INTELLIGENT NODES IN DISTRIBUTION SYSTEMS - OPERATING CONCEPT

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ABSTRACT

Due to gradually increasing loads, medium voltage distribution feeders come closer to their voltage and current limits. Furthermore the introduction of distributed generation (DG) causes larger voltage variations. In this paper a control and protection concept is proposed for so called Intelligent Nodes (INs) applied at medium voltage level. Firstly the control concept is described and illustrated with an example grid. Secondly the reliability impact of the introduction of an IN is analysed and requirements to the protection concept of INs are given.

INTRODUCTION

The maximum loading and the maximum level of DG penetration of medium voltage distribution feeders is limited because of redundancy, safety and reliability constraints and current and voltage limits [1]. During the repair and maintenance of a feeder the loads will be switched to another feeder to limit or avoid customer interruption time. In traditional distribution systems the required capacity to enable this switching action needs to be reserved on each of the concerned cables, thus limiting the allowable loading on each feeder. The amount of DG also needs to be limited to avoid large voltage variations. These DG units cannot support the voltage during contingencies. Existing standards require DG units to trip off-line during a contingency from a safety point of view.

In [2] and [3] the concept and main benefit of an Intelligent Node (IN) is elaborated, illustrating how an IN can facilitate increased loading and higher DG penetration by sharing redundancy and controlling power flows. In this paper a related application of the IN is shown: (continuously) improving voltage profiles by balancing active and reactive power amongst multiple (>2) feeders connected to one IN. The test grid that will be used in this paper is shown in Figure 2. It consists of several cable feeders each hosting only loads, equally distributed along the length. One 1MVA generator is included in the grid. The dashed rectangle shows the location of the IN that will be studied later. Two configurations are considered: with and without an IN. In the situation without the IN, all feeders are connected to one node that replaces the IN.

Figure 1 shows the voltage profiles, for the given configuration, as displayed in Figure 2. All loads have cos(φ)=0.9, the generator has cos(φ)=1.0.

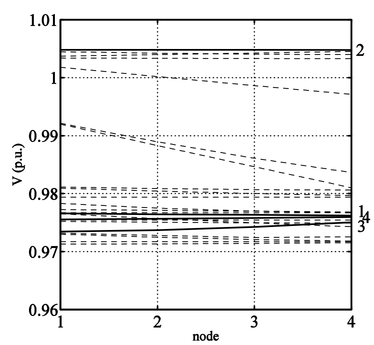


Figure 1 Voltage profiles without IN

The numbered solid lines in Figure 1 represent the feeders connected to the IN. The dashed lines represent the other feeders.

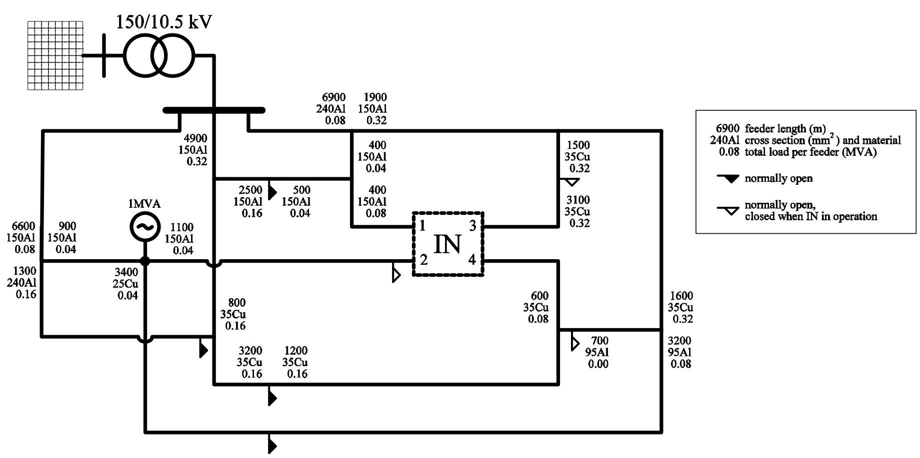


Figure 2 Test grid for IN-concept

CONTROL CONCEPT

The control objective of the IN is to minimize the difference between the global minimum and the global maximum voltage in the connected feeders. An iterative approach, Cauchy's gradient method [4], is used to find the optimal settings for the IN. This method is chosen because of its straightforward nature, and because no local minima or maxima are expected.

