Reactive Power Management to increase network connection capacity

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Abstract: The energy industry is seeing a shift to an increased amount of small generators embedded within the distribution network from the traditional centralized dispatch of large generators at the transmission system. The increasing number of distributed generators results in new constrains on the distribution systems and traditionally would have resulted in the installation of more network infrastructure. This project investigates the potential to control the reactive power of existing generators within the distribution network to increase the available capacity for new connections as a potential flexibility service. This study presents a potential service using an optimization algorithm to determine the optimum generator reactive power to reduce either voltage, reactive power flow or a combination of both. The optimisation algorithm makes use of a particle swarm optimisation to test multiple different reactive power set-points and find the global optimum. Time series results are presented showing that optimising for voltage or reactive power reduction increases generation connection capacity, but no single method is suitable for all generation and load conditions. The combined method trialled in this study does not achieve a balance between voltage and thermal headroom to increase the connection capacity through the use of a weighting factor calculated prior to optimisation.

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1 Introduction

As an increasing number of distributed generators connected to distribution networks, technical constraints arise that can limit the total amount of generation a network can host. To overcome these technical constraints and continue to operate a safe, secure and reliable network, traditionally network reinforcements would require the installation of additional network infrastructure. An alternative approach is to increase the utilisation of existing assets to reduce or delay the need for traditional network reinforcements. Western Power Distribution (WPD) in partnership with PSC UK Ltd is carrying out a Network Innovation Allowance funded project termed the Virtual Statcom [1].

The objective of the Virtual Statcom project is to determine the technical feasibility of increasing network connection capacity; for both generation and load, through the implementation of an algorithm to control and coordinate the reactive power output of existing generators in the distribution network. If the project demonstrates benefit it will enable more generation and load to be connected to the distribution network without the need for network reinforcement.

This paper details the implementation of an optimisation algorithm which determines the set-points for each connected generator within a WPD 33 kV bulk supply point (BSP). The optimisation algorithm applies a particle swarm optimisation methodology to determine the optimum reactive power import or export for each generator and thus maximise the available headroom for new generation. To achieve this, the objective function of the algorithm aims to minimise a combination of system voltages and thermal losses depending on the limiting constraint. The optimum reactive power set-points are used in power system studies performed in Siemens Power System Simulator for Engineering PSS®E to quantify the increase in generation or load connection capacity.

2 Methodology

Power system limits

Table 1 shows the power system limits that apply to the study simulations run for the Virtual Statcom algorithms.

Network connection capacity

The connection capacity of a network is defined as the total amount of generation or load that can be connected to a network without violating pre-defined operational, physical and statutory limits. A concurrent scaling approach has been implemented to determine the connection capacity for generation or load. A high-level overview of the algorithm, implemented in PSS®E, to determine generation connection capacity for a given network configuration is as follows:

(i) Place new generators at selected networks buses.
(ii) Scale the new generators until network issues arise.
(iii) The sum of the new generators and the existing generation is the network generation connection capacity.

Contingency identification

The Virtual Statcom may have greater potential for increasing the connection capacity during particular contingencies. The contingencies considered in this analysis were: a single circuit, a single transformer/voltage regulator and a single generator (for voltage step limits). Bus sections are not considered as a credible contingency for the Virtual Statcom project. An algorithm is used to identify the contingencies for the network zone under study.

Table 1 Virtual Statcom power system limits

bus voltage limit low	0.94 p.u.
bus voltage limit high	1.06 p.u.
voltage step limits	±3%
thermal limits	100%

Feeder group analysis

In this paper, feeder groups are referred to. A feeder group is defined as a radial feeder or parallel feeders from the BSP bus. Fig. 1 presents an example for WPD’s Tiverton 33 kV BSP with four different feeder groups identified.

3 Optimisation algorithm

It is anticipated that on a future system there will be a range of potential tools and services available to operate the system and these will be selected based on the optimum from a system stability and overall cost viewpoint. The Virtual Statcom may be able to increase capacity on the network for some network configurations more than others. Therefore, the optimisation algorithm is applied for each contingency configuration.

