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Coordinated reactive power control to achieve minimal operating costs

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ABSTRACT

This paper deals with the influence of distributed generation (DG) on distribution losses in medium voltage (MV) distribution networks. The aim was to minimize the losses and operation costs with only DG reactive power compensation with respect to voltage constraints. Thus, the active power flows are not affected as any attempt of active power curtailment causes financial loss for DG owner. The advantage of technologies that build up new smart grids is the possibility of developing new approaches of network management. In this paper, a coordinated reactive power control is presented which takes advantage of real-time data measurements from the network. The load-flow algorithm is implemented into the coordinated control, which determines the optimal operating point using a modeled network for every generator separately. The aim of the algorithm is to minimize the reactive power flow. The solution is evaluated by means of computer simulations. The simulated network is a part of the Slovenian medium-voltage distribution network. The presented results illustrate that the algorithm results in fast, simple and efficient energy loss allocation with an acceptable level of accuracy.

Introduction

When operating distribution networks, there is always reactive power present due to electrical loads and capacitances of the power lines and cables. A part of the loss is due to reactive power that travels back and forth in power lines, all the way from power sources to the load points [1]. The reactive power also has a profound effect on the security of power systems because it affects voltages throughout the system. However, loss minimization and voltage control are competing objectives and minimizing losses does not ensure voltage control, usually both objectives exclude each other [2].

To minimize losses and achieve maximal economic benefits, reactive power flow has to be controlled, which has been the topics of many papers and many different solutions are already implemented [3–13]. To compensate reactive power flow most common and spreaded solution in distribution networks are capacitor banks which act like source of reactive power. With a proper control voltages can be controlled and losses reduced. Different solutions to obtain optimal switching schemes are presented in papers such as [14–18]. DGs can decrease losses by providing local complementary reactive power [1]; they can be modeled as active power sources which are also capable of injecting and consuming reactive power [19–21]. Their advantage is that they are scattered uniformly across the network and can be thus more efficient in minimizing the losses. Inverter-based technologies enable fast and reliable response to the network needs especially in the case of voltage rise [2]. In our previous work [22] it is also shown that the majority of the savings can be obtained by setting optimal reactive set-points of DG in compare to classical On-Load Tap Changer (OLTC) control.

DG usually work with a constant power factor ($\cos\varphi = 1$) and do not provide any ancillary services to the network. At present many countries already prescribe the usage of static $Q(U)$ characteristic for the contribution with local voltage control (example Slovenia [23] or European project MetaPV [24]). However, these solutions have limited control possibilities due to the lack of a communication infrastructure. Information and communication technologies (ICT) and smart meter implementation have enabled DG to take advantage of unused reactive power capabilities and to participate in emerging markets with reactive power. In today's competitive electricity market, the establishment of an adequate reactive power pricing methodology is becoming a key issue in providing the voltage control ancillary service [25]. However, there are many open questions in the literature related to dispatch of reactive power, many of them raised and discussed in [2,26].

The aim of presented research was to develop a control algorithm to minimize the operation costs, which is very simple in structure, but still effective, and thus suitable for implementing it into the SCADA as an application for controlling DG inverters. To

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solve non-linear objective functions, evolutionary algorithms came into existence [27]; many papers have started to use intelligent techniques such as genetic algorithm, particle swarm optimization, fuzzy logic, fuzzy wavelet network, and artificial neural networks [28] to obtain optimal operating points when dealing with a large number of DG. This paper shows that effective coordinated control solutions can be still achieved only by using well known load-flow calculation with the combination of simple step-by-step algorithm which minimizes the objective function. By allocating the reactive power of DG taking into account the reactive power dispatching costs, the point of minimal operation costs can be achieved. Furthermore, the issue of fair opportunity costs and oversizing of invertersis [29] is also addressed.

The problem formulation and control system design is presented in Section 'Control system design'. The simulated network and the simulation results are shown in Section 'Study case'. Finally, conclusions are drawn in Section 'Conclusion'.

Control system design

As the active and reactive power of the loads and generators in the network are constantly monitored and measured with smart meters, this data can be used to generate a coordinated control algorithm. The heart of the presented control system is a load-flow algorithm, which minimizes the losses in small steps using a modeled network. Possessing periodically power measurements, the simulations are carried out to minimize the reactive power flow. In a number of load-flow steps the optimal reactive power of the DG is determined and new set points sent to the generators to correlate their outputs. With the increasing processing power of computers, the number of necessary load-flows is not of crucial consideration, as long as the algorithm converges reliably which is of great importance when making industrial applications.

Fig. 1 presents a part of the distribution feeder and shows the direction of the power flow. The generators generate active power but their spare reactive power capabilities are unused. If DG could produce or consume a certain amount of reactive power, the reactive power that travels along the feeder could be minimized.