For illustration purposes, Figure 3 shows a graphical impression of the application of the gradient method for maximization of a 2-variable problem. By applying small disturbances in the direction of the coordinate system, the gradient of the objective function is determined. Iteratively applying a stimulus of a certain magnitude in the direction of the gradient will bring us to the desired operating point.

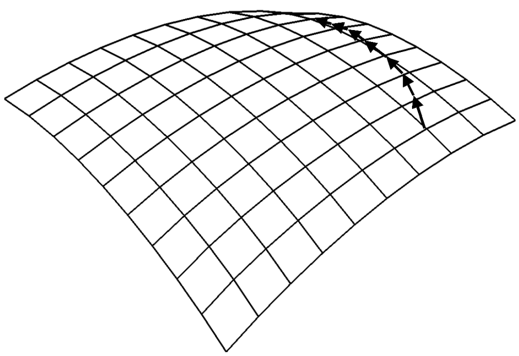


Figure 3 Illustration of iteration path for 2D-problem

The IN may be seen as a black box which can have different internal topologies. A very versatile topology would for example be based on back-to-back converters connected to a common DC-bus, as shown in Figure 4. The main advantage of using power electronics as the main technology in the IN is the speed at which it can respond to system changes. This topology allows full control of active and reactive power flow amongst feeders. When no storage or generation is connected to the DC-bus, the active power of all converters has to add up to zero. For reactive power such a limitation does not exist: the IN can supply to or consume reactive power from each feeder independently.

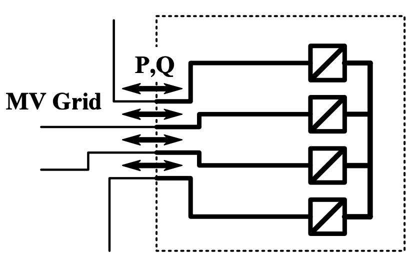


Figure 4 Example of Intelligent Node configuration

By injecting active power in one of the feeders, the voltage profile of that feeder is 'bended' upwards, and by taking active power from that feeder it is bended downwards, as is illustrated in Figure 5 for a grid with two feeders: one with DG and one with only loads.

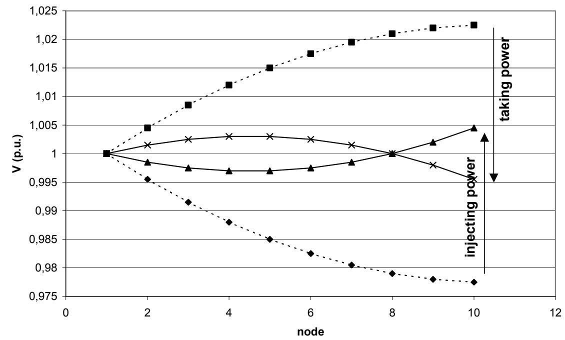


Figure 5 Bending of voltage profiles

The gradient method is based on determining the effect of each variable on the objective function in order to find the steepest gradient towards the maximum or minimum of the objective function. The primary IN control parameters are the active and reactive power injected into each feeder. The space of possible controller settings, in case of four feeders, is spanned by the vectors S1 – S8, as shown in Table 1. The space spanned by these vectors inherently fulfils the zero-sum requirement for active power and leaves full control freedom for reactive power.

