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Impressum
Published by

Publisher: Rector of the Ilmenau University of Technology
Univ.-Prof. Dr. rer. nat. habil. Dr. h. c. Prof. h. c. Peter Scharff

Editor: Marketing Department (Phone: +49 3677 69-2520)
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(Phone: +49 3677 69-2860)
Univ.-Prof. Dr.-Ing. habil. Jens Haueisen

Editorial Deadline: 20. August 2010

Implementation: Ilmenau University of Technology
Felix Böckelmann
Philipp Schmidt

USB-Flash-Version.

Publishing House: Verlag ISLE, Betriebsstätte des ISLE e.V.
Werner-von-Siemens-Str. 16
98693 Ilmenau

Production: CDA Datenträger Albrechts GmbH, 98529 Suhl/Albrechts

Order trough: Marketing Department (+49 3677 69-2520)
Andrea Schneider (conferences@tu-ilmenau.de)

ISBN: 978-3-938843-53-6 (USB-Flash Version)

Online-Version:

Publisher: Universitätsbibliothek Ilmenau
ilmedia
Postfach 10 05 65
98684 Ilmenau

Home / Index:
http://www.db-thueringen.de/servlets/DocumentServlet?id=16739

OPTIMAL PLANNING AND OPERATION OF POWER SUPPLY IN LIBERALIZED ENERGY MARKETS

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ABSTRACT

This paper outlines new approaches of using the possibilities offered by controllable inverters of distributed generation plants (DGP) in terms of voltage-reactive power optimization (V-Q-Optimization) and active power-reactive power optimization (P-Q-Optimization). Based on an actual example the differences in active and reactive power flows at two scenarios are discussed. Benchmark – and hence the objective function – is the minimization of distribution losses caused by the transmission of electrical power. In addition the effect of DGP on the voltage profile to counter local voltage changes is demonstrated. The approaches are evaluated by simulation computations based on the measurements and grid parameters of a real distribution grid within the framework of the E-Energy project "eTelligence".

***Index Terms* -** optimization, distribution system, Energy Management System, distributed generation, optimal power flow

1. THE ETELLIGENCE PROJECT

Within the framework of the technology competition E-Energy by the German federal government four lighthouse-projects are sponsored by the ministry of economy and technology (German: Bundesministerium für Wirtschaft und Technologie – BMWi) and two other lighthouse-projects by the ministry of environment, conservation and reactor security (German: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit – BMU).

"eTelligence" is one of the projects sponsored by the BMWi implementing concepts of the energy supply of the future including a regional energy marketplace at the area of Cuxhaven, a city at the North Sea coastline. At first the focus is on the trade of electrical power and associated ancillary services offered and enquired by the market participants. The implementation of the integration of the different market participants is realized by the project partners EWE AG, BTC AG, OFFIS e.V., energy&meteo systems, Öko-Institut and the Fraunhofer Energy Alliance represented by the Fraunhofer ISE and the Fraunhofer AST [1].

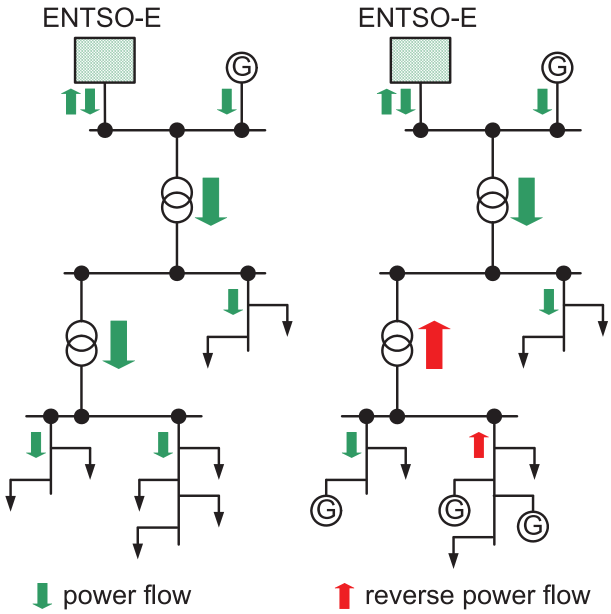

Figure 1 Examples of power flow in the past (left hand side) and today (right hand side)

Distribution grids representing an important part of electric power supply. The Fraunhofer AST is the subproject leader at the subproject "Smart distribution grid" and develops und test concepts for an optimal distribution grid operation. Utilizing high-resolution measurement equipment and state of the art forecast and optimization tools the local reactive power compensation is influenced by calculated variable und load-oriented grid bits on the local energy marketplace. This approach holds a large potential for a more environmental and economical distribution system operation as well as an increase of energy efficiency, cf. [2] and [3].

