AN EVOLUTIONARY PROGRAMMING TOOL FOR ASSESSING THE OPERATIONAL VALUE OF DISTRIBUTED ENERGY RESOURCES WITHIN RESTRUCTURED ELECTRICITY INDUSTRIES

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Abstract

There is growing world-wide and Australian interest in the greater potential role of distributed generation and demand-side resources within the electricity industry. These distributed resources can offer promising economic and environmental benefits for power system operation. There are considerable challenges, however, in developing modelling tools that can explore the operational value of such resources within restructured electricity industries. This paper describes a Dual Evolutionary Programming approach where software agents for power system resources co-evolve optimal operational behaviours over repeated power system simulations. The tool is applied to a simple case study exploring the potential operational synergies between significant PV penetrations and distributed energy storage options including controllable loads. The case study demonstrates this tool's capabilities in modelling the potentially complex operational behaviours of these distributed resources including stochastic PV outputs and loads with varying daily demand profiles, thermal energy storage, charging and discharging constraints and self-leakage.

1. INTRODUCTION

Electricity industries world-wide are entering a period of fundamental change under the driving forces of market-base restructuring, growing climate change concerns and the emergence of a range of distributed resources that represent possible alternatives to conventional, centralised, electricity supply options.

1.1 Distributed resources

Distributed resources are technologies within the distribution system that can actively participate in power system operation [1]. They include:

- renewable energy sources including solar, photo-voltaics (PV) and thermal, wind and biomass,
- small-scale fossil fuelled generation and combined heat and power (CHP) plants powered with engines, gas turbines or fuel cells,
- direct energy storage such as chemical 'battery' technologies, super- conducting magnetic systems and flywheels, and
- electrical end-uses that can actively respond to changing conditions; for example, 'smart' buildings that can control their heating and cooling to exploit inherent thermal energy storage.

Such resources have some markedly different characteristics from conventional centralised power system resources, including their:

- technical operation as seen, for example, with renewable resources whose energy flows are intermittent,
- small unit scale yet potentially large numbers that might be aggregated into significant resources,
- potential environmental benefits from utilising renewables or enabling highly efficient energy end-use; for example, through cogeneration,
- location near end-users, and
- potential ownership by end-users and close integration with their processes and equipment as seen, for example, with cogeneration.

1.2 The operational value of DRs

Distributed resources bring a rather different range of potential values to electricity industry operation than conventional resources. The operational 'energy' value within an electricity industry represents the combined outcome of changing costs and benefits of all participating generation, network elements and electrical demands. This energy value therefore varies over time and location while being subject to a range of uncertainties such as contingencies. It also incorporates various 'Quality of Supply' attributes and, hence, associated ancillary services.

The operational arrangements of traditional monopoly utilities and restructured electricity industries alike do not fully capture all of these energy values. For example, the Australian National Electricity Market represents one of the more successful market designs worldwide, however, restructuring to date has been largely at the wholesale level and retail markets still do not provide appropriate time, location and Quality of Supply price signals [2].

The possible energy value of distributed resources depends on timely energy provision, yet also includes their potential to reduce network costs, and improve Quality of Supply for end-users. Maximising this value and awarding it to the appropriate participants will require considerable changes to present industry arrangements. One important requirement, certainly for high penetrations of distributed resources, will be more formally integrating their operation into ongoing market processes [3].

1.3 Tools for scheduling DRs

In this paper we describe an evolutionary programming tool that can explore the potential value of large penetrations of distributed resources actively participating within a restructured electricity industry. The tool focuses particularly on the operational decision making scheduling challenges within the industry at half to one hour decision making intervals over a time horizon of days to weeks.

This is a challenging optimisation task even in the absence of distributed resources. There are competing participant objectives and potential market power, inter-temporal links with respect to unit commitment and fuel scheduling and considerable uncertainty. Overall industry performance is determined by the coordinated interactions between all participants.

Distributed resources add additional challenges. Their integration into electricity markets will see greater numbers of participants in the market. They may have very complex operating characteristics including dependence on intermittent renewable energy flows, or integration into industrial processes. Their owners will often have primary objectives that don't specifically relate to energy production.

The tool we have developed shows some promise in exploring the coordinated operation of large amounts of distributed resources. In Section 3 and 4 we describe its application to assessing the operational value of PV, and its potential synergies with distributed energy storage options.

