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Reliable and efficient operation of closed-ring distribution grids supported by distribution automation

Robert J.W. de Groot [a,*,1], Johan Morren [a,b], Johannes G. Slootweg [a,b]

[a] Electrical Energy Systems (EES) Group within the Department of Electrical Engineering of Eindhoven University of Technology (TU/e), De Rondom 70, 5612 AP Eindhoven, The Netherlands
[b] Enexis B.V., Magistratenlaan 116, 5223 MB 's-Hertogenbosch, The Netherlands

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ABSTRACT

Closed-ring operation of distribution grids has several advantages over the more commonly used open-ring distribution grid topology. Power flows will naturally balance out between the feeders of a (typically) ring shaped medium voltage distribution grid. This leads to reduced peak loading of components, and therefore reduced grid losses. As such, investments in grid reinforcement can be postponed or avoided, while operational costs can be reduced. The negative side-effect of closed-ring operation, reduced reliability of supply, can be (largely) mitigated by implementing distribution automation. This paper discusses and analyses the potential grid loss reduction of closed-ring operation, the effects on reliability and possible mitigations and finally field-test results to validate the theoretical analysis.

1. Introduction

Distribution system operators (DSOs) face the challenge of coping with the effects of the *energy transition*. This entails the widespread introduction of (small-scale) distributed generators (DG), the growing share of electric vehicles (EV) and the ongoing electrification of household energy consumption, which are all examples of trends in the energy landscape that will affect DSOs. Due to these trends, power flows will become more dynamic and may reverse in direction, while peak loads increase [1–3].

As increasing peak loads require a larger grid capacity, DSOs can cope with these effects (in the traditional manner) by increasing network capacity. Although this is technically a sound approach, it may not be the most economical manner to do so [4]. Reduction of peak loads (on individual grid assets) can be achieved through several *smart grid* solutions.

Examples of solutions that shift peak loads in time include demand side management (DSM) [5] and battery energy storage systems (BESS) [6]. DSM and BESS can be effective in reducing peak-loads and enabling the efficient use of available grid capacity, but BESS is generally a rather costly investment that is often not very cost-effective [7], while the impact of DSM is usually relatively small [8]. Furthermore, it requires the DSO to implement, operate and maintain new technologies in its grid, that it might not be experienced with (yet).

Alternatively, closed-ring operation of (normally radially operated, ring-shaped) distribution grids can contribute to a reduction of grid losses and a more efficient use of available capacity. By operating the grid in a closed-ring layout, currents will 'naturally' be balanced out between two feeders. Closed-ring operation can function as a long-term solution for achieving improved distribution grid operation, preceding, in addition to, or alongside the earlier mentioned technologies (DSM and BESS). Closed-ring operation as such requires relatively small capital and operational expenditure. This is especially true when distribution automation (DA) is already present in the concerned grids and the opportunity to operate in a closed-ring lay-out is seen as an additional benefit from DA roll-out. In such cases, closed-ring operation supported by DA often will be the *low hanging fruit* among the technology options available for grid operators to reduce losses, facilitate DG implementation and postpone grid reinforcement. Would closed-ring operation not provide sufficient improvement (anymore), DSOs may decide to integrate technologies such as DSM and BESS as well. Postponing implementation of such smart grid technologies may have the additional benefit of allowing the technology to mature further.

As can be seen from Fig. 1, the used capacity within a distribution grid is rather low in terms of *energy* capacity, while further growth of power consumption is limited because the maximum *power* capacity is being approached. Flattening of load-profiles in distribution grids, will result in a reduction of peak loads, as well as a (potential) increase of energy capacity utilization.

Furthermore, the reduction of peak-loads will result in a reduction of grid losses. The losses observed in a cable or line are proportional to the square of the current flowing through it. This

* Corresponding author.
E-mail address: r.j.w.d.groot@tue.nl (R.J.W. de Groot).
1 Present address: 264F Compassvale Bow #10-84, 540264, Singapore.

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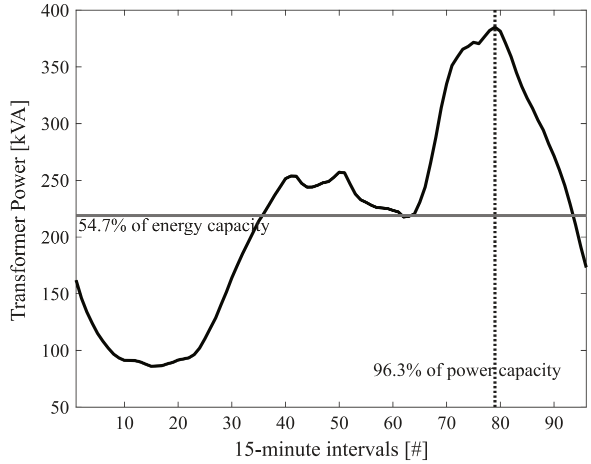

Fig. 1. An overview of energy and power capacity utilization of an MV distribution grid.

implicates that the flatter the load-profile, the lower the resulting losses over a given period of time are (given that the same amount of energy is transported).

This paper will first discuss the advantages of closed-ring operation. Furthermore, some downsides of closed-ring operation are addressed and solutions are proposed. After that, the way DA can assist in closed-ring operation and how it can increase grid reliability is discussed. Finally, the grid loss reduction observed in a field-test, in which two grids are operated in closed-ring, are presented and compared with results obtained from simulations.

