DECENTRALISED VOLTAGE AND THERMAL MANAGEMENT TO ENABLE MORE DISTRIBUTED GENERATION CONNECTION

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ABSTRACT

This paper presents a decentralised control scheme of a distributed generator to actively respond to voltage and thermal issues in a distribution network. An operation scheme providing a local voltage control by adjusting the reactive power output of the generator is proposed. Generation curtailment is employed to relieve overloaded lines as well as to support the voltage regulation scheme. These control mechanisms do not require sophisticated communication links and hence can avoid high investment costs that would be required for a centralised measurement and communication system. Results show that the proposed schemes respond effectively to the voltage and thermal constraints, allowing further penetration of generation capacity.

INTRODUCTION

Significant volumes of medium-to-large scale renewable generation, particularly wind power, are expected to connect to (rural) distribution networks. Nonetheless, the traditional design of such networks, where the power supply is unidirectional, can present several technical challenges and can limit the capacity of new generation developments. In addition, the variability of wind resource can pose new challenges on the operation of the network. For these reasons, Smart Grid technologies; the advanced operation of distribution systems (aka active network management), have gained momentum. Real-time monitoring, one of the key characteristics of Smart Grid technologies, can enhance the network control performance and allow more generation capacity to connect. However, such an approach requires communication systems that may bring about undesirably high investment costs.

A decentralised control algorithm based upon reactive power control and generation curtailment is proposed here to provide adequate voltage and thermal management and enable more renewable generation capacity as a consequence. The proposed control allows a generator to utilise, under normal conditions, a fixed power factor whereas a voltage control (P-V bus-like control) is used to respond to voltage rise. The curtailment scheme is employed to reduce the power output of the generator to maintain the line thermal limit and also, as the last resort, to assist reducing voltage rise. The proposed control schemes are applied on a test feeder and a generic UK (rural) distribution network. Simulations over 1-hour and 24-hour periods (with 1-minute intervals) are carried out in PSS/E software interfaced with Python. Performance of the schemes is assessed on the basis of the ability to cope with voltage and thermal constraints in order to facilitate more generation connection.

DECENTRALISED CONTROL SCHEME

Generally speaking, it could be said that the maximum distributed generation (DG) capacity that can be connected to a given network is that with which no voltage and thermal limits is breached under any load condition (without contingencies). This approach is also known as 'fit and forget'. Generation capacity beyond that point cannot be connected unless, for instance, the capabilities of the DG unit are actively managed to avoid surpassing the statutory limits.

The proposed control algorithm for voltage and thermal management is illustrated in Fig. 2. The algorithm comprises 2 targets: voltage and thermal control. Each control target is activated according to the measured current and voltage signals used to estimate the voltage and thermal loading capacity for every time step, i.e. 1 minute for this study. If voltage constraint is identified, the voltage control will be activated. Likewise, if thermal constraint is detected, the generation curtailment scheme will be applied. In case both constraints are detected simultaneously, priority will be given to thermal management as the voltage control will cause more reactive power flow to be absorbed by the generator. The voltage control and generation curtailment mechanisms are explained in the following subsections.

Power Factor and Voltage Control

The voltage control employs the capability of a generator to inject or absorb reactive power for voltage support [1], [2]. The algorithm is shown in Fig. 2. At normal condition, the generator is operated at fixed power factor, e.g., unity power factor. During voltage rise, the generator estimates and delivers the required reactive power (within its design capabilities) to keep its voltage at the upper limit (minus voltage deadband). To model this, the generator is treated as P-V bus. Once the voltage rise is reduced below the upper limit, the generator goes back to control its fixed power factor. A voltage deadband is also applied to prevent voltage breaching the upper limit and to ensure the approach does not interfere with voltage regulation from the substation transformer.

Generation curtailment

Generation curtailment is applied for two purposes: thermal and voltage control. Both schemes operate independently based on the constraint being detected by the measurement. The algorithm for thermal and voltage control is explained as follows.

Curtailment for thermal management. Such a scheme is able to maintain the power flows of a circuit (cable or overhead line) that is immediate to the connection point of the generator, i.e., the one prone to thermal issues, within its limits, minimising tripping of the renewable DG unit (e.g., a wind farm). The scheme reduces the generator's power output when the instant circuit capacity exceeds a given trimming threshold which can be set according to the standard or seasonal line capacity. The amount required to be trimmed is calculated based on the needs of the loads and (constant, e.g., CHP) generators in the vicinity of the wind farm. For instance, as shown in Fig. 1, those participants connected to bus 3 (load and DG1) will need to be taken into account to determine the *safe* output of the wind farm DG2.

$$DG2_{outputSafe} + Load + Losses + DG1 \leq Cap_{Intact} \quad (1)$$

where Cap_{Intact} is the actual capacity of circuit and $DG2_{outputSafe}$ determines the total MW required to be trimmed based on the generator's ramp-up rate. Being a decentralised approach, it is envisaged that the load, losses and generation (DG1) values are estimated based on historic data. Here, a time delay is also used before the generator is allowed to increase its power output when the thermal constraint is cleared out (the instant that the circuit capacity is below the trimming threshold). Appropriate time delay setting can avoid damage due to the continuous increase/decrease of the DG power output and can enhance the control process.