2. DUAL EVOLUTIONARY PROGRAMMING

The general dual evolutionary programming (DEP) method for analysing decentralised coordination of power system operation is described in [4]. The method is based on a relatively general modelling framework for power system resources, the electrical network and decentralised system coordination. Each resource has a decision agent responsible for direct control of that resource and all interactions with a system coordinator – typically the market/system operator in a restructured industry. To model the decision making of these agents, DEP uses:

- a future benefit (benefit-to-go) function to incorporate the impacts that an agent's present decisions will have on its future operation, and
- a declared benefit function that describes an agent's communications with the system coordinator.

Finding the most appropriate specific instances of these future and declared benefit functions for each agent is achieved using evolutionary computation as outlined in Figure 1. Feasible behaviour 'solutions' for an agent are a set of future benefit and declared benefit functions over the scheduling period. The performance of a particular feasible solution for each agent is determined through repeated power system simulations. Agent objectives may be individually profit maximising, collaborative within a portfolio of resources or aim to contribute to industry-wide optimal outcomes. Evolutionary methods of selection, recombination and random variation are then used to evolve the population of solutions over repeated simulations.

The approach here is called Dual Evolutionary Programming because these functions driving behaviour are in the dual space – that is, they are not physical output, decisions for the resources but, instead, the expected value of different physical outputs. Actual physical operation for each resource is determined by the system coordinator, as seen in electricity markets.

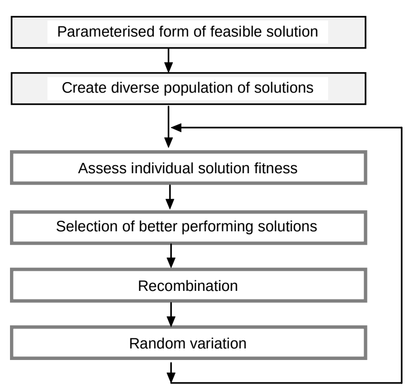

Figure 1. General procedure for evolutionary programming.

Natural evolution has proven to be a remarkably robust and effective optimisation approach for independent participants in complex, highly interconnected and uncertain environments. Although evolutionary computation can not claim to fully emulate this process, it appears to be a powerful approach for some problems with similar attributes.

Evolutionary computation can also offer good computational performance for some problems because it combines elements of both global and local search methods [5]. The initial population of solutions will generally be broadly spread over the feasible solution space. This coarse global search, however, quickly narrows to promising local areas of this solution space.

There are also some potential disadvantages of evolutionary computation to consider. These include the lack of guarantee of optimality, and potential difficulties in finding the most appropriate evolutionary ‘settings’ for population size, elitism, recombination rate and random variation rate.

With respect to our particular optimisation problem, DEP requires only that operation of the resources and power system can be simulated, and some measure of performance calculated under different instances of agent behaviour. This allows the tool to accommodate complex resource models with inter-temporal links that can overwhelm strictly analytical approaches. DEP can also optimise complex objective functions, including potentially competing objectives between agents, and objectives that can only be evaluated over time; for example, risk averse behaviour. It is also possible to incorporate resource uncertainties into agent behaviour; for example, participants can evolve future and declared benefit functions that depend on forecasts of wind or solar input over the coming day.

3. CASE STUDY: POTENTIAL OPERATIONAL SYNERGIES BETWEEN PV AND DISTRIBUTED STORAGE

Wind energy and photovoltaics are both promising renewable energy resources that seem likely to play an increasingly important role in electricity industries world-wide. Both represent highly variable (including short to longer-term cycles), somewhat controllable (output can be reduced) and somewhat predictable (useful forecasts are available) electricity sources. PV is also one of the most distributed generation technologies with typical unit sizes in the kW range.

The case study presented here assesses the potential operational impacts and system-wide energy value of high levels of PV generation. The operational characteristics of PV and its penetration level (proportion of total generating capacity that is PV). are clearly relevant.

The other important factors are the operational characteristics, individual penetration levels and resulting combinations of all the other power system resources. In existing power systems, these resources are predominantly centralised generation.

The variable operating costs of PV are negligible. High levels of PV can therefore reduce the use, and hence total operating costs, of other fossil-fuelled generation. PV power output, however, varies across daily and seasonal cycles and is somewhat unpredictable because of fluctuations in the weather. PV is of highest system operational value when its generation is at times of high demand, and therefore offsets expensive peak plant. High PV penetrations may become increasingly economically inefficient because of diminishing reductions in the operating costs of other generation. Furthermore the ramping and cycling constraints of large thermal plants may become more important with high PV penetrations

Future power systems with high levels of PV are, however, likely to also have significant penetrations of other distributed technologies. Exploring the operational impacts and value of PV then requires consideration of its interactions with these resources, as well as with centralised generation.