2. MOTIVATION FOR INFLUENCING REACTIVE POWER FED-IN VIA A LOCAL ENERGY MARKETPLACE

The increased fluctuating feed-ins from renewables at distribution grids and active load management leads to a significant change on the system behaviour and the distribution grid will no longer operate in an optimal way.

I.e. consequences are a limitation of installs of distributed generation units (e.g. photo-voltaic systems and combined heat power), an increased danger of imper-

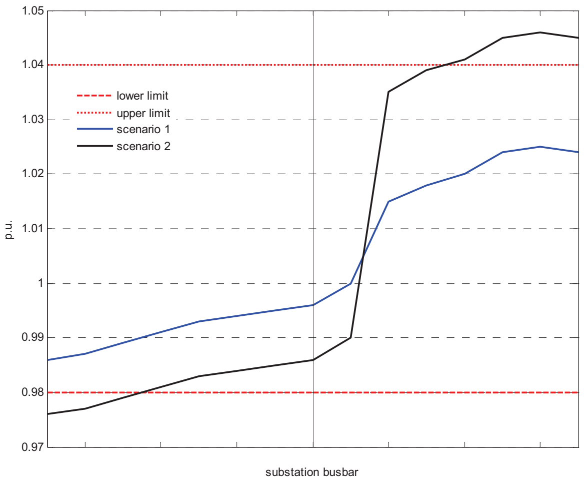

Figure 2 Voltage profile at two branches (left: load dominated; right: fed-in dominated) and the influence of the tap changer position

missible voltage profiles and line protection not adapted to the situation.

As it can be seen in Fig. 1 the configuration of the electrical distribution system and the resulting power flow has been changed in a significant way. In the past large power plants fed in electric power at supreme and high voltage level. This power was transported unidirectional via the distribution system to the consumers on medium and low voltage level. Substations and in the end the grid layout itself was designed and implemented to work in an optimal way under this defined conditions. But nowadays on medium and low voltage level distributed generation units and small power plants are installed.

Results of the fed-in on lower voltage levels are the inversion of power flow at increasing frequency, the raising of the node voltage at the same time and impermissible voltage profiles. To picture the problem Fig. 2 shows two scenarios of a medium voltage grid consisting of two branches connected via a substation busbar (SSB) where the voltage is controlled by a tap changer only. The vertical black line shows the position of the SSB, to the left the voltage profile of a load dominated branch and to the right the voltage profile of a fed-in dominated branch can be seen.

Status quo is represented by scenario 1. The tab changer is on 1.00 p.u. position and all limits are redeemed. Scenario 2 shows the future voltage profile if the number of distributed generation units on the right branch is growing and the tab changer position has to be changed to 0.99 p.u..

In this case the upper and lower voltage limits are broken at secondary substations at the end of the two branches. To avoid this effect methods of reactive power fed-in via DER to drop the voltage at certain grid nodes are developed.

This paper outlines degrees of freedom in control of distributed generation units and load management by utilization of high-resolution measurement equipment and state of the art forecast and optimization tools as well as information and communication technology (ICT) which allow an active operation control in consideration of an optimal usage of the distribution grid. Additionally typical use cases based on real measurements are presented and discussed to show the effects of “smart” distribution system operation on voltage profile, active and reactive power flow.

The utilization of information and communication technology (ICT) is mainly driven by a demand for real-time optimization between generation fed-in and load demand. It is urgent if more and more fluctuating generation (e.g. combined heat power, photo-voltaic systems or micro turbines) is installed to a distribution grid by private households, small industries or e.g. at indoor swimming pools. These plants range from small scale plants with a rated power of some kW up to large scale plants with a rated power of 5 MW. Therefore an optimized distribution grid operation with special concerns about the fluctuating generation and renewables with the marginal condition to fit the requirements of the liberalized energy market is required.

