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Large-scale integration of distributed energy resources in power networks

Boštjan Blažič[1], **Igor Papič**[1]

[1] *Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, SI-1000 Ljubljana, Slovenija*
E-mail: bostjan.blazic@fe.uni-lj.si

Abstract. The focus of the European Union (EU) energy policy is on the promotion of low-carbon technologies and renewable-energy sources. In pursuit of this target, EU countries are setting up adequate support schemes (e.g. feed-in-tariffs). This is giving rise to different generation technologies and growing share of small scale generation in power networks. The paper deals with the impact of distributed energy resources (DER) on network operation and key technologies that would enable DER large-scale penetration in power networks. A concept of active distribution networks and its main building blocks is introduced.

Keywords: distributed energy resources (DER), active networks, voltage profile, power quality

Vključevanje visokega deleža razpršenih virov v elektroenergetska omrežja

Povzetek. Politika Evropske unije (EU) na področju energetike je osredotočena na promocijo obnovljivih virov energije in virov z nizkimi stopnjami emisij toplogrednih plinov. Temu sledijo tudi politike držav članic, ki npr. s premijami za odkup električne energije spodbujajo rabo takih virov. Zaradi energetske politike in čedalje boljše dostopnosti novih tehnologij nenehno raste delež razpršenih virov (RV) električne energije v omrežjih (slika 1). V članku je opisan možen vpliv RV na omrežja in navedene so ključne tehnologije, ki omogočajo integracijo velikega deleža RV.

Tradicionalna omrežja sestavlja centralno vodeno prenosno omrežje [1], na katero so priključene velike proizvodne enote, in pasivno razdelilno omrežje, ki dobavlja električno energijo odjemalcem. S čedalje večjim deležem RV, to je relativno majhnih virov, z omejeno možnostjo vodenja ali brez nje, se spreminja tudi vloga razdelilnega omrežja, kjer se kaže potreba po aktivnejšem upravljanju omrežja in priključenih virov ter bremen [2].

Večji delež RV lahko znatno vpliva na obratovanje omrežja [3] – [5]. Eden od problemov je vzdrževanje ustreznega napetostnega profila v omrežju, ki ga je treba zagotoviti z ustrezno koordinirano regulacijo napetosti. Kot prikazuje slika 2, je napetost na koncu voda med obratovanjem generatorja DER1 precej drugačna od tiste, ko generator ne obratuje. RV lahko povzročijo tudi nepravilno delovanje zaščite (sliki 3 in 4) in vplivajo na kakovost napetosti. Poleg tega obstaja nevarnost neželenega otočnega obratovanja, ki je nevarno za ljudi in za priključene naprave.

Opisane težave otežujejo večanje deleža RV in jih lahko rešimo z aktivnim upravljanjem omrežja. Pri tem glavni izziv predstavlja vodenje velikega števila virov električne energije [7] – [18]. Temeljne tehnologije, ki omogočajo delovanje aktivnega omrežja (slika 5), so zlasti viri električne energije z možnostjo krmiljenja, hranilniki električne energije, sodobne kompenzacijske naprave ter napredne informacijske in komunikacijske tehnologije. Aktivno omrežje je zasnovano v obliki lokalnih con, ki lahko obratujejo povezano s prenosnim omrežjem ali otočno. Tak način omogoča veliko fleksibilnost obratovanja in odjemalcem zagotavlja visoko zanesljivost dobave.

Razvoj omrežja je sicer težko napovedati, vendar lahko sklepamo, da se bo delež RV povečeval, kar bo zahtevalo tudi postopno večanje avtomatizacije omrežja. Kljub vsemu bo najverjetneje hrbtenica omrežja še vedno prenosno omrežje z večjimi proizvodnimi enotami.

Ključne besede: razpršeni viri električne energije, aktivna omrežja, napetostni profil, kakovost električne energije

1 Introduction

Traditionally, the electrical power system consisted of the transmission system supplied by large power plants and distribution power systems delivering electrical energy to consumers [1]. The power system structure began to change with the introduction of the electrical energy market, society environmental concern and availability of new technologies. Furthermore, the emphasis of the European Union (EU) policy has been towards increasing the share of power generation from renewables and reduction of greenhouse gas emissions. This has resulted in the advent of distributed energy resources (DER) that are becoming an important part of power systems (Fig. 1). The introduction of DER may seriously affect network operation, especially because of a large number of uncontrollable and relatively small sources. In this paper two main subjects are addressed. The first is the impact DER may have on power networks and the second is the question of network topology and control which would allow efficient integration of a large DER share.