Curtailment for voltage control. The curtailment scheme for voltage control is considered as the last resort, i.e. if the reactive power control is not successful. The mechanism is similar to the generation curtailment for thermal management in that the DG output is trimmed by a ramp-up rate until the voltage rise is clear. A time delay is also applied in a similar manner as that for the generation curtailment thermal management.

CASE STUDY: 3-BUS TEST FEEDER

To demonstrate the control behaviour of the reactive power control and the generation curtailment scheme on voltage and thermal problems, a simple 3-bus feeder is tested over a 60-minute time period under worst case (maximum generation and minimum demand). One firm generation and one wind farm are assumed to supply the feeder where the reactive power control and the generation curtailment scheme are only applied to the wind farm. The system voltage at bus 3 and the thermal profile of line 2-3 when the wind farm is operating with normal fixed power factor, reactive power control, generation curtailment for voltage scheme and generation curtailment for thermal control are examined.

The test feeder. As shown in Fig. 1, is a double-circuit between bus 2-3 consisting of one 33kV/11kV transformer between bus 1-2. Demand and generation are connected at bus 3. The peak demand is 2.2MW. Demand and

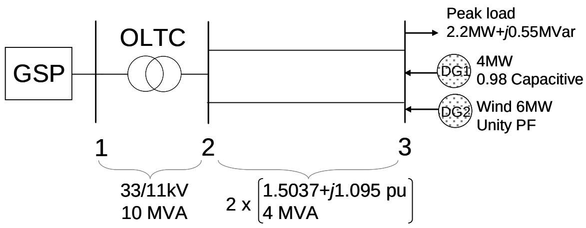

Fig. 1 A 3-bus test feeder.

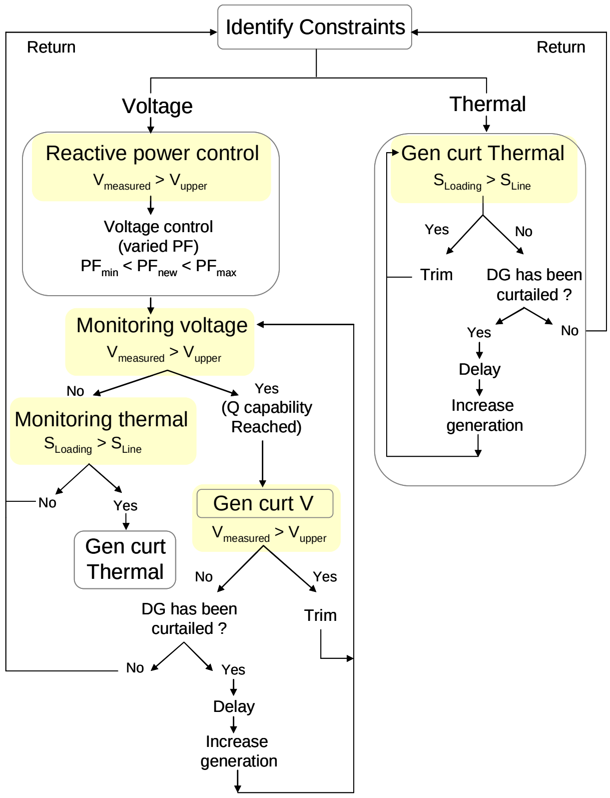

Fig. 2 Functional diagram of the voltage and thermal control.

generation profiles of a 60-minute period at 1 minute interval is shown in Fig. 3. The demand and wind profiles were obtained from central Scotland on 14th August 2003 where the wind speed data was produced using a generic wind power curve [3]. The chosen period was in the summer where the demand was relatively low but with high wind speeds. DG1 represents a generator producing constant power of 4MW at 0.98 power factor (capacitive). A 'fit and forget' approach for DG2 would lead to a maximum of 5MW of capacity. Here, a 6MW wind farm is used for the study in order to apply the proposed control mechanisms.

The ramp-up rate of the wind farm is assumed to be 1MW/minute and has reactive power capability of 0.95 power factor (inductive/capacitive). The voltage deadband is set to 0.25% of the upper voltage limit. The generation curtailment scheme is applied at the wind unit's ramp-up rate and the delay time is chosen at 5 minutes. The trimming threshold is set to 95% of the maximum capacity of the line.