In avoidance of installing new and expensive reactive power compensation devices at the distribution grid the distribution system operation uses the available distributed generating and load shifting units. Minimization of transmission losses and provision of ancillary services (e.g. reactive power control, voltage control and frequency control) are the major aims. Today most of the distributed generation units are still able to be used as actuators for the “intelligent” distribution system operation. However, there are no economical and statutory incentives and first of all no suitable ICT infrastructure. This paper shows and discusses possible approaches.

3. USAGE OF NON-LINEAR OPTIMIZATION

The solving of complex non-linear optimization problems has high requirements on the mathematical formulation of the particular problem. Describing the boundary condition by utilizing equations as well as inequalities is much more difficult than at linear programming (LP) problems or problems from the field of mixed integer linear programming (MILP). For itself the finding of a start solution to have a basis for the search for local optima is a great challenge at this kind of optimization problems. Depending on the utilized type of method to solve the problem for it the formulations have be prepared carefully. The aim is to find a globally optimal solution as far as possible. But up to now this is a serious problem because it is impossible to prove respectively to guarantee the global behavior of an optimum for all non-linear problems [4].

In the field of electrical energy supply systems the interrelations between the explanatory variables are described by the rules of the complex AC calculation. The interrelations between real part and imaginary part of the complex variables are characterized by trigonometric functions reducing the number of appropriated solvers for non-linear programming (NLP) problems. Not all available NLP solvers support trigonometric functions.

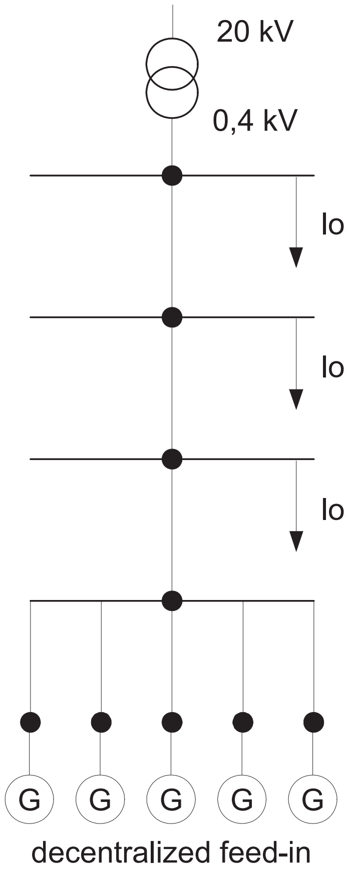

Figure 3 Grid structure of the investigated low voltage grid with settlement characteristic (poor load and distributed generation)

To model the optimization problem the energy management system (EMS) developed by the Fraunhofer Application Center System Technology (AST) was used. The optimization module of the EMS provides an easy-to-use possibility to create models via a graphic editor. Various components are comprised to a model. The single model components, e.g. photo-voltaic systems, branches or loads, encapsulate the mathematical code for each sub-function. By interconnecting components to a model the entire code is generated from the single code fragments. Thereby it is possible to fit the model structure rapidly to changes. Within the optimization module the mathematic descriptions of the components are formulated in GAMS (General Algebraic Modeling System) and solved by means of a commercial NLP solver.

Load flow optimization using a non-iterative procedure is a great challenge. This is caused by the complex behavior of NLP models for load flow calculation. But exceeding a certain model size, which is hard to define, the NLP solvers are not able to find a solution. Therefore finding an appropriated formulation of boundary conditions to be abided at these optimization problems has an enhanced matter.

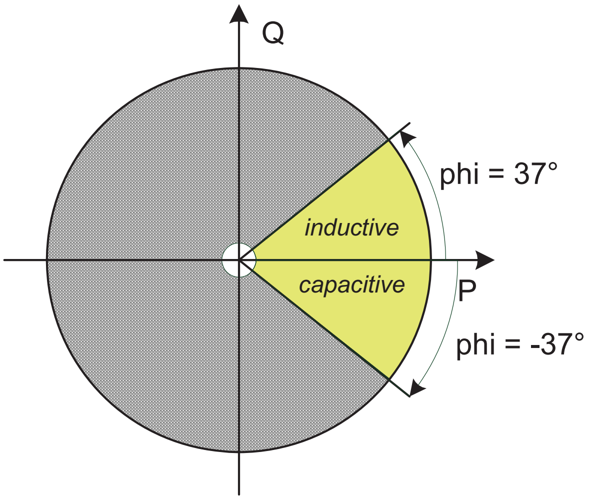

Figure 4 Area of operation (colored) of the inverters at the photo-voltaic systems

4. MINIMIZATION OF GRID LOSSES AT THE LOW(ER) VOLTAGE GRID WITH NLP OPTIMIZATION MODEL

(Electric cables) overhead lines absorb either inductive or capacitive reactive power depending on their design, the voltage level and the resulted operating point. The coverage of the reactive power demand of a cable occurs basically in both directions of the wire ends. In order to keep cable losses as small as possible and in order to keep the voltage profile at a good level an optimal reactive power spreading at both wire ends is necessary, cf. [5].