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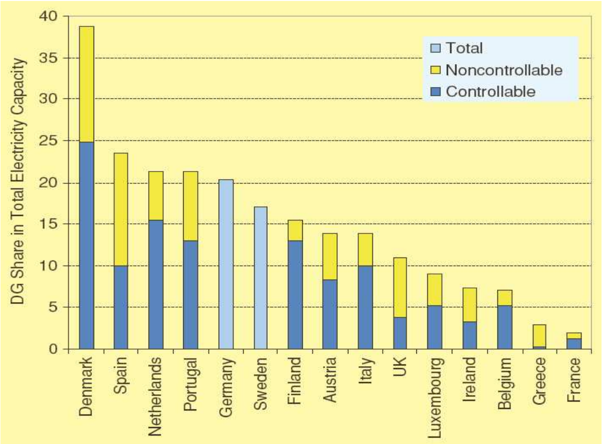

Figure 1. Share of DER in the total generation (EU-15, 2003)
Slika 1. Delež RV v celotni generaciji (EU-15, 2003)

2 Distributed energy resources

There is not a unique definition of the significance of DER [2]. However, this term is mostly used to describe energy sources that are connected to distribution networks. The rated power of DER is relatively small if compared to large power plants at the transmission level. In some cases also wind turbines aggregated in wind power parks and connected to the transmission network are treated as DER. The term DER includes storage technologies. In the next sections some common DER will be briefly addressed.

2.1 DER technologies

DER technologies can be divided into those based on fossil fuels (internal combustion engines, mini- and micro-turbines, fuel cells, etc.), those based on renewable sources (wind, biomass, hydro power, photovoltaics, etc.) and energy storage devices (batteries, flywheel, super capacitors…) [2].

DER use synchronous, induction generators and power electronic converters for electricity generation and connection to the network. Synchronous generators require a constant rotation speed and are not often used in DER applications. Their advantage is in the possibility of independent active- and reactive-power control. Induction generators are often used for being simple, robust, requiring no synchronisation and providing some damping for a variable speed energy source (e.g. wind turbine). However, they consume reactive power which is especially considerable at the start and therefore requires reactive power compensation. In contrast to synchronous generators, induction generators do not contribute to symmetrical faults but draw large currents in the case of unbalanced disturbances. For wind turbine applications double-fed induction generators are also used. Power electronic converters are used to connect dc sources (photovoltaics, storage devices, fuel cells, etc.) and their use is likely to increase in the future.

In the next section the impact of DER on network operation is discussed.

3 Impact of DER on network operation

This section provides an overview of DER impacts on network operation. The following topics are addressed: network voltage profile, protection operation, islanded operation, power quality and reserve capacity.

3.1 Network voltage profile

Distributed energy production may lead to variations in the voltage levels, especially due to fluctuating power flows and complicated reactive power equilibrium caused by insufficient control [2]. Even though DER may contribute to power loss reduction, it is difficult to perform voltage regulation with traditional control strategies. A typical voltage profile of a radial distribution line with DER connected to the LV level is shown in Fig. 2. The taps of the HV/MV transformer are adjusted so that the most distant customer voltage is within the required limits for maximum and minimum loading conditions. Voltage boost due to the MV/LV transformer is also shown. DER change power flows in the line and therefore also the voltage levels. If the voltage is maintained within limits by appropriate tap selection, problems may arise when the line is heavily loaded and DER are out of operation or vice-versa. Such situation may cause excessive or too low voltages at the end of the line.

3.2 Network protection

The main function of network protection is to provide security and safety of supply by isolating and clearing faults. Unit protection, which is usually designed by the unit manufacturer, protects the equipment from damage. The entire protection should be coordinated to assure selectivity and avoid unnecessary operation [3].

The connection of synchronous and induction generators causes an increase in fault currents in the case of a fault. The fault current contributions depend on the generator type, its parameters and distance from the fault. If DER are quickly switched off in the case of a nearby fault, they do not contribute substantially to fault levels. If distributed generators need to be tripped following a nearby fault, the consequences of a disconnection of a large number of distributed sources additionally overloading the faulted system, must be born in mind, too. These of course can worsen the system stability.

One way of protection mis-operation is unnecessary tripping of a non-faulted component of the power system. Such operation may occur when DER feed an upstream fault (Fig. 3). A fault occurs at Line 2. The fault will then be fed by the current from the network and from the generator DER1 connected to Line 1, as shown with the red line. If the short-circuit current of DER1 exceeds the limit of the overcurrent protection of Line 1, the feeder will be unnecessarily disconnected.

