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Voltage control in distribution networks with distributed generation

Blaž Uljanić[1], Tomaž Pfajfar[2], Igor Papič[1], Boštjan Blažič[1]

[1] University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, 1000 Ljubljana, Slovenia
[2] Reinhausen 2e Ltd., Tehnološki park 24, 1000 Ljubljana, Slovenia
E-mail: blaz.uljanic@fe.uni-lj.si

Abstract. One of the goals of the European energy policy is to reach the "20-20-20" targets which by 2020 foresee a 20 % increase in energy efficiency, a 20 % reduction in CO_2 gas emissions and a 20 % increase in power production from renewable energy sources. As a result there will probably be a substantial increase in the share of renewable (and dispersed) energy sources in final consumption and accelerated investment in renewable energy sources and their integration into the electric power system. The nominal power of distributed generation (DG) is relatively small and it is not concentrated in just one part of the network but throughout it. Due to their limited power, DG sources are connected to the distribution network. Their production depends on a number of factors and is difficult to predict. Inclusion of a large share of DG in the distribution network was not planned when the network was designed. As DG affects network operation, some difficulties may be expected. One of the first ones is most likely to be violation of the set limits because of the changes in network voltage.

The paper is structured as follows. First, changes taking place in power network due to DG connection are described. To follow are a description of the impact of DG on the network voltage states and analytical determination of its impact on the voltage. Possible voltage control strategies with DG are shown by means of network simulations. The paper end by comparing losses incurred in different voltage-control regimes.

Keywords: Voltage control, voltage profile, distributed generation, network losses

1 INTRODUCTION

The electric power system consists of large power plants, HV transmission system, HV/MV transformer stations, MV distribution network, MV/LV transformer stations and LV network. Energy flows from large power plants through the network and transformer stations to end consumers.

Due to the increasing environmental awareness and EU dependency on the import of fossil fuels, European countries agreed on the so called "20-20-20" goals which by 2020 foresee a 20 % increase in energy efficiency, a 20 % decrease in CO_2 gas emissions and a 20 % increase in production from renewable energy sources. As a consequence of different support schemes, the share of renewable energy sources is rapidly increasing. Distributed generation (DG) usually involves one of the renewable energy sources with a small rated power and dispersed in the distribution network. If the share of DG is high, generation may change the direction of the power flow, which is now possible in both directions-from the HV level to the LV and vice versa. Network operation (voltage control, protection settings and power quality) is currently not yet adapted to high shares of DG. DG sources may also have a negative impact on the power quality and can present a potential danger for islanded operation.

2 DG EFFECT ON THE VOLTAGE PROFILE

DG units that are connected to the distribution network change the feeder voltage profile [1]. These sources usually have limited possibilities of control or are without it and usually do not participate in voltage control. However, compliably with the new distribution network grid code DG voltage control is required [2].

Network operators have to maintain voltage levels within the limits set by the SIST EN 50160 standard [3]. The standard determines the parameters of the voltage quality. It determines the limit of disturbance levels in the MV and LV network, at all consumer points of common coupling (PCC). At consumer PCC, the voltage can be described by thirteen parameters.

Fig. 1 presents the voltage profile of a radial feeder with a distributed source (G) connected at the end. When this source operates, the voltage at the PCC is raised and the network losses are reduced. When it does not operate, the voltage profile is determined by the load and regulation transformer. There may be problems when the feeder load is small and the DG unit operates

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or when the feeder load is high and the DG unit does not operate. In such operation states the regulation transformer may not be able to keep the voltage inside the set limit values.