In particular, there may be useful synergies between PV and other distributed resources that reduce any undesirable operational impacts of the individual resources, and add operational system value beyond the values of the resources when implemented individually.

Of particular interest are the potential synergies between PV and distributed resources that incorporate some form of energy storage. In a general sense, energy storage is any means of decoupling times of electrical energy production and its end-use. These resources therefore include direct energy storage with batteries and other technologies, some cogeneration and CHP plants and ‘energy limited’ generating plants whose operation is constrained by fuel supply or renewable energy inflows.

Most importantly perhaps, distributed storage can include electrical loads where the end use service itself is stored. Examples include heating, cooling and refrigeration loads with inherent thermal energy storage. Another example is industrial batch processes that stockpile the intermediate products. These loads can all potentially have some flexibility in their times of electricity consumption [6].

In existing power systems there is generally only limited coordinated use of load storage. Examples include off-peak tariffs for domestic hot water services and time-of-use or real-time tariffs for large consumers. For power systems without significant hydro-electric resources, cost effective centralised energy storage options are often extremely limited. In contrast, there is the large potential of distributed storage resources, particularly controllable loads. The capital costs of converting existing uncontrolled loads into distributed storage resources may also be quite low in many cases, requiring only communications links and intelligent controllers. Current efforts in the Australian NEM and elsewhere to implement Advanced Metering Infrastructure support these developments [2] [3].

A major component of the operational value of energy storage in power systems derives from its ability to charge at times of low electrical demand (and hence low variable energy costs), and then discharge when high demand would otherwise require expensive peaking generators.

By decoupling times of fluctuating PV generation and electrical demand, storage is of particular value in maximising the contribution of PV towards reducing the operating costs of thermal generators.

3.1 Power system model

Our case study has a simple power system consisting of an electrical load, a PV source with stochastic fluctuations in power output, a number of conventional thermal generators and a range of storage resources, all connected to a single bus as shown in figure 2.

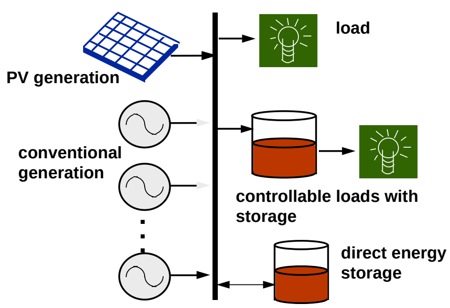

Figure 2. Power system model for the case study.

We are interested in the system-wide operational value of these resources and given that there are no network constraints and losses, the large numbers of small-scale installations for distributed PV and types of distributed storage can be modelled as single, aggregated, resources.

The daily system electricity demand and operating characteristics for the eight thermal generators are given in figure 3. Each generator is modelled with a constant incremental cost and they are dispatched in merit order (cheapest to most expensive) to meet demand.

Conventional generation								
Capacity (MW)	1200	600	500	400	300	300	250	250
Cost ($/MWh)	26	29	78	85	132	137	143	147

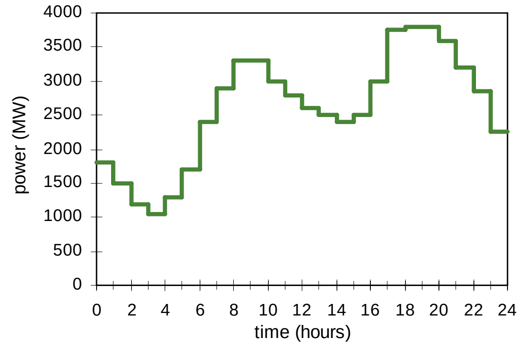

Figure 3. Power system load profile and thermal generating plant capacity and operating costs.

Random fluctuations in PV generation are modelled using a simple two-state (sunny and cloudy) Markov chain for solar insolation, and hence power output as shown in Figure 4. The profile of these states and the transition probabilities between them for any time period used here are derived from field data provided by a PV array located in Sydney, Australia.