Table 1 Space of control vectors Si

	P1	P2	P3	P4	Q1	Q2	Q3	Q4
S1	1	-1/3	-1/3	-1/3	0	0	0	0
S2	-1/3	1	-1/3	-1/3	0	0	0	0
S3	-1/3	-1/3	1	-1/3	0	0	0	0
S4	-1/3	-1/3	-1/3	1	0	0	0	0
S5	0	0	0	0	1	0	0	0
S6	0	0	0	0	0	1	0	0
S7	0	0	0	0	0	0	1	0
S8	0	0	0	0	0	0	0	1

Starting from the initial condition, where no active or reactive power is injected by the IN, successively each IN control vector is applied with small amplitude dSi and a power flow calculation is performed, see also Figure 6. The resulting effect dVi on the overall voltage range is calculated. Per iteration step the maximum reduction of the voltage range is obtained by applying a linear combination of the vectors. Each vector is applied with a factor proportional to its effect on the global voltage range. Repeating these steps results in the optimal settings for the IN to minimize the global voltage range, i.e. the difference between maximum and minimum values.

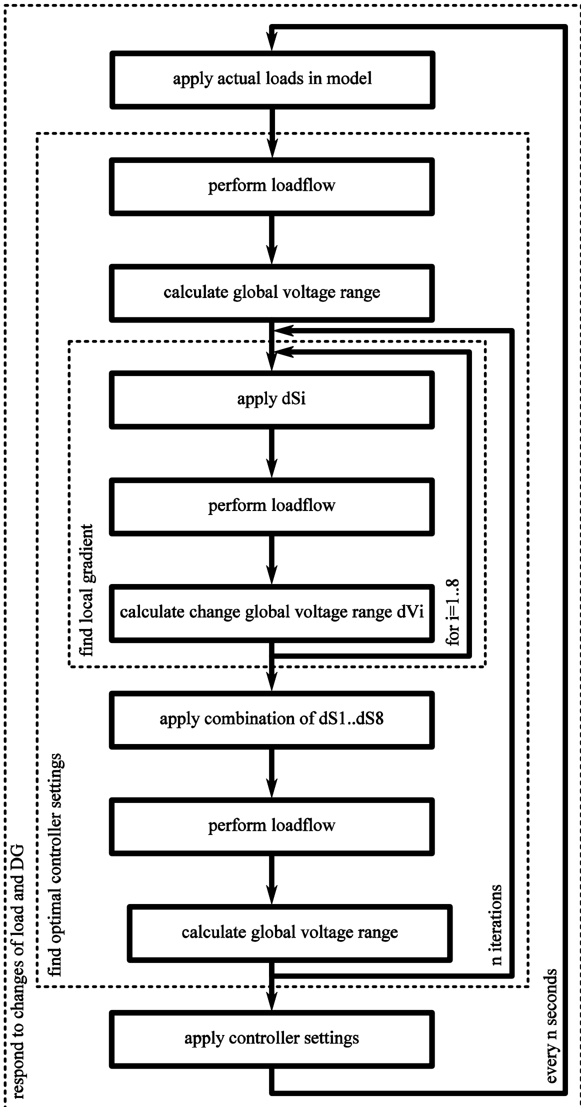
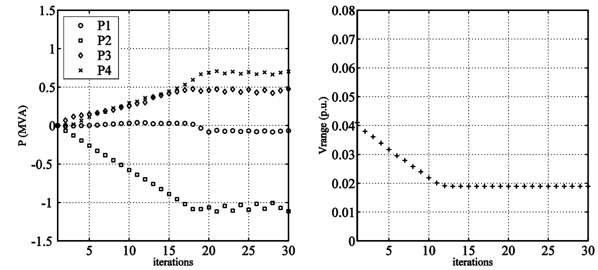


Figure 6 Iteration path to optimal controller settings

This control method only optimizes towards minimum voltage range; other factors such as power transfer limitations of cables and transformers or losses are not included in the optimisation. A requirement to the IN is to calculate new controller settings at time intervals small enough to follow the load and generation variations.

APPLICATION CASE

The control concept from the previous paragraph is now applied to the test grid of Figure 2 with the limitation that no reactive power injection is used at this time (dS5..8 are not applied). The iteration results are displayed in Figure 7 showing the individual injected active powers and the resulting voltage range.



a) b)

Figure 7 Iteration paths of a) injected power and b) resulting global voltage range

Figure 8 shows the resulting voltage profiles with an IN. These profiles are to be compared to the profiles in Figure 1. In this specific situation, the difference between the global minimum and the global maximum voltages is reduced from 3.4 % to 1.9 % if we compare it to the situation without the IN and from 4.1 % to 1.9 % if we compare it to the configuration with the IN connected, but not injecting any power.