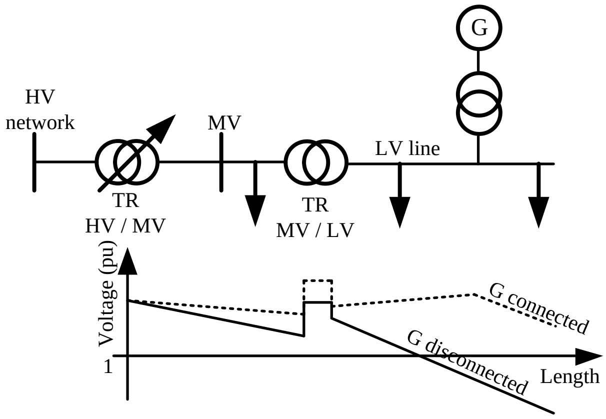

Figure 1: Voltage profile of a radial distribution line with DG units.

One possible solution to the problem is to limit the DG scope. However, this would seriously affect integration of DG in the network, which is not in line with the adopted energy policy. The second option is to make DG to actively participate in voltage control.

Some of the options for maintaining the voltage levels within the set limits are [4]:

- primary-voltage control in distribution stations with OLTC (on-load tap changing) transformers,
- reinforcement of the network,
- reactive-power control of DG,
- active-power control of DG,
- installation of voltage regulators,
- use of compensators.

To provide voltage control at a minimal cost, only options with DG units (reactive-power management) and OLTC transformer will be discussed. Active-power control will not considered in as electric power producers are not interested in it.

3 ANALYTICAL DETERMINATION OF THE IMPACT OF DG UNITS ON THE NETWORK VOLTAGE

In normal power-system the energy flows from high- to low-voltage levels (i.e. from generation units connected to the transmission network to consumers connected to the distribution network) which makes the voltage drops to be the highest close to the loads. When DG units are connected to the network, the energy flow can change and is dependent not only on loads but also on DG units. The result is the change in the voltage drop value.

In Fig. 2, a simple network with DG unit is shown. The transformer presents the transformer station. It is followed by an MV line and a busbar, where the DG source and the consumer are connected.

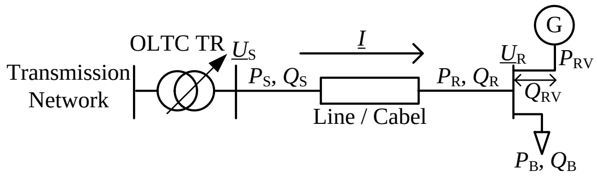

Figure 2: Simple network with a DG unit.

Symbols in Fig. 2 denote the following:

- $\underline{U}_S$, voltage at the substation busbar,
- $\underline{U}_R$, voltage at the DG PCC,
- $\underline{I}$, current (feeder),
- X, R, line reactance and resistance,
- $\underline{Z}_b$, load impedance,
- P_S, Q_S, active and reactive power at the beginning of the line,
- P_R, Q_R, active and reactive power at the end of the line,
- P_{RV}, Q_{RV}, active and reactive power of DG.

For the generator PCC the following equation can be written:

$$\underline{U}_R \cdot \underline{I}^* = P_R + jQ_R \Rightarrow \underline{I} = \frac{P_R - jQ_R}{\underline{U}_g^*} . \quad (1)$$

The voltage at the substation busbar can be written as:

$$\underline{U}_S = \underline{U}_R + (R + jX) \cdot \underline{I} . \quad (2)$$

If the voltage at the generator terminal is selected as reference $\underline{U}_R = \underline{U}_R^* = U_R \angle 0^0$, we can write the following equation:

$$\underline{U}_R = \underline{U}_S - \frac{RP_R + XQ_R}{\underline{U}_R} - j\frac{XP_R - RQ_R}{\underline{U}_R} , \quad (3)$$

from which it follows:

$$\underline{U}_R = \underline{U}_S - \Delta U - j\delta U . \quad (4)$$

Fig. 3 shows a phase diagram for equation (4).

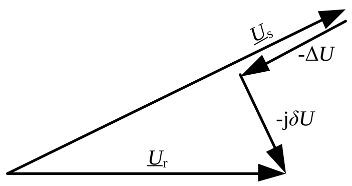

Figure 3: Voltage phase diagram.