Another way of protection mis-operation is a failure of tripping a faulted component of the power system. A fail-to-trip situation may occur for a downstream fault as shown in Fig. 4. If the short-circuit current is mainly composed of the current from the DER1 unit (close to the fault point), protection may not disconnect the faulted line. Auto-reclosure systems represent an additional difficulty.

Possible solutions to the above issues may include protection coordination, use of directional protection, connection of generators with separate lines to the MV bus, etc. It should be noted that the above mentioned solutions are not always viable.

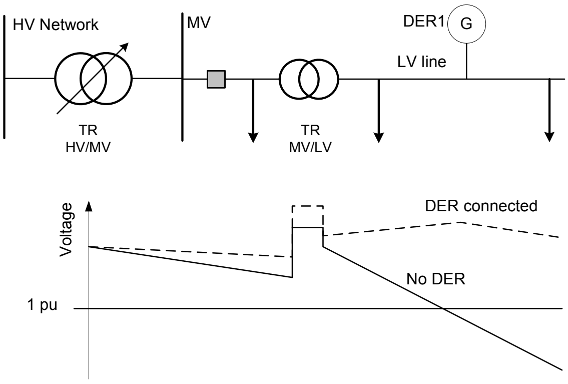

Figure 2. Voltage profile of a distribution line with DER
Slika 2. Napetostni profil radialnega voda z RV

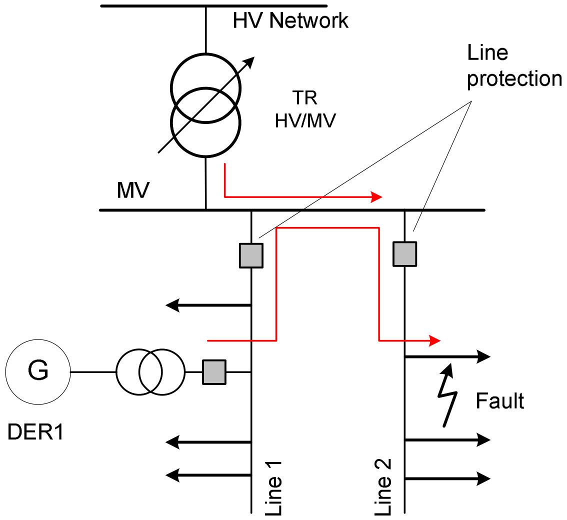

Figure 3. Unnecessary protection operation
Slika 3. Nepotrebno delovanje zaščite

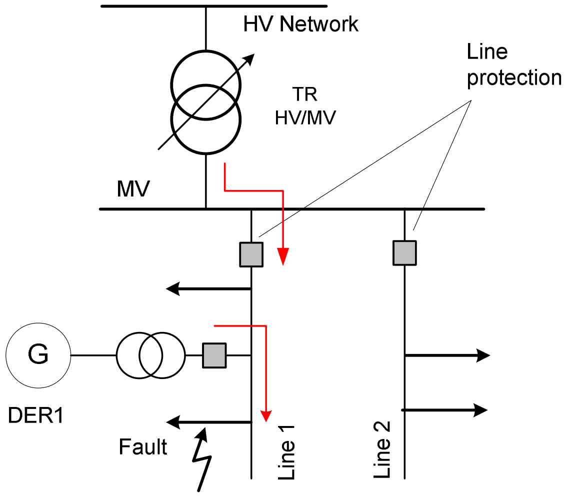

Figure 4. Protection fail-to-trip
Slika 4. Nedelovanje zaščite

3.3 Islanded operation

Operation in an electrical island (or islanded operation) occurs when in the case of loss-of-mains DER continue to supply loads in the isolated area [4]. Such operation is usually considered unacceptable. Unintentional islanding represents an electric shock hazard and causes frequency and voltage variations that may damage equipment. To prevent such situations, suitable protection is required which detects islanded operating conditions and disconnects DER from the grid. Protection for detection of islanded operation can be based on frequency, current and voltage measurements. Finally, although islanded operation is traditionally non-desirable, it can certainly contribute to the continuity of supply and easier restoration of a network following a fault.

3.4 Power quality

Although DER can improve power quality in general (including positive effects for voltage support and power-factor correction), large-scale introduction of DER may lead to poorer quality if operation of DER is not properly controlled and coordinated [5].

Transient voltage variations are the consequence of larger current changes that can be caused also by connection or disconnection of DER. Disconnection of a loaded generator is usually problematic and may cause voltage transients.

