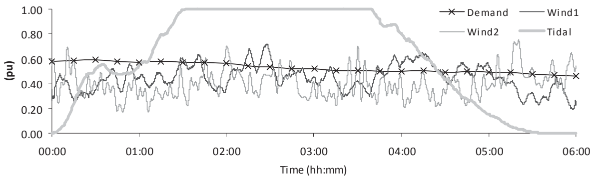

Figure 2: High Resolution Load and DG Profiles

For pseudo-real time evaluation, high resolution time series generation profiles, shown in Figure 2, were obtained from historic and modelled resources for two independent wind farms and tidal resource measurement. Wind resource profiles had a second by second resolution; modelled tidal resource profiles had a resolution of thirty seconds; and, a varying demand pattern with a resolution of fifteen minutes. The demand pattern and tidal resource are linearly interpolated inside the pseudo-real time simulator for sequential power flow solutions and in the OPF for forecast data. A key advantage in the methodology is that it is easily scalable to an arbitrary time scales. This will allow for extensive analysis on the frequency and scale of the variability in future networks. In the following analysis, a steady state time interval of 10 minutes was chosen for the OPF interval period, while steady-state power flow solutions were performed at intervals of 1 minute to simulate, and visualise, the high frequency variation in network power flows.

Results

A simple initial evaluation of the network's ability to integrate new generation capacity would be to consider the conventional passive approach to network regulation and curtailing DG output systematically to restore network conditions when statutory limits are breached. In this scenario, the restricted voltage targets for the OLTC and VR are retained and the DGs are operated with power factor control to prevent interference with alternative network control infrastructure. Power factor settings of 0.97 capacitive, Unity and 0.97 inductive, are considered and a variable adaptive PFc scheme is studied to simulate the potential for individual hybrid DG control.

Due to the adopted locations of DG and the characteristics of the resource, it is the voltage differential between buses 11 and 12 which constrains further DG power production most of the time.

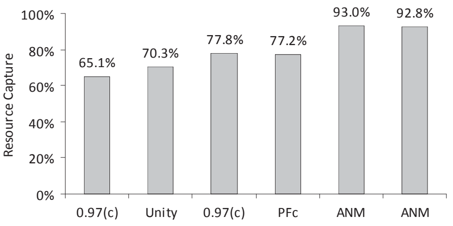

Figure 3: Percentage of Available Energy Captured during Case Study

Voltage profiles at these actively constrained buses (11 and 12) are depicted in the following discussion. With the passive approach, as the tidal energy resource ramps up, the voltage at bus 12 quickly exceeds the statutory limits resulting in the vast majority of the available power being curtailed. This is to be expected as the DG connection is vastly oversized for this type of connection. Figure 3 shows comparatively small improvements in handling the voltage rise issue with the transition from a capacitive power factor to an inductive one. However, even with a paradigm shift in the operation of DGs, as illustrated by the adaptive PFc approach, which merely serves to mitigate the voltage rise in these conditions, DNOs will never exploit the full change in the methodology of distribution networks themselves.

By changing the operational paradigm and adopting online active control algorithms for wide area network regulation these further means of ANM can substantially increase the headroom and reduce the energy curtailed when network power flows become problematic, as shown in Figure 3. In terms of control strategies, the methodology here aims to make the best use of the existing system by relaxing the pre-defined voltage targets for the OLTC and VR. The existing infrastructure is then utilised to perform network wide, CVC in combination with PFc and energy curtailment to extract, year on year, the maximum resource from existing networks.

Preliminary results from the receding-horizon OPF emphasise the real potential of existing networks given a globally optimum and synergetic approach to network control. In the first instance, the OPF is formulated with a single-period (next step) control horizon.

Greatly improved energy capture from the network is demonstrated and the voltage profile at the constraining buses is actively regulated to ensure quality of supply. Incidents of voltage violation are for the most part small and quickly resolved. That being said, with the quick ramp-up of the tidal resource at around the tenth minute, we see the OPF initiate a pre-emptive network condition that causes the network to experience a voltage drop. All voltage perturbations in the simulations, such as this, result directly from the use of forecast data and, particularly in this example, the rounding and/or sampling of highly variant load and resource values. The present data analysis approach is to sample maximum anticipated loading and generator levels in each single step scenario.