From Fig. 3 we can see that the difference in amplitudes $\underline{U}_S$ and $\underline{U}_R$ is due to ΔU, which is in phase with $\underline{U}_S$, while the difference in the phase angle is mainly due to δU.

The voltage amplitude at the DG source PCC can be approximated as:

$$U_R \approx U_S - \frac{RP_R + XQ_R}{U_R}. \quad (5)$$

For the generation node we can write:

$$P_R = P_B - P_{RV},$$
$$Q_R = Q_B \pm Q_{RV}.$$

Assuming that the generator produces no reactive power and the worst situation in the network is when $P_b = Q_b = 0$ and that the generator produces its maximum active power, the voltage at the connection point of the DG source can be expressed as:

$$\underline{U}_R \approx \underline{U}_S + \frac{R \cdot P_{RV}}{U_R}. \quad (6)$$

From equation (6) it can be concluded that the voltage at the generator PCC depends on resistance of the line, voltage at the transformer substation and the active power produced by the DG source.

4 SIMULATED NETWORK

Fig. 4 shows a simplified single-phase diagram of the simulated network located in Savinjska dolina, Slovenia. The 20 kV MV network is fed by an OLTC transformer of the rated power of 20 MVA (regulation range ±12 taps with regulation step 1.33 %). The reference voltage is set to 1.0375 %. In the network there are 13 micro hydro-power plants (µHPP), with the total power of some 2.5 MVA. Two µHPP have synchronous generators, those of the others are asynchronous (Table 1). All generation units are connected to the 20 kV network and to the grid through 20/0.4 kV transformers. The loads are modeled as *R-X* impedances, which are voltage-dependent (in the range 80 %-120 %) and operate with cosφ=0.95. The load diagrams are made on the basis of measurements of three feeders connected to a transformer station at Rastke. The types of the load patterns are shown in Fig. 5.

In our stability studies, which were based on simulations, the RMS values were considered. One day in real time is illustrated with 144 s in simulation; so 1 second represents 10 minutes. The value 0 represents the time 00:00:00 and the value 144 represents 24:00:00. In the DIgSILENT PowerFactory simulation program, simulations are made with the RMS values which allow calculation of electromechanical transients and also consider dynamics of the control algorithms. The measurement points (MP) where voltage measurements were made are shown on a single-phase diagram (see Fig. 4) and are positioned in the network according to where the maximum and minimum voltages are expected. The generators were assumed to produce their maximum power throughout the simulation. As foreseen by the SIST EN 50160 standard, 95 % of the 10-minute mean RMS values of the voltage should be under normal operating states and without considering interruptions of voltage supply in MV networks within ±10 % of the nominal voltage. In our simulations, the upper and lower voltage limits were defined. For the upper limit +5 % and for the lower limit -5 % deviations from the nominal voltage were selected. The tolerance area for voltage control was 1 %. By choosing the upper voltage limit, the highest voltages are eliminated. Besides that, the lowest voltages need also be considered and for the voltage drop on MV/LV transformers and the lines should be accounted for. This was estimated at 4 %.