Some types of prime movers, especially wind turbines, may cause flicker, resulting as changes in luminosity of lamps. These disturbances travel far over the network and heavily affect consumers in a large area. The DER impact on stability depends upon the source type. The insertion of a significant number of DER based on rotating generators can cause power oscillations during network fault conditions. Induction generators, for instance, draw large inductive currents when over-speed, so they depress the network voltage even further and may cause voltage instability. Furthermore, a fault may cause disconnection of a large number of DER and the consequent loss of power depresses the frequency even further.

3.5 Reserve capacity

Due to the intermittent nature and availability of some DER (wind, solar, hydro…), they introduce additional uncertainty in the estimation of power production, which is crucial for effective production and consumption balancing. In contrast, the power production of traditional large power plants can be assessed accurately. Therefore, the increasing share of intermittent DER may require an additional reserve capacity. A considerable effort has been made for effective prediction of wind power and heat demand (in connection with combined heat and power (CHP) units). Prediction techniques may enable operation of DER with less reserve capacity.

3.6 EU experiences with DER integration

Within the SOLID-DER project [6], a survey based on a questionnaire was made dealing with problems related to DER integration. The survey was carried out in countries, partners of the project.

In Denmark, one of the main issues is protection. Installation of directional protection relays is proposed as solution. Another issue is stability of the network in the case of faults. When a large power unit is disconnected, the system frequency drops. To recover stability, it is necessary to disconnect consumer supply by cutting off 50/60 kV stations. Uncontrolled reactive-power flows are also a cause for concern. In Spain, temporary situations cause problems with voltage regulation; the connection or disconnection of DER causes the voltage levels to exceed the set limits. Another problem is caused by the intermittent nature of wind power plants affecting the daily consumption/production balancing. Cases of unintentional islanding have been also reported: distributed generators remain connected despite the loss of mains. In Austria voltage level problems are reported. They mostly occur in cases of low consumption and high DER production or vice-versa. In Poland the increasing number of DER units makes it difficult to maintain the required power quality and lowers the continuity of supply. The main source of problems is the large number of uncontrollable DER units. DER in the Czech Republic are mostly CHP. They do not cause mayor problems in network operation. However, studies have shown that serious impacts on network operation can be expected if the wind power capacity exceeds 700 MW. The Hungarian electrical energy production is characterized by a high share of base-load plants (nuclear, thermal). During some low-demand hours, the nuclear plant had to be adjusted downwards also because of mandatory energy purchase from renewables. To maintain system stability, the proposed wind developments have been capped to 313 MW. In Lithuania, Bulgaria and Slovenia, DER penetration is very low and so far it has caused only local network problems.

As seen from the country reports, network operators are often forced to limit the DER penetration in order to enable reliable system operation and adequate level of power quality. The mitigation of problems caused by DER would help to increase their share in electrical energy production.

4 Active distribution networks

The main technical challenge regarding DER is related to the control of a large number of small energy sources. Distribution systems will probably have to evolve from a passive to an active network providing adequate protection and enabling power-flow control [7]. Introduction of distribution system automation should be gradual. The first stage should involve automation of the distribution substation where a lot of automation and communication equipment is already installed, the next stage automation of feeders and DER control, and the last stage the integration of customer systems.

Various definitions and concepts are available for active distribution networks. An active network is actively managed and represents an energy exchange system [8] – [13], it can be divided into local control areas which can operate connected to the transmission network or autonomously and must enable local voltage and frequency control. The latter is achieved by means of controllable power sources, loads and energy storage and by means of custom power devices.

It is evident, that ICT will play an important role in active network control.

4.1 Distribution system architecture

An active distribution network enables efficient connection between the point of energy generation and energy consumption. It interacts with connected customers and allows monitoring and control of generators and loads.

A promising architecture that enables operation with high DER penetration can be a local control area where automation is used to support a relatively small local power system (Fig. 5). Such an area can be defined as a medium or low voltage network with DER, local storage devices and controllable loads.