Caused by the higher ratio of impedance R to reactance X (R/X-ratio) of the transmission media on lower voltage level – values between 3 and 9 – the potential of reducing distribution losses via local reactive power feeding to serve the reactive power demand of the cables is very low. But if the reactive power demand of local assets, e.g. consumers as well as generators, can be served locally and not by the point of common coupling (PCC) with the medium voltage level, the potential is increasingly higher. Normally it has positive influence on the grid losses at the higher voltage level, too.

On the basis of the included example it will be shown, how grid losses can be minimized at the coupled network area via the usage of the optimization of the local reactive power supply of distributed generation. The shown example includes a network area with five photovoltaics, nine cable segments and three loads. The grid structure is shown in Fig. 3. The R/X ratio at the example selected here is 3.5. The inspection period is set to one day with a discrete temporal resolution of 15 minutes. Because of that there are 96 time steps in the optimization horizon. Based on the weather forecast the required demand of the loads and the apparent power of the photovoltaics have been forecasted. The voltage level in the investigated network is 0.4 kV and the higher voltage level is 20 kV. The point of transformation between both voltage levels is defined as *slack*. The voltage at the lower voltage level of the transformer has

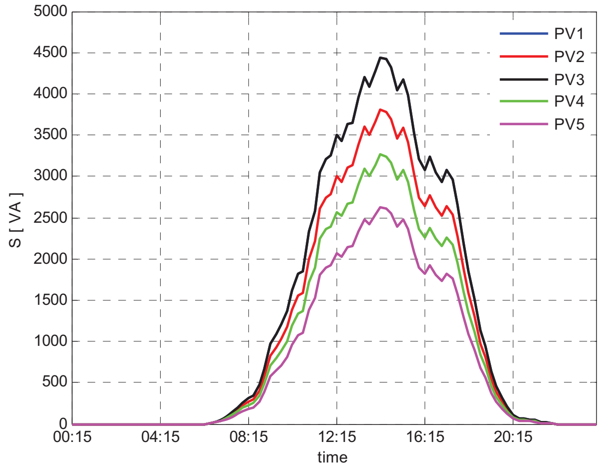

Figure 5 Forecast of apparent power

been set exactly to 400 V and is considered as unswayable. The voltage range at the photovoltaics and the loads varies from 380 to 420 V. Thereby the usual tolerances are approved in the low voltage network. The absolute power factor (PF) at the inverter, which should be minimally observed, is 0.8. That means photovoltaics are able to supply either inductive or capacitive reactive power with an angle range φ between -37° and +37°. In Fig. 4 the corresponding P-Q-diagram is shown. The variable power factor represents an important degree of freedom at this optimization task. Through this, the terminal voltage of the photovoltaics and at the loads is indirectly affected and its value assume in the above-mentioned borders. The active and reactive power flow to the higher or respectively from the higher voltage level through the slack manipulates the power loss of the cables and therefore the voltage drop between the wire ends. The performance data of the forecast apparent power of the photovoltaics ranges maximum between 2.5 and 4.5 kVA. The involved profiles are shown in Fig. 5.

The loads within the grid are supplied with active power only. The peak load differs between 2 and 4 kW. To examine the supply of reactive power from the photovoltaics only for the electrical lines, the power factor was set to 1. The profiles for the load forecasts are pictured in Fig. 6.