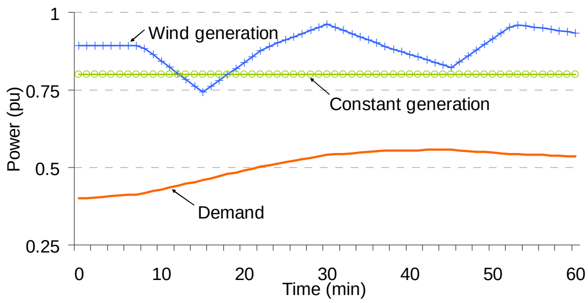

Fig. 3 60-minute time series for demand and generation profiles.

Results

Comparison of voltage profiles at bus 3 for each and the combined control schemes is shown in Fig. 4. At normal fixed power factor, the upper voltage limit is already breached at the beginning of the measurement as well as between minutes 20^{th} to 40^{th} and after minute 48^{th} due a large amount of power being produced at low demand. With the generation curtailment scheme, voltage rise over those periods is reduced but the problem still exists according to the time delay mechanism of the generation curtailment scheme. Similar behaviour can be observed when all schemes are activated simultaneously. This is because the priority has been given to the thermal management when both constraints are detected. However, when the reactive power control is adopted, voltage rise can be managed effectively.

Thermal loading capacity of line 2-3 tends to follow the voltage at bus 3 as they are dependent on the generation being supply to the system. The thermal overloading is an issue when the wind farm operates with a fixed power factor during the periods where voltage rise occurs, as shown in Fig. 5. The generation curtailment scheme for thermal management can manage the thermal overloading problem over those periods. Although line overloading can still be observed, the duration is relatively short (2-3 minutes) and might be acceptable in certain cases. Sensitivity analysis of the time delay adjustment may also be used to enhance the control mechanism. The generation curtailment scheme for voltage control is slightly different from that of the generation curtailment for thermal management as they are dealing with different control targets. The voltage rise and thermal overloading problems are reduced when the voltage and thermal control mechanisms are simultaneously adopted.

CASE STUDY: 12-BUS NETWORK

Simulation of a 12-bus rural distribution system populated with variable demand and wind generation is carried out over a 1-day period at a 1-minute interval. Performance of the proposed control schemes is assessed on the basis of the ability to cope with voltage and thermal constraints and to facilitate more generation connection as a consequence.

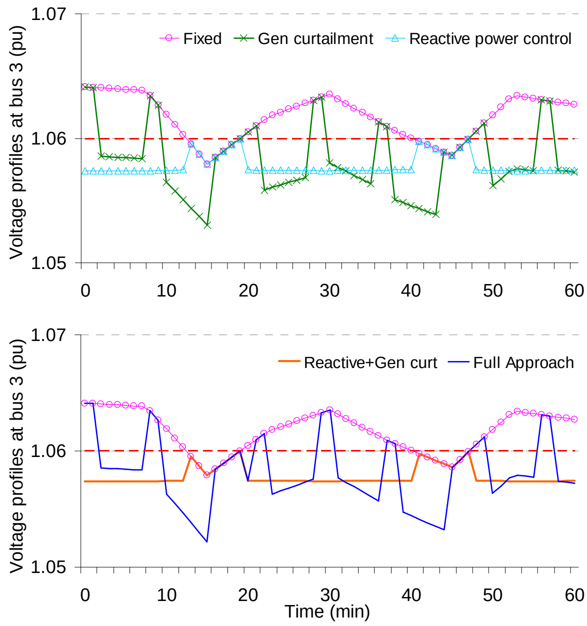

Fig. 4 Voltage profiles (pu) at bus 3 for: (top) fixed power factor, generation curtailment voltage, reactive power control and (bottom) reactive control & generation curtailment thermal and full approach. Voltage limit = 1.06 pu.

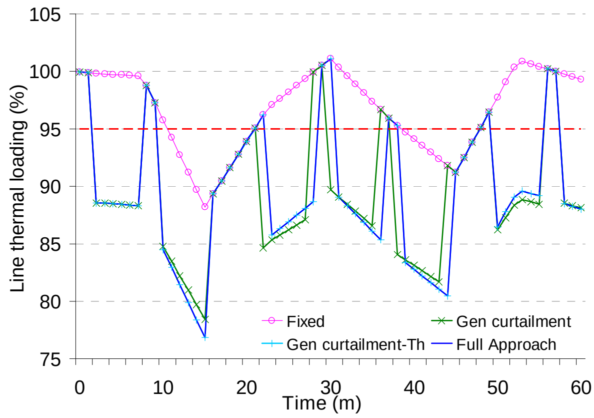

Fig. 5 Thermal loading capacity (%) of line 2-3 for: fixed power factor, generation curtailment voltage, generation curtailment thermal and full approach (trimming threshold = 95%).