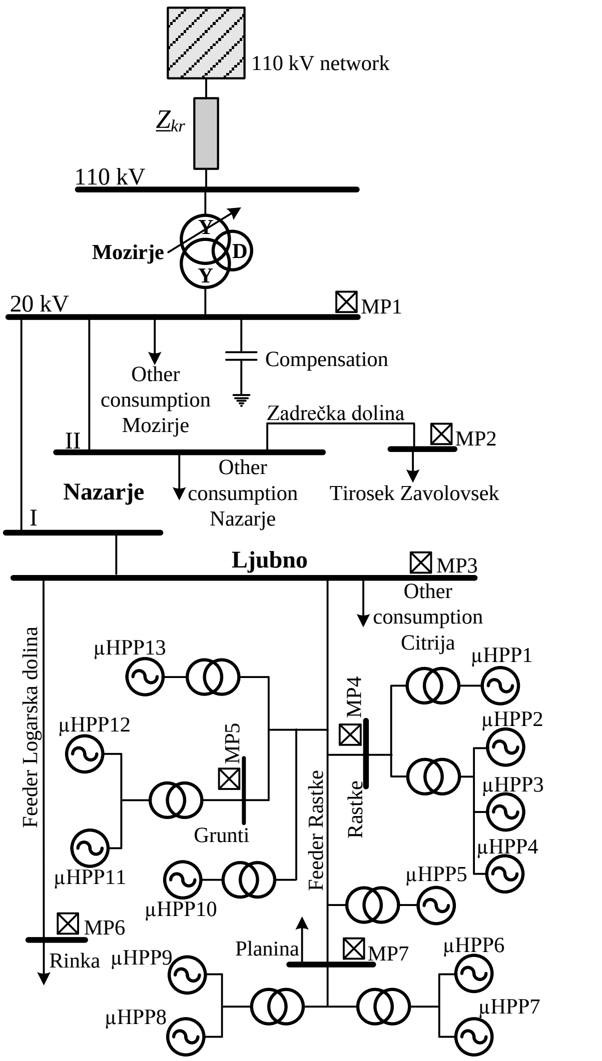

Figure 4: Simplified single-line diagram of the network.

Table 1: Data of the network generators

Mark	Rated power / kVA	Generator type
µHPP1	22	Asynchronous generator
µHPP2	132	Asynchronous generator
µHPP3	810	Synchronous generator
µHPP4	594	Synchronous generator
µHPP5	19	Asynchronous generator
µHPP6	110	Asynchronous generator
µHPP7	80	Asynchronous generator
µHPP8	160	Asynchronous generator
µHPP9	45	Asynchronous generator
µHPP10	56	Asynchronous generator
µHPP11	56	Asynchronous generator
µHPP12	56	Asynchronous generator
µHPP13	287	Asynchronous generator

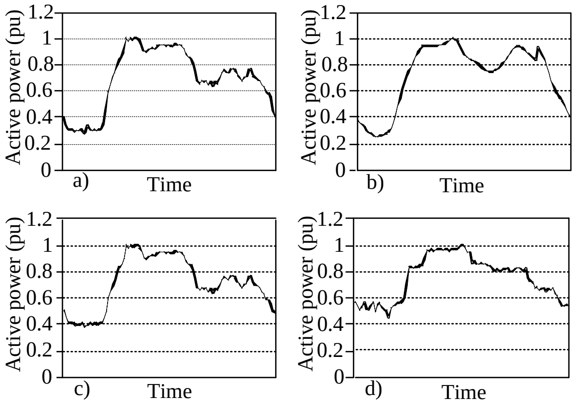

Figure 5: Types of the daily load patterns.

5 Simulation results

In this chapter we show simulation results for the scenarios listed in Fig. 4.

5.1 Classical voltage control

In classical voltage control this is only the OLTC transformer that controls the voltage in the network. The OLTC HV/MV transformer has 25 control positions. The time delay between switches is typically set to 2-3 minutes and deviation can be 1 % of the desired value. The desired value refers to the voltage on the busbars in the substation and is usually set from 2.5 % to 5 % above the nominal value. The transformer changes its tap positions with regard to the measured voltages and reference voltage. In Fig. 6, the transformer control scheme is shown.

In Fig. 7, the MP voltages for classical voltage control are shown. As seen, the transformer cannot keep voltages within the set values. The maximum voltage is 1.073 p.u. (at the Grunti substation) and the lowest is 0.958 p.u. (at the TP Tirosek Zavolovšek substation). If the reference voltage was set to a lower value, voltages would be too low in some points of the network (for the selected limits).