Let us assume that reactive power is flowing through the feeder from the main substation to the end of the feeder. The reactive power that reaches *Busbar 1* can be written as:

$$Q_{1j} = Q_{2i} + Q_{L1}. \tag{1}$$

If the generator G_1 produces reactive power equal to Q_{1j}, the reactive power flow from *Line 1* will be zero resulting in minimal losses in this line. Next, if the generator G_2 produces reactive power in the same way (equal to Q_{2j}) the reactive power through *Line 2* will also be minimal. Thus, if the reactive power capacity of all DG is unlimited, the reactive power flow through the feeder and losses will be minimal.

Unfortunately, the reactive power of DG is limited and in many cases the network operator cannot acquire reactive power from them. If DG owners are not financially stimulated to generate or consume reactive power they will not participate in the ancillary services. The problem is even more complex as the losses do not vary linearly; optimization of a generator influences losses throughout the entire system and the effect is also different for each generator separately. If a generator changes its current generation and injects more reactive power into the grid, the loss reduction will be different for each generator. Therefore, the algorithm has to determine the loss reduction due to reactive power change for each generator. The power losses in the line *j* can be determined by the following equation:

$$Losses_{ij} = \frac{P_j^2 + Q_j^2}{U_j^2} R_{LINE,ij}, \tag{2}$$

where P_j and Q_j are active and reactive power receiving end busbar, $R_{LINE,j}$ is the line resistance and U_j is the voltage at the node *j*. Let us assume there are no reactive power losses and analyze reactive power distributed in Fig. 2. The feeder line is rather general, and due to compensation along the feeder and no DG penetration, the active power line is spread in indifferent directions along the feeder as observed in Fig. 2(a). If the generator tries to minimize the losses in the above described case, the reactive power flow changes from the generator to the beginning of the feeder where the beginning of the feeder (OLTC substation) presents slack bus. It can be seen from Fig. 2(b) that in lines where the reactive power flow has the same direction as the line touching the generator node, the losses were reduced and in the opposite cases the losses were increased.

The sum of losses for every line using (2) can determine the change in losses i.e. loss reduction. If the power change is $Q_{G,STEP}$ the losses change is:

$$Losses\ change \approx \sum_{j=1}^{N} \left(\frac{P_j^2 + Q_j^2}{U_j^2} R_{LINE,j} - \frac{P_j^2 + (Q_j - Q_{G,STEP})^2}{U_j^2} R_{LINE,j} \right). \tag{3}$$

$Q_{G,STEP}$ is negative, in the case it has the opposite direction. *N* represents the last line in which the change is made, as described in Fig. 2. Loss reductions are calculated for every generator separately. That generator, where losses i.e. losses costs are reduced for the largest share, changes its output for $Q_{G,STEP}$ in the current iteration. The load flow is then run once again (new voltages, consumption and generation data are obtained) and procedure repeated. The algorithm stops when the change in output of any generator does not anymore reduce but increases the losses or if the voltage limits are reached. Solving power flows with different reactive power injections introduces errors in (3) and power flow-input data for loss allocation process due to different bus voltages to consumers and DG [30]. However, since the step change is relatively small,

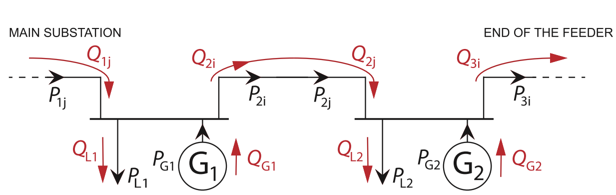

Fig. 1. Example of reactive power flow toward the end of the line.

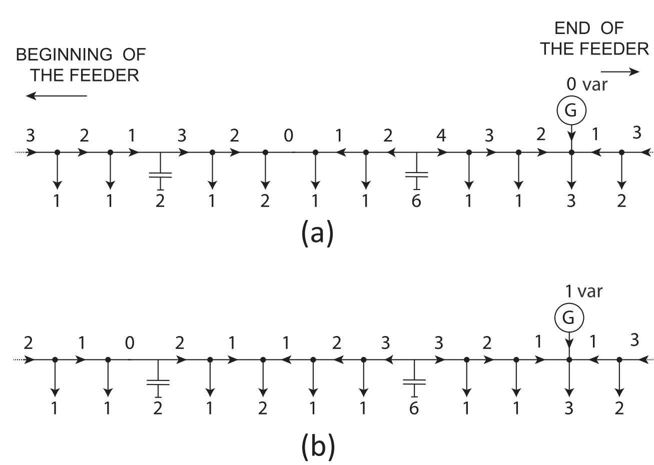

Fig. 2. Reactive power flow when DG is not participating in loss minimization (a) and when DG reduces the reactive power flow in the line coming from the substation (b).