As illustrated in Figure 4, voltage continuation is restored, via an error signal and an immediate re-analysis, using sampled current state load and resource values.

To mitigate the frequency and severity of any network regulatory violations, current work is investigating how the extension of the control horizon may improve continuity and stability of the OPF method. In the multi-period formulation of the OPF, the next step horizon is extended by six 10 minute intervals. The time-wise VR tap settings for the test case are shown in Figure 5; here we see some evidence that the receding-horizon evaluation can smooth

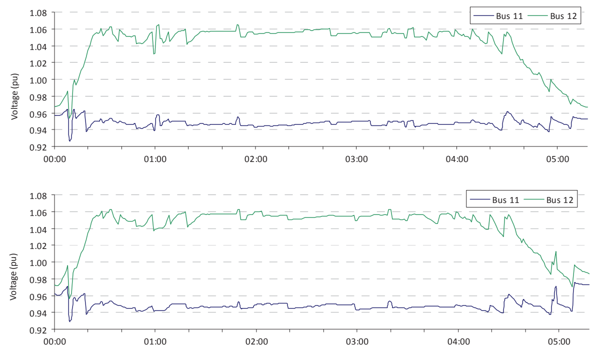

Figure 4: Voltage Profiles for single step OPF formulation (Top) and Extended Control Horizon (bottom).

the ANM reconfiguration. For example, better continuation of the tap settings can be seen around the 1 hour mark during the problematic ramp-up of the tidal energy resource and during the 2 hour mark where the wind resource at bus 16 rises and falls sharply. It is anticipated that further improvements can be achieved in the extended control horizon methodology. Fundamentally, the methodology is flexible and also applicable to higher resolution timescales of steady-state intervals. In additional studies of the multi-period OPF, the control horizon is divided into five 2 minute intervals with linearly interpolated forecast data and solved periodically. With the higher resolution control process, the stark steps in voltage levels caused by the fast-acting changes in the tidal resource output have been mitigated, but further examples of discontinuous control switching were introduced and as it stands, may not be all together completely practical.

Further work is blending a means of optimal network operation into the energy capture OPF to specifically target high resolution discontinuous control switching. In future, tuning of the control stepping sequence may be accomplished to improve the frequency and speed of control actions matching individual network topologies with bespoke controller protocols.

Finally, it should be noted that the extended outlook in the receding-horizon application has the potential to pre-warn DG developments and DNO control circuits of probable impending changes, and may develop a sense of continuing the ‘wait-and-see’ approach to control actuations in distribution networks.

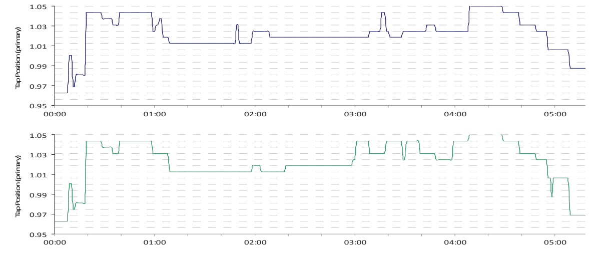

Figure 5: VR Tap Settings on the primary winding for single step (Top) and horizon (bottom) formulations.

CONCLUSIONS

A receding-horizon OPF technique is introduced to maximise the energy capture from intermittent and spatial variable renewable energy resources. Initial findings of the research are reported and the resulting ability of pseudo-real time control strategy is demonstrated. Results emphasise how fully coordinated and synergetic use of distribution network can avoid having to constrain renewable capacity and significantly increase energy production and economic performance of DG in weak or congested networks. Preliminary tests indicate that real time active control measures can result in frequent and discontinuous control switching. The receding-horizon methodology retains the ability to improve continuity and stability of steady-state control settings and further work promises to match re-configurable network set-points with individual network topologies with bespoke controller protocols.

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