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The Analysis of a Rural Distribution Network with Distributed Generation in Catchment Area of Stara Planina

Jordan Radosavljević, Miroljub Jevtić, and Dardan Klimenta

Abstract: The rural distribution network with 11 micro hydropower plants (MHPs) of 10 kW to 50 kW, in catchment area of Stara Planina, is analyzed in the paper. The network is characterized by: higher generation than consumption, outstanding variation of generated energy during a year, permanent increase of number of constructed and connected MHPs and significant space dispersion of MHPs. In such network the voltage deviations were appeared out of standard limits. After operation of MHPs during three years, their cost efficiency is analyzed and procedure of voltage regulation in the network is developed in the paper. The procedure includes calculation and setting of optimal off-voltage tap changer positions at transformers, twice in year, i.e. in season with higher generation and in season with lower generation. At outlying nodes (near outlying MHPs), where voltage was not regulated within standard limits (using this procedure), voltage regulation is performed by two autotransformers of 0.95/0.4 kV that are posted on posts of outlying nodes supply line. This procedure is proposed as a model which can be applied in future similar rural networks with MHPs that will be constructed in West Balkan countries after acceptance of EU directives about renewable energy sources.

Keywords: Distribution network, distributed generation, micro hydropower plants, energy cost, power flow, voltage regulation, short circuit.

1 Introduction

MASS CONSTRUCTION of micro hydropower plants (MHPs) in West Balkan countries is not started. These counties were not accepted, on time, Europe Union planes about renewable energy sources. Area of Stara Planina on East Serbia

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The authors are with Faculty of Engineering in Kosovska Mitrovica, Kneza Miloša 7, 38220 Kosovska Mitrovica, Serbia (e-mail: radjor73@yahoo.com).

is rural area from that the most of people were emigrated. One part of rest of people was constructed 15 MHPs of 10 kW to 50 kW at little river Trgoviski Timok, with idea of survival and sustainable development. Accordingly, these people are ready for use of EU directives about renewable energy sources. This unique area in Serbia can be used as a model for other similar cachment areas of West Balkan. At the moment, 11 constructed MHPs were connected, and 6