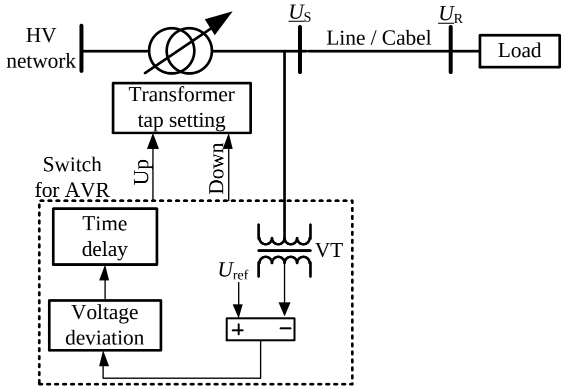

Figure 6: Classical voltage - control concept in RTP.

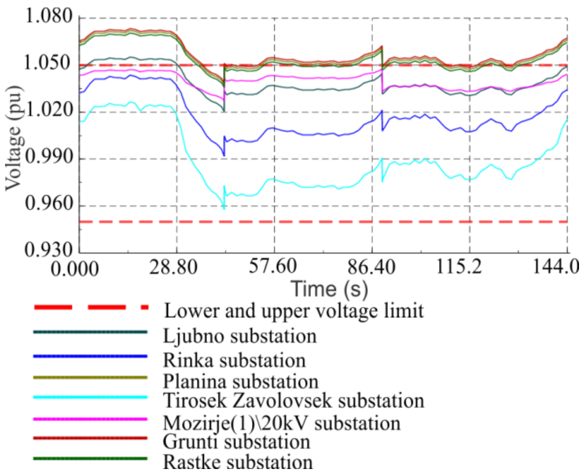

Figure 7: Classical voltage control – MP voltages.

5.2 Classical voltage control and reactive-power control

Besides classical voltage control, synchronous generators (SG) can also be used to control voltage. Any SG may, depending on its operating point, produce or consume reactive power. SG operation is limited by its operating diagram which is defined by the following curves: the rotor and armature thermal limit and the end-region heating limit [5].

Based on the operating point and operating diagram, the value of the reactive power is determined. The actual reactive power is determined with the static characteristic and the measured voltage. The static characteristic used in our case is shown in Fig. 8. Based on the operating chart, limits Q_{max} and Q_{min} that the generator can inject into the network are defined. If the voltage is between the limits (i.e. U_{min} or U_{max}), the generator produces the reactive power that is defined by the characteristic (Fig. 8). If each generator produces/consumes the reactive power that is defined by the characteristic, then the needed reactive power is shared between the generators. Such control assures a more stable operation. The control range (0.96-1.04

p.u.) is narrowed by 1 % in order to avoid conflict with other controllers.

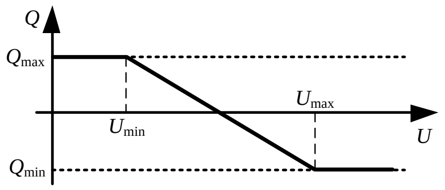

Figure 8: Static characteristic of SG.

In Fig. 9, the MP voltages in the network during classical voltage control and reactive-power control are shown. SG participation is partly helpful, as the voltages are lower than in classical control and thus it is easier to keep the voltages within the set limits. The highest voltage value is 1.060 pu (at the Rinka substation) and the lowest is 0.964 pu (at the Tirosek Zavolovšek substation). Besides SG participation in voltage control voltages in some network points (at the Rastke, Planina and Grunti substations) exceed set limits.

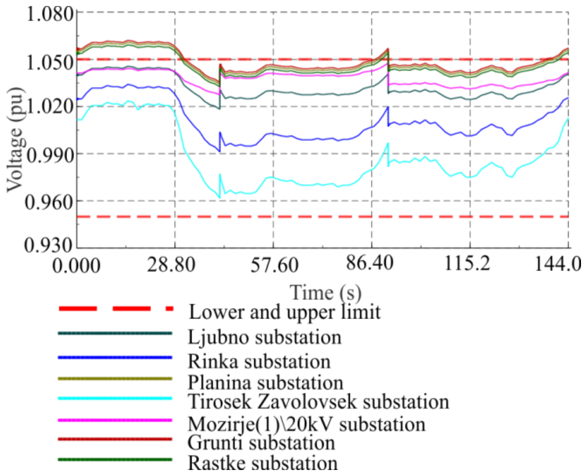

Figure 9: Classical voltage control and reactive-power control – MP voltages.