Initial conditions and generator constraints

To determine the optimum reactive power set-point for connected generators, each generator is allocated a reactive power range. The reactive power range is determined by the reactive power that corresponds to 0.95 power factor leading and lagging at maximum real power output. To facilitate the proof of concept study, the actual reactive power capability of each generator is ignored and it is assumed to be capable of this reactive power range over the generators real power range. However, the allowable reactive power range for each generator is reduced if voltage step violations are caused at the range limits.

Feeder group weighting factors

Initial research and optimisation results highlighted the trade-off that exists when aiming to increase a networks generation connection capacity [2]. Optimising to reduce losses results in higher network voltages, therefore reducing the voltage headroom for new generation. Optimisation to reduce network voltages results in lower network voltages, therefore reducing the thermal headroom for new generation. To determine whether to focus the optimisation on reducing voltages or reducing losses, weighting factors per feeder group are needed. The calculation determines if a feeder group is closer to a thermal limit or voltage limit. At a high level the following was implemented to determine the weighting per feeder group:

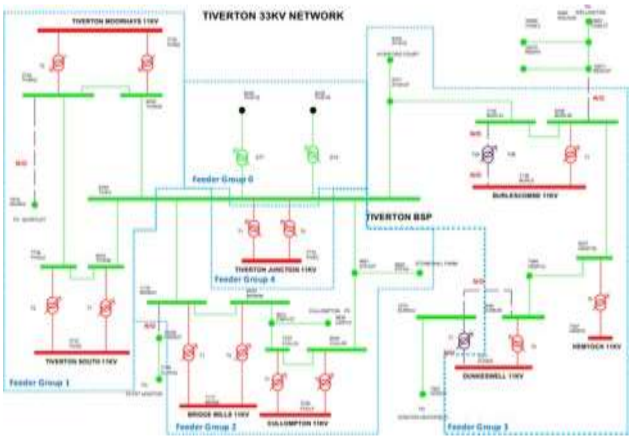

Fig. 1 *Tiverton 33 kV BSP feeder groups*

(i) Calculate initial voltages at all busbars in feeder group and supply branch loading (circuit/transformer).
(ii) Add new generators to every busbar.
(iii) Increase total feeder group generation by 10% using new generators.
(iv) Calculate new voltages at all busbars in feeder group and supply branch loading (circuit/transformer).
(v) Apply (1) to calculate weighting factor (l)

$$l = \frac{\Delta T}{\Delta V} \tag{1}$$

where

$$\Delta T = \frac{100\% - T_{\text{initial}}}{T_{\text{after}} - T_{\text{initial}}} \tag{2}$$

$$\Delta V = \frac{1.06 - V_{\text{initial}}}{V_{\text{after}} - V_{\text{initial}}} \tag{3}$$

where T_{initial} is the initial loading on a branch (circuit or transformer); T_{after} is the loading on a branch (circuit or transformer) after generation increase; V_{initial} is the initial busbar voltage; V_{after} is the busbar voltage after generation increase.

Optimisation calculation

The Virtual Statcom optimisation makes use of a particle swarm optimisation to test potential generator set-points for the existing generators within the system. The primary aim of the optimisation is to resolve network constraints in PSS®E. The secondary aim is to find a global solution within the search space by moving particles around. Each particle’s location in the search space is influenced by its local best-known position as well as the global best known position for the entire particle swarm [3].

The optimisation has been implemented using the following procedure for each particle until either an optimised value is found, or an iteration limit is reached:

(i) Modify generator set-points for particle.
(ii) Check voltages and thermal flows remain within limits, otherwise the particle is deemed invalid.
(iii) For each feeder group calculate:
  (a) Average voltage of busbars across allowable range (4)
  (b) Average reactive power flow for the supply branches and transformers (5)
(iv) Confirm an improvement in either the thermal or voltages (depending on the weighting factor) for all feeder groups

$$V_p = \text{mean}\,\frac{V_{\text{updated}} - V_{\text{lower\_limit}}}{V_{\text{upper\_limit}} - V_{\text{lower\_limit}}} \tag{4}$$

$$Q_p = \text{mean}\,\frac{Q_{\text{updated}} - Q_{\text{lower\_limit}}}{Q_{\text{upper\_limit}} - Q_{\text{lower\_limit}}} \tag{5}$$

where subscript *updated* represents the new value and *lower_limit/ upper_limit* represent the lower and upper voltage or reactive power limits for the busbar/branch.