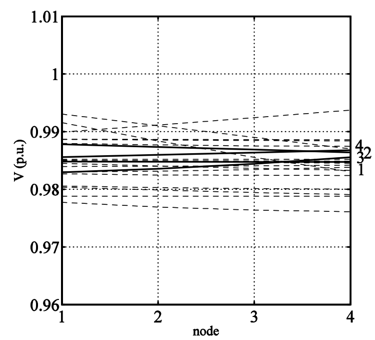


Figure 8 Voltage profiles with IN

Including reactive power in the control algorithm results in a narrower global voltage range of 0.9%. However, this is not realistic without including further limitations: to obtain this narrow global voltage range the control algorithm of the IN needs to inject large amounts of reactive power: the cos(φ) of the power taken by the two feeders associated with the IN would be only ca. 0.6, capacitive.

The grid configuration was not optimized after application of the IN. The central feeder originating from the MV busbar is not affected by the IN; a possible optimization is to include this feeder in the control concept by changing the positions of one or more normally open switches.

RELIABILITY CONSIDERATIONS

Reliability is one of the most important factors determining the design and operation of a distribution grid. The concept of an IN must fit in this practice. In this paragraph an analysis is made of how the application of an IN influences the reliability of the distribution system.

First the consequence of an IN not fulfilling its function is investigated for several operating conditions, next the changed consequences of grid failures are analysed. Finally protection requirements for the IN and the grid are formulated.

Normal operation

During normal operation the function of the IN is to control power flow continuously to reduce voltage variations, e.g. due to DG. When the IN fails to actively control voltage profiles this might result in stronger voltage variations; depending on load and generation conditions this can lead to values exceeding allowed limits. If possible, going into bypass mode during IN malfunctioning can reduce voltage variations to some extent: currents will flow according to the path of least impedance. In this situation a fault on any of the connected feeders will lead to disconnection of all connected feeders, so this situation should not be maintained for extended periods of time. Another disadvantage of uncontrolled power flow is that some of the connected feeders may be overloaded. Disconnection on the supply side due to an overloaded feeder will result in cascading overloading of all associated feeders, an unwanted situation.

Grid fault

During a circuit fault, the IN must block short circuit currents and disconnect itself from the faulted feeder. When the IN fails to perform this function, this will lead to a faulted but energized feeder, which is a serious safety hazard, similar to the risk of loss of mains detection in DG units [5].
After a fault in the grid the IN can help reduce the consequences. Since the IN contains voltage and current measurement equipment for control objectives, these data can be used to help fault localization, thus decreasing the customer outage time.

Reconfigured system due to repair or maintenance

During a reconfigured system the function of the IN is to continuously distribute power flow to use shared redundancy. When the IN fails to actively distribute power flows this will result in disconnection of the supplied feeder and customer interruption time. Going into bypass mode has the limitations as described in the section about normal operation.

Protection requirements to IN and grid

To prevent safety hazards, the IN must detect a short circuit on its connected feeder and disconnect and isolate the associated feeder in a safe way until the fault is found and isolated.
During a situation where the IN initially failed and went into bypass mode, the protection equipment of the grid should prevent trips due to feeder overloading, and signal the IN to exit bypass mode instead, to avoid a total system outage.

CONCLUSIONS

In this paper a basic control concept is proposed for an IN to reduce the global voltage range within a distribution system. The control concept is based on the iterative gradient method to find the optimal setting. The choice of control vectors inherently satisfies the zero-power-sum requirement. An example grid is analysed and the voltage profile improvements are calculated. The iteration paths of the injected power and the resulting global voltage range are shown. In the example grid the global voltage range is reduced from 3.4 % to 1.9 %. The requirements to the IN and the grid are described in qualitative terms in order to maintain reliable operation of the distribution system.

FUTURE RESEARCH

Future work for the control concept will concentrate on including system constraints, iteration refinements and iteration stopping conditions. The protection concept will be implemented in software models.

ACKNOWLEDGMENTS

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