5.3 *Central-voltage control*

In central voltage control, the voltages are measured in several points of the network (Fig. 4). Measurements are entered in the control algorithm which defines the reference voltage continuously. When the algorithm changes the transformer tap position, it also takes into account that none of the voltages violates the set voltage limits.

As seen from Fig. 10 the voltages are within the set values (0.95-1.05 p.u.). The transformer needs to change the tap position four times to keep the voltages within the set limits.

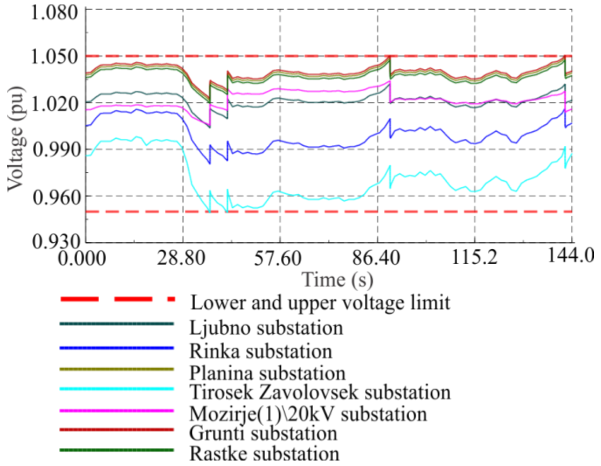

Figure 10: Central voltage control – MP voltages.

5.4 *Central-voltage control and reactive-power control*

Despite the fact that the voltages are measured in several critical points of the network, we cannot assure that we will be able (because of the operating states) to select the correct transformer tap. Consequently, we are not able to maintain voltages within the set limits. If SGs contribute to voltage control, we can, due to their participation in voltage control, reduce the difference between the highest and the lowest voltage in a certain period of time and consequently increase the flexibility of the network. In central voltage control, SGs can also contribute to voltage control. The main difference between central voltage control with or without reactive power control with SGs appears as smaller range between the minimum and the maximum voltage.

As shown in Fig. 11, the voltages are within the set limits. If there were more DGs, this would be the only appropriate voltage control concept. Compared to the central voltage control, the tap should in this case be changed three times to keep the voltages within the set limits.

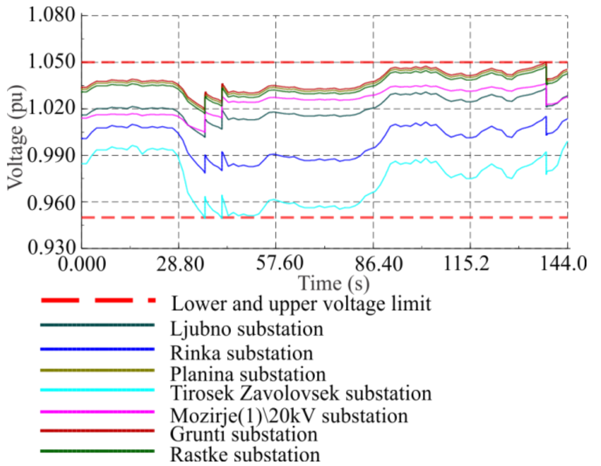

Figure 11: Central voltage control and reactive-power control – MP voltages.

6 NETWORK LOSSES

In the control strategies described above, power flows are different and so are consequently also power losses. DG sources reduce the line load, which results in reduced network losses. When penetration of DG sources in the network is high, the lines are more loaded and consequently power losses are increased, too.