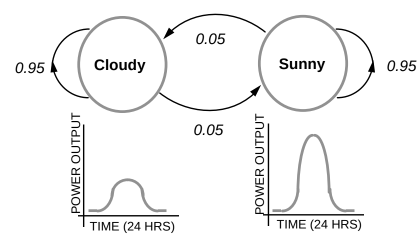

Figure 4. Markov-chain of PV output for Monte-Carlo simulations of power system operation.

Two different storage loads are considered. It is assumed that some component of the system demand is a form of controllable energy storage. The hourly electricity demand profiles of LoadStore1 and LoadStore2 are given in Figure 5. For these loads, storage levels increase in a given time interval if more power is consumed from the bus than is required by the current end-use electrical demand. Similarly, levels decrease if end-use demand exceeds power consumption from the bus. Studies are also performed for a direct energy storage resource, BatteryStore.

Operational characteristics for the three storages are given in Table 1. The general model for these storage resources is quite complex and includes time-varying electrical demand, effective storage capacities, charging rates, possible charging and discharging losses and self-discharge (leakage). The three storage resources can be viewed as aggregated models of large numbers of similar small-scale installations. The storage technologies being modelled by each of these resources might, for example, be industrial refrigeration for LoadStore1, space heating for LoadStore2 and battery plants or pumped hydro stations for BatteryStore.

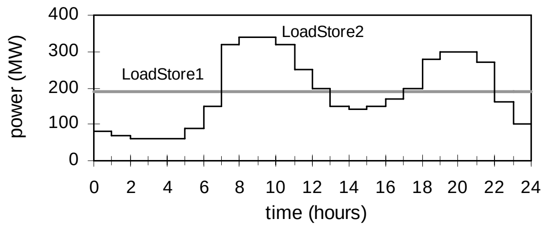

Figure 5. Daily demand profiles for the two distributed loads with inherent energy storage.

Table 1. Operating characteristics of storages.

	storage capacity (hrs of load)	time (hrs) for full charge/discharge	dis/charge efficiency (%)	selfdischarge %stored energy/h
LoadStore1	12	12 / 12 (set by load)	100 / 100	0.2
LoadStore2	7 (av. load)	2.7 / - (varying load)	100 / 100	2.0
BatteryStore		7 / 7	90 / 90	0.2

4. CASE STUDY RESULTS

For the case studies exploring 'PV and distributed storage' scenarios, power system operation was first simulated with increasing levels of PV generation but no energy storage. The reduction in system costs obtained from PV was determined by Monte-Carlo simulation of stochastic PV generation and consequent power system operation at hourly intervals over 30 days.

These cost reductions with respect to increasing levels of PV penetration are shown in figure 6. The rate of reduction in system costs falls at higher PV penetrations as the less expensive thermal plants begin to be offset and, eventually, when PV is effectively spilt.

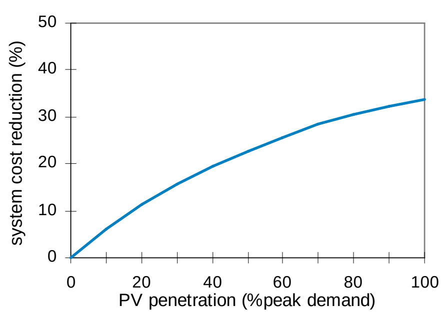

Figure 6. System operating cost reductions for increasing PV penetrations.

In subsequent studies the distributed storage resources were introduced into the power system. BatteryStore penetration is defined to be its rated storage capacity, as a proportion of total daily system energy consumption. For LoadStore1 and LoadStore2, penetration is defined to be the controllable load's daily energy consumption, as a proportion of total daily energy consumption. The reduction in system costs that can be obtained with these storage resources is calculated by optimising the operation of these storages using DEP. For the initial studies, each storage resource was implemented individually, without any other storage in the power system.

Figure 7 shows electricity demand, stochastic PV generation and DEP solutions of optimal storage trajectories for BatteryStore and LoadStore2, separately, over an example four days of simulated power system operation. The optimal BatteryStore storage trajectory clearly depends on PV output, while the trajectory of LoadStore2 appears to be much less dependent.

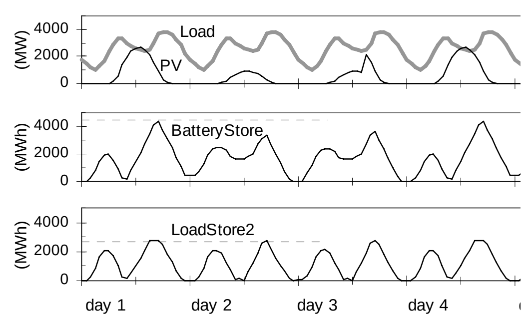

Figure 7. Simulated operation of power system over four days with optimal storage behaviour.