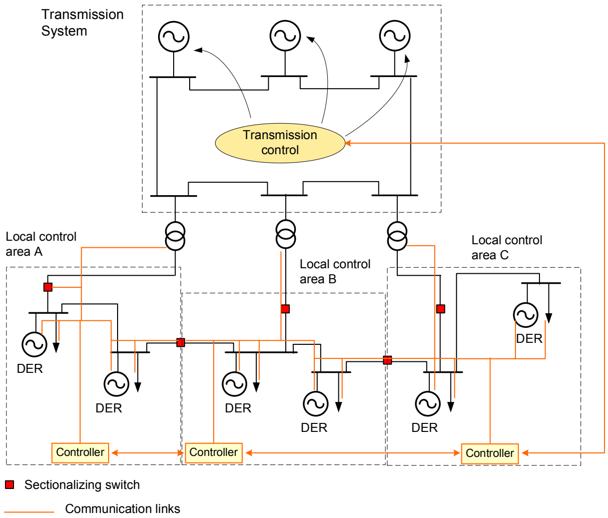

Figure 5. Active distribution network concept
Slika 5. Koncept aktivnega razdelilnega omrežja

An active network operates mostly connected to the main grid, however, it can automatically switch to islanded mode (e.g. in the case of faults) and re-connect after restoration of the faulted system. The concept is also attractive because it enables high integration of DER without a massive re-design of present distribution systems. The active network keeps the already present control structures of the distribution system: protection devices, control devices and reconfiguration devices. The active network adds a fourth component to the distribution system: power flow control. Power flow is controlled to maintain the required voltage levels and frequency. This can be achieved by means of generation and load control, remotely controlled switchgear, active compensation devices, etc. For isolated operation some form of energy storage is needed to ensure energy balance. Using DER, energy generation has been moved closer to loads, which can contribute to the reduction of losses and to the removal of distribution and transmission bottlenecks, and can enable effective reactive power and voltage control. Implementation of active distribution networks increases also the system reliability as DER are allowed to operate autonomously in the case of network faults.

Some basic technologies used in active networks are described next.

4.2 Communication and control system

As seen from requirements for stable and efficient operation of an active, widespread communication between controllable devices and control units is essential [10], [14]. With advanced communication and control, an automated and fully controllable distribution system can be achieved.

The control system (Fig. 5) can be based on various topologies. One possibility for example is the use of central processing units (also called master controllers), while the second is to operate on the peer-to-peer concept where controllable components communicate with each other without a master control. The major disadvantage of central processing units is that a failure of the central unit may result in active network break-down. On the other hand, implementation of such system may be easier if compared to the peer-to-peer concept. The control system can also be a mixture of both concepts. Controllable equipment (sources, loads) can be autonomous to some extent, e.g. responding to grid events autonomously using just local information.

4.3 Monitoring, forecasting and control

To allow for optimal operation of an active distribution network, control of all the controllable devices must be coordinated. This requires extensive real-time information [15] on the network condition and control of system components, including DER, customer load and controllable compensating and switching devices. Future operating conditions should be predicted too, to enable development of actions for efficient system performance. Future operating conditions can be estimated on the basis of production and consumption forecasting. Forecasting of electricity prices affects system operation [16].

Effective forecasting of intermittent energy sources can decrease the required reserve capacity which is represented by conventional power plants. The results of typical production prediction models used today have a root mean-square error between 10 to 15 % of the installed capacity.

4.4 Advanced power electronics equipment

In transmission networks, flexible AC transmission system (FACTS) devices have been introduced to improve the quality of power supply and to increase network stability. The same principles with appropriate modifications can be adopted also for distribution networks [17], [18]. The basic operation principles of FACTS devices in distribution networks remain the same although their operating characteristics may differ considerably. Technologies can be divided into three groups: network reconfiguration devices, compensating devices and DER with additional compensating functionality.

5 Conclusions

Though it is difficult to predict how the power system structure will develop in the future, it can be assumed that it will be gradual. Today, the electrical power system is developing in the direction of two power production areas; the first is the area of the existing large-scale power plants connected mainly to the transmission network, and the second one is the area of a large number of distributed sources connected to the distribution network. There are even some who predict that in the future power networks there will be no large–scale power generation and that decentralized power generation will be dominant.

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Boštjan Blažič received his B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from the University of Ljubljana, Slovenia, in 2000, 2003 and 2005, respectively. From 2000 to 2006 he worked as a researcher at the Faculty of Electrical Engineering in Ljubljana where he works as an assistant since 2007. His research interests include power quality and mathematical analysis and control of power converters.

Igor Papič received his B.Sc., M.Sc. and Ph.D. degrees, all in electrical engineering, from the University of Ljubljana, Slovenia, in 1992, 1995 and 1998, respectively. From 1994 to 1996 he was with Siemens Power Transmission and Distribution Group in Erlangen, Germany. Since 2004 he is an associate professor at the Faculty of Electrical Engineering in Ljubljana. In 2001 he was a visiting professor at the University of Manitoba in Winnipeg, Canada. His research interests include control and modelling of FACTS devices and Power Conditioners.