4 Results

Studies have been carried out for a range of WPD network zones consisting of different ratios of generation/load, normal running arrangements. This section presents a summary of some results for WPD's Tiverton 33 kV BSP based on historic generation and load measurements.

The results presented here are for 1 h time steps on 10 October 2018 (Fig. 2) with a contingency on the BSP 132/33 kV Transformer GT2. These results present a comparison between optimising to: (i) minimise network thermal losses, (ii) minimise network bus voltages and (iii) a combination of bus voltages and thermal losses.

Optimisation to minimise thermal losses

Optimisation to minimise thermal losses causes the networks generators to export reactive power such that is supplied closer to the load sites. If the system is looking to optimise for losses only and there is sufficient reactive power available in the system, this results in network bus voltages increasing to or close to the upper voltage limit of 1.06 p.u.

Fig. 3 shows the generation connection capacity pre-optimisation (blue line) and post-optimisation (red line) when the optimisation has considered minimising thermal losses alone. Although the losses on the system have reduced the generation, connection capacity reduces in most time steps as a result of the significantly higher system voltages. There is an exception during mid-day when the existing generation exceeds the load resulting in a reverse power flow (RPF) across the supply transformer (GT1). Pre-optimisation, the RPF rating of GT1 is limiting the connection capacity and therefore post-optimisation, the reactive power flow across the transformer is reduced allowing for an increase in connection capacity.

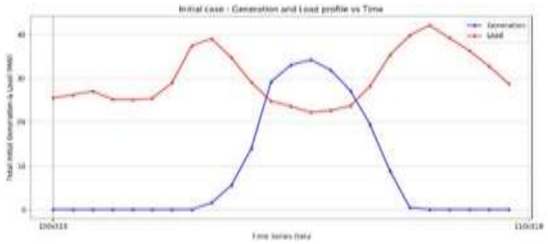

Fig. 2 *Tiverton generation and load 10 October 2018*

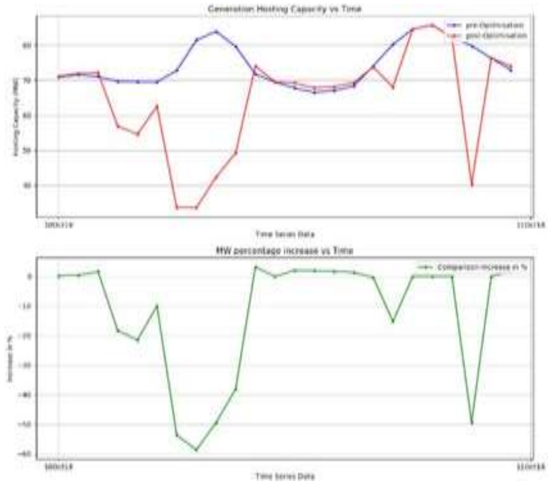

Fig. 3 *Minimise thermal losses optimisation results*

Optimisation to minimise bus voltages

Optimisation to minimise bus voltages alone results in the existing generators fully importing reactive power up to their power factor limit or the voltages reach their lower limits (0.94 p.u.). This will result in lower bus voltages but an increase in thermal loading and therefore losses in the network.

Fig. 4 shows that all time steps the connection capacity is either the same or reduced as a result of reducing system voltages. This implies that generally, during this contingency, the connection capacity is being limited by the thermal loadings limits rather than voltage limits.

In this case, during mid-day, when Tiverton's generation exceeded demand, the post-optimised system has a lower connection capacity. In optimising to minimise the voltages in the system, all generators are absorbing reactive power causing increased reactive flow across GT1. This increases the loading on GT1 and therefore the RPF limit is reached sooner when evaluating the connection capacity.