12-bus distribution system. The system used in the study is a simplified version of the EHV1 33kV radial distribution system for Active Management available at [4]. The simplified system, as shown in Fig. 6, consists of 12 buses with 10 demand points located in rural area. The peak demand is 38.16MW. Two generation plants: a combined heat and power (CHP) unit and a wind farm are connected at bus 12. The demand and wind generation were of central Scotland on 25^{th} August 2003 [3]. The CHP unit produces a full rated power output of 4MW at 0.97 power factor (inductive). The proposed voltage and thermal management schemes are implemented to the wind farm in order to manage the voltage problem at its connected bus and the overloading of line between buses 10-12. The critical level of generation of the wind farm is

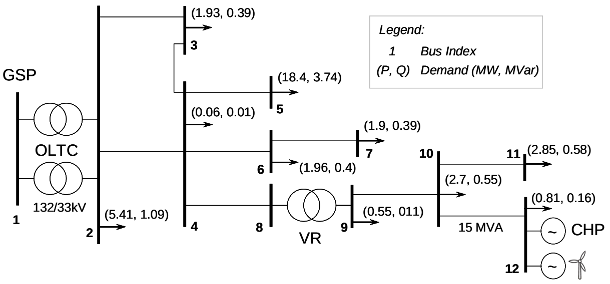

Fig. 6 A simplified 12-bus rural distribution system.

6MW. At this level, voltage and thermal limits are exceeded in certain demand/generation scenarios.

The ramp-up rate of the wind unit is also assumed at 1MW/minute with the reactive power capability of 0.95 inductive/capacitive. The voltage deadband is also set to 0.25% below the upper limit. The delay time for the generation curtailment scheme is set at 5 minutes per measurement cycle. The trim threshold of 98% of the maximum line capacity is used, assuming that the overloading problem of the line is not likely an issue compared to the previous case study.

Overall performance

The overall performance of the proposed control schemes are summarised in Table 1. For voltage mitigation, the reactive power control has shown the most effective response to completely overcome the voltage rise whereas the generation curtailment scheme is able to cope with the problem for around 95.14% of the 24-hour simulation time. The combined reactive power control with the generation curtailment for voltage and thermal scheme appears to mitigate the voltage rise (only 2% of the time voltage rise still occurs) because of the action of the reactive power control. For the thermal management, the reactive power control seems to create the overloading of line for a slightly longer period, even compared to the fixed power factor approach. On the other hand, the generation curtailment scheme for thermal control appears to be the most effective amongst the other control types, achieving around 84.9% ability to cope with line overloading. In terms of wind energy production, if the thermal constraint is not considered, the reactive power control could yield around 3% more energy than solely adopting the generation curtailment scheme. In reality, this cannot be achieved as the thermal limitation of the line will prevent such operation of the DG unit. Thus, when taking into account the thermal constraint, the energy production is much lower.

This analysis considers the system where both the voltage and thermal problems are the binding constraints. The combined reactive power control and the generation curtailment scheme can be, as demonstrated, implemented simultaneously, albeit not necessarily is effective during

Table 1 Summary of the overall performance of the proposed control schemes based on a 24-hour simulation.

Total wind generation over the simulation period (MWh)					
Fixed	**Gen curt**	**Reactive power control**	**Reactive Control & Gen curt**	**Gen curt Thermal**	**Full Approach**
158,829.7	153,775.2	158,710	158,710	143,229.7	143,157.6
Voltage rise above the upper limit					
Yes	Yes	No	No	Yes	Yes
Period where voltage upper limit is exceeded (%)					
19.15	4.86	No	No	13.32	2.01
Thermal Limit exceeded for line 10-12 (Maximum power flow is around 101.3%)					
Yes	Yes	Yes	Yes	Yes	Yes
Periods where the thermal limit is breached (%)					
59.75	53.57	62.87	62.87	15.13	18.25

the whole time-series analysis. This is due to the effect of the ramp-up mechanism of the generation curtailment according to the set time delay. Hence, the priority of the control mechanisms and the time delay settings may also need to be adjusted based on the system characteristic to whether the voltage or the thermal loading is more likely to become an issue in order to improve the control performance.

CONCLUSIONS

Voltage and thermal constraints are a significant limitation to the integration of renewable generation into distribution networks, particularly rural areas. In this work, decentralised control schemes employing reactive power control and generation curtailment has been demonstrated to effectively respond to voltage rise and thermal overloading problems in order to allow more capacity to be connected. However, adjustment of the control settings, i.e. voltage deadband, power factor capability, time delay and trimming threshold, may require a sensitivity analysis based upon network topology, demand characteristic and generator type. The proposed approach offers an alternative low-cost option to allowing the integration of new renewable generation capacity.

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