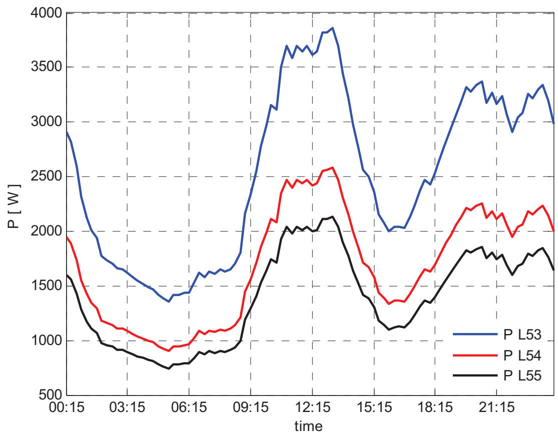

Figure 6 Load forecasts

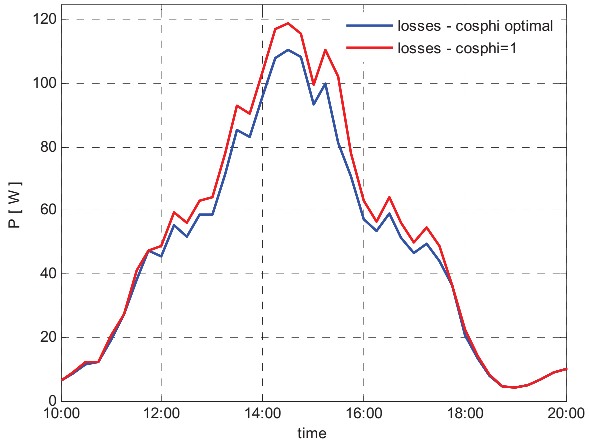

Figure 7 *Grid losses (constant and optimal power factor)*

It is obvious, that there are time frames where the load coverage can only be achieved by photovoltaics. In these cases a complete change of power flow within the grid level will occur, i.e. the electrical power to cover the required load will not be delivered by the preliminary grid level. Instead electrical power will fed into this pre-located grid.

Target of this study was to identify the impact of a non static power factor for photovoltaics on the energy transport to minimize the grid losses. Therefore two scenarios where defined. In case 1 the power factor of the photovoltaics within the optimization model was set to 1. In the second case the power factor was set to a minimal absolute value of 0.8. The results of the calculated optimizations are pictured in Fig. 7.

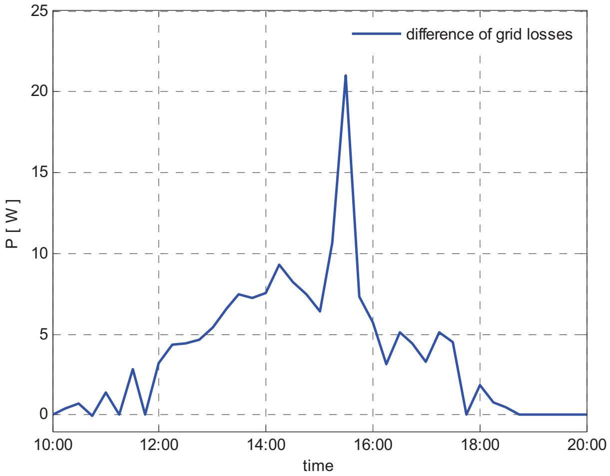

Figure 8 Saved grid losses with optimal power factor

To visualize the results for the time where the impact of photovoltaics is especially high, the time frame from 10:00 am to 8:00 pm was selected. It can be shown, that in case two, where a variable power factor was chosen, a reduction of grid losses could be achieved. The difference between the results of case one and case two is shown in Fig. 8. The maximum value is 20.5 VA. The amount of the saved grid losses is approximately 7 %. In Table 1 the main results are visualized.

	PF = 1	PF = opt.
grid losses	2418 VA	2257 VA
saved losses [abs]	161 VA	
saved losses [rel.]	6.65 %	
max. difference [abs]	20.5 VA	

Table 1 Main results of optimization

The influence of the voltage at the load points through decentralized feed-in in the local network can be shown exemplarily at the load point *load 1*. Its voltage profile is shown in Fig. 9. Additionally the active power flow at the *slack* is also shown in Fig. 9. Thereby it can be displayed, that because of the power flow reversion there is a voltage lifting at the morning hours and a voltage drawdown in the evening hours at the load point. The influencing of the voltage in the low voltage area is marginal. From the medium voltage area there can be immense problems resulting from the high voltage differences at the partial networks.