Generally, power losses for the network shown in Fig. 2 can be expressed with no DG source by the following equation:

$$L = I^2 R = \frac{P_R^2 + Q_R^2}{U_R^2} R . \tag{7}$$

If power losses for the same network are written with a DG source, the following equation applies:

$$L = \frac{(P_B - P_{RV})^2 + (Q_B + Q_{RV})^2}{U_R^2} R . \tag{8}$$

As shown above, SG can be used for voltage control. The voltage can be reduced by consuming the reactive power, but looking at equation (8), we can see that consumption of the reactive power from the network increases power losses.

The total network losses for classical voltage control and the differences between other voltage control concepts and classical voltage control are shown in Fig. 12. The losses in classical voltage control for a simulated network are 4.925 MWh, for classical voltage control and reactive-power control 5.244 MWh, for central voltage control 4.964 MWh and for central voltage control and reactive-power control 5.188 MWh. Network losses are different for each of these controls as power flows are different, too. It can be seen that losses are higher in cases where SGs contribute to voltage control than in cases where they do not. Where the network voltages are too high due to high penetration of the DG sources, generators that contribute to voltage control by producing the reactive power increase losses.

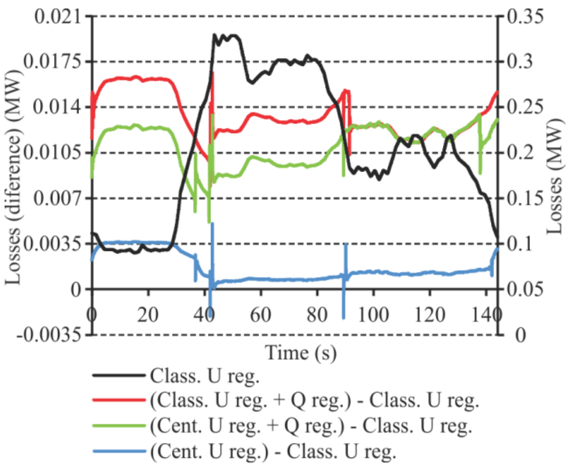

Figure 12: Losses in classical voltage control and differences between the classical and other control strategies.

7 CONCLUSION

The growing environmental awareness has made dispersed generation to become ever more important. Exploiting renewable energy sources is being supported by governments with various grants in order to increase the share of renewable energy sources and to stimulate technological development in this area. In Slovenia the share of dispersed generation is not yet as high as to affect the network parameters. In a network in which penetration of these sources exceeds a certain level, they have to participate in voltage control. Consequently, the reference values for the MV/LV transformers have to be precisely redefined. The network should be managed in the way assuring its optimally reliable and safe operation.

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Blaž Uljanić received his B.Sc. degree in electrical engineering from the University of Ljubljana, Slovenia, in 2009. Currently he is a researcher at the Faculty of Electrical Engineering in Ljubljana. His research interest is in distributed generation.

Tomaž Pfajfar received his B.Sc. and Ph.D. degrees, all in electrical engineering, from the University of Ljubljana, Slovenia, in 2004 and 2009, respectively. From 2004 to 2009 he was a researcher at the Faculty of Electrical Engineering in Ljubljana. Currently he is technical director at Reinhausen 2e Ltd., a spin-off company of the University of Ljubljana, Slovenia. His research interests include power quality, compensation devices, distributed generation and active network operation.

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 employed with the Siemens Power Transmission and Distribution Group in Erlangen, Germany. He is currently a 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 power conditioners, FACTS devices, power quality and active distribution networks.

Boštjan Blažič received his B.Sc., M.Sc. and Ph.D. degrees, all in electrical engineering, from the University of Ljubljana, Slovenia, in 2000, 2003 and 2005, respectively. He is presently an assistant at the Faculty of Electrical Engineering, Ljubljana. His research interests encompass power quality, distributed generation, mathematical analysis and control of power converters.