Comparison of thermal and voltage optimisation

Comparing the results for thermal and voltage only optimisations shows that there are multiple cases where generation connection capacity is decreased when optimising either to minimise thermal

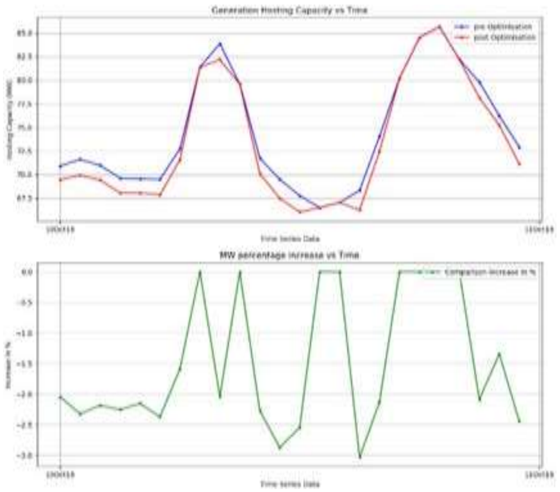

Fig. 4 *Minimise bus voltages optimisation results*

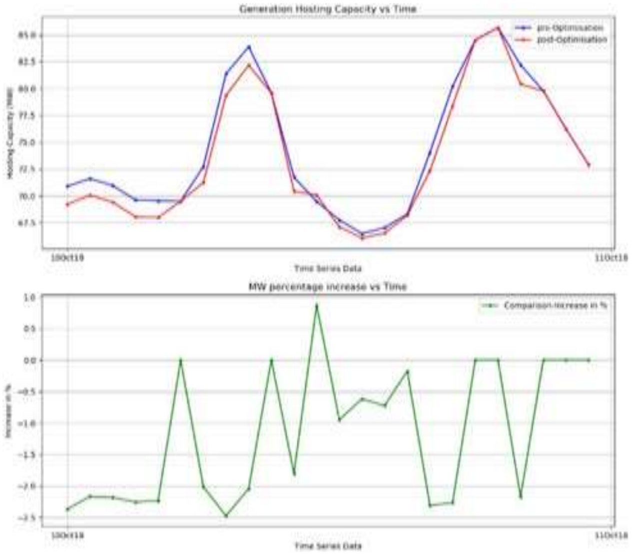

Fig. 5 *Combined thermal and voltage optimisation results*

losses or bus voltages. This indicates that the reactive set-points for the network's generators in the pre-optimised case (based on the measured values) are already achieving a balance between thermal and voltage constraints.

Combined thermal and bus voltage optimisation

The previous sets of results have shown the impact that optimising to focus purely on voltages or thermal optimisation has. The following results show that by determining the likely impact of generation on the system using the feeder group weighting factor detailed above (Section 3.2) it was only possible to improve the post-optimisation in one time step (Fig. 5).

Analysis has shown that the feeder group weighing approach to optimisation does not accurately approximate a networks generation connection capacity due to the feeder group weighting factor not being able to account for the non-linear nature of network bus voltage without running multiple power flows.

5 Conclusion

This paper demonstrates that optimisation of a network to increase the generation connection is complex. If an optimisation algorithm targets a reduction in network losses, the voltage headroom is reduced and can result in a reduction of generation connection capacity. Conversely, if the optimisation algorithm targets a reduction in network bus voltages, the thermal headroom is reduced and can result in a reduction in generation connection capacity.

Additionally, whether an optimiser should be targeting either thermal or voltages changes depending on the generation and load dispatch throughout the day. It is also dependant on the specific network running arrangement that is considered.

The paper presents a combined optimisation approach to address the problem of choosing voltage or losses optimisation and achieve a balance between thermal and voltage headroom to increase a networks generation connection capacity. The results presented here demonstrate that different reactive power dispatches have an effect on the generation connection capacity of a network. However, the feeder group weighting approach does not provide benefit in all cases. For the Virtual Statcom to increase the generation connection capacity in a constrained system with the control of existing generator reactive power, an alternative optimisation approach is required, maximising the connection capacity is a potential approach but has higher computational burden.

As a flexibility tool the Virtual Statcom has the potential to be used as a real-time system tool to resolve or reduce network constraints and operate networks with reduced voltages or thermal loadings. However, modifications to the Virtual Statcom approach are needed to develop a distribution planning tool that is able to utilise reactive power to resolve network constraints and increase network connection capacity.

6 References

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