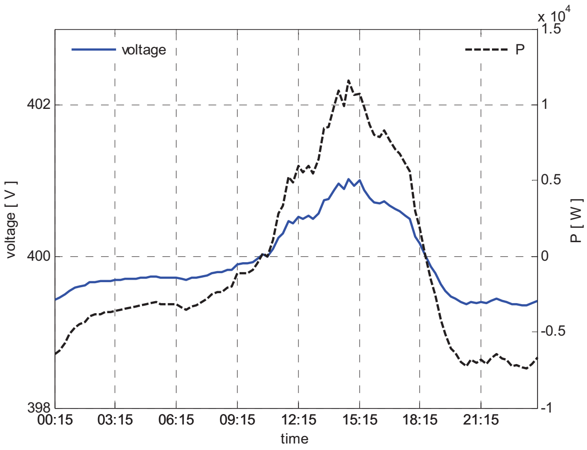

Figure 9 Voltage at load 1 *and active power at the slack*

5. CONCLUSION

By reference to this example it could be shown, that the optimization via using a NLP model at the optimal power flow calculation is possible. The effects which are in context with the decentralized feed-in could be demonstrated. By choosing the variables of the power factors at the inverters of the photovoltaics it is possible to minimize the network losses. The optimal scheduling of active deployment of reactive power through decentralized feeding facilities requires a software system with a market conforming interface. The EMS of the Fraunhofer AST provides this interface and furthermore it is possible to model and also to run the optimization task in this program. The challenge was the mathematical formulation of the nonlinear constraints, which are enabling the solving of the NLP model.

6. OUTLOOK

A remarkable part of the decentralized generated power will be injected at the medium voltage area in the near future. Because of that the voltage-reactive power behavior is of peculiar interest. At the medium voltage area there is a significant lower *R*/*X* ratio. The maximal values are circa 2. Nevertheless values less than 1 are also normal. Because of this, there are crucial higher reactive power losses than in the low voltage area. Automatically there are, here in case of decentralized feed-in, high percentage voltage differences between the single network parts (cf. Fig. 11). The minimization of these voltage differences, additionally to the network losses inside of an NLP model, will be the task which will be solved in the future.

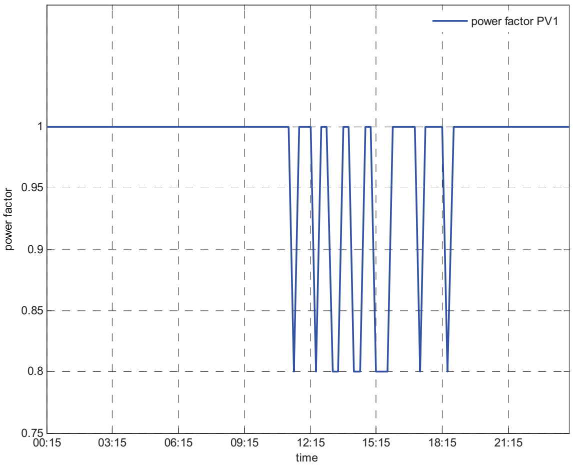

Figure 10 Optimal power factor of photovoltaic PV1

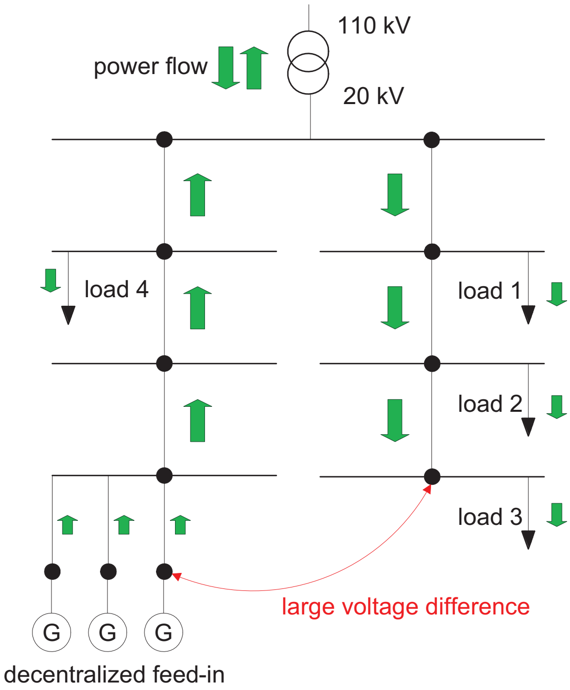

Figure 11 Large local voltage difference caused by decentralized feed-in

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