2. Distribution grids

Especially in areas with higher customer densities, (cable) distribution grids are typically ring-shaped (see Fig. 2). However, these ring-shaped grids are usually operated in a radial manner. The reason for doing so, is the relative low complexity of protection schemes for radially operated grids. As power flows are (without the presence of distributed generation) unidirectional in radial grids, such a grid can typically be protected by installing an overcurrent relay at the beginning of each feeder. The added advantage of having a normally-open point (NOP) between the ends of two feeders, and physically building grids in a ring-shaped layout, is the fact that during maintenance or repair works at any part of the grid, power can be re-routed by temporarily closing the NOP, while opening the grid elsewhere (see Fig. 2).

The downside of radially operated grids (laid out in ring-shape) is the fact that available capacity is potentially left unused. In Fig. 2(a), this is illustrated by one feeder (1) supplying a large load, while the other feeder (2) is left under-utilized. This may result in a situation whereby feeder 1 suffers from overloading or may need to be reinforced, while feeder 2 has sufficient capacity left. Removal of the NOP may lead to the situation depicted in Fig. 2(b), in which feeder B now has a supporting role in supplying power to the large loads. Related to the imbalanced currents seen in radially operated grids, is the fact they typically perform worse compared to closed-ring operated grids in terms of grid losses.

3. Closed-ring operation

The impact of closed-ring operation of distribution grids on grid loss reduction, improvement of voltage profiles, reliability and (complexity of) protection schemes is further investigated in this section.

3.1. Loss reduction

In closed-ring operated grids losses are being reduced because currents through each half of the distribution ring are being re-distributed in a more balanced manner once the NOP is removed (see Fig. 2). The loss-reducing effect is larger with strongly imbalanced feeder currents. Notwithstanding the fact that DSOs usually determine an optimal location for the NOP, as load grows and load patterns become more volatile, increasingly dynamic power flows will be present in (future) grids. This means the optimal location of the NOP may vary significantly on short timeframes. In [9], grid loss reductions of up to 10% could be observed in simulations. However, these simulations were performed with synthesized load profiles. In this paper, the grid loss reductions that can be observed in real-life closed-ring operated grids are demonstrated in chapter V of this paper, where both simulation (with actual load profile data) and field-test results are presented.

3.2. Improved voltage profiles

Closed-ring operation has an effect on the voltage profiles that can be observed in distribution rings. Since voltage related problems within the distribution grid tend to increase with the implementation of DG [10], closed-ring operation is especially interesting for grids with DG. Grids consisting of underground power cables have X/R values typically between $\frac{1}{3}$ and 3. When a DG unit supplies current to the grid, the voltage $\overrightarrow{V}$ will change to $\overrightarrow{V}_{DG,new}$. The difference between those voltages ($\Delta\overrightarrow{V}_{DG}$) can be calculated as follows:

$$\Delta\overrightarrow{V}_{DG} = \overrightarrow{Z}\cdot\Delta\overrightarrow{I} \quad (1)$$

The voltage difference has a component $\Delta V_{DG,r}$ in phase with $\overrightarrow{V}_{DG}$ and a component $\Delta V_{DG,x}$, perpendicular to $\overrightarrow{V}_{DG}$. According to [11], the two components can be approximated by:

$$\frac{\Delta V_{DG,r}}{\overrightarrow{V}_{DG}} \approx \frac{1}{S_{SC}}\left(P_{DG}\cdot\cos\left(\varphi_{SC}\right)+Q_{DG}\cdot\sin(\varphi_{SC})\right) \quad (2)$$

$$\frac{\Delta V_{DG,x}}{\overrightarrow{V}_{DG}} \approx \frac{1}{S_{SC}}\left(P_{DG}\cdot\sin\left(\varphi_{SC}\right)-Q_{DG}\cdot\cos(\varphi_{SC})\right) \quad (3)$$

With:

$$\tan\left(\varphi_{SC}\right) = \frac{X_{SC}}{R_{SC}} \quad (4)$$

Whereby P_{DG} and Q_{DG} are the active and reactive power injected by the DG unit(s), X_{SC} and R_{SC} are the short-circuit reactance and resistance of the grid and S_{SC} is the short-circuit power of the grid.

From these equations, it can be seen that the voltage changes due to active and reactive power of the DG units depend on the X/R ratio of the short-circuit impedance, and the ratio between the rated DG power (S_{DG}) and the short-circuit power (S_{SC}) at the point of connection. Addition of Eqs. (2) and (3) leads to:

$$\overrightarrow{V}_{DG,new} = \left(\overrightarrow{V}_{DG}+\Delta V_{DG,r}\right)+j\cdot\Delta V_{DG,x} \quad (5)$$

From the previous analysis, it can be seen that voltage change due to local generation gets smaller when the short-circuit power increases (relative to the connected DG power), the value of $\cos(\varphi)$ increases and with a decreasing X/R ratio of the short-circuit impedance.

In Fig. 3, simulation results comparing the relative short-circuit powers along a feeder (equal cable impedances between substations) between an open- and a closed-ring layout are shown. In case of the closed-ring layout, the other feeder (forming the ring) is identical. It can be seen that the short-circuit power increases when the grid is operated in a closed-ring layout. Furthermore, the