Optimal system cost reductions for increasing penetration levels of the individual controllable loads are shown in Figure 8 for two cases: no PV and 70% PV penetration. Diminishing returns with higher storage penetrations can be observed in all cases. While small amounts of storage can be used to offset the most expensive thermal 'peaking' plant generation, additional storage can only then be used to offset less expensive generation.
The results demonstrate clear operational synergies between PV and LoadStore2, and between PV and BatteryStore. The system cost reduction available when both PV and storage are present is significantly greater than the sum of their separate impacts. For LoadStore1, by contrast, there is little added benefit.

When considered with a number of other DEP simulation studies, several operational characteristics for storage resources can be identified that appear to impact on the operational synergies between distributed storage and PV.

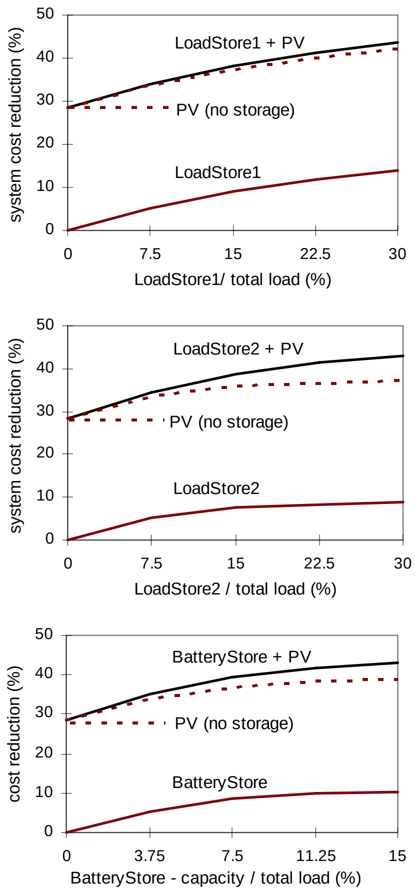

Figure 8. Reduction in system operating costs for increasing storage penetrations without PV, and with 70% PV penetration. The dotted line represents what cost reductions might be expected from PV and storage if no synergies existed.

One factor is charging and discharging rates for the storage. At high PV penetrations considerable generation is available for a relatively short period of the daily cycle. Storage has to be able to charge quickly to take full advantage of this output. Another factor is storage self discharge. Peak PV generation occurs just before the evening peak. This can reduce losses in 'leaky' storages (such as LoadStore2) that might otherwise have to charge overnight for the following evening peak.

Determining optimal power system operation with a number of different storage resources is a considerably more complex problem than the single storage case. Figure 9 shows the example four days of simulated power system operation given in Figure 7. Now, however, the optimal storage trajectories of BatteryStore and LoadStore2 include the case where both storages are present in the power system at the same time. While there is only a slight change to the LoadStore2 trajectory from its trajectory when implemented alone, the BatteryStore trajectory changes markedly in the presence of the other storage.

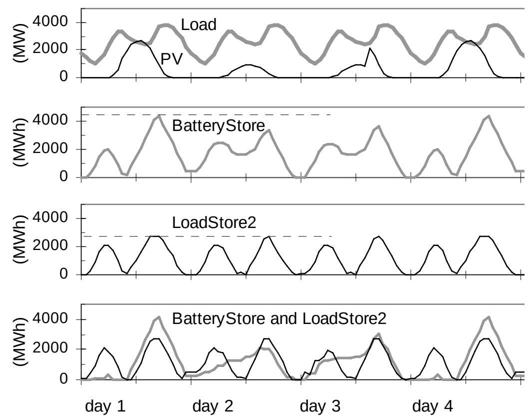

Figure 9. Simulated operation of power system as for Figure 7, but now including optimal storage operation when both storages are present.

5. CONCLUSIONS

This paper has described an evolutionary programming tool intended to help explore some of the operational issues associated with integrating distributed resources into the operation of restructured electricity industries.

The tool is demonstrated on a simple but illustrative case study – that of potential operational synergies between high PV penetrations within power systems and the availability of distributed energy storage options. This approach would appear to have promising capabilities for exploring a range of the operational issues raised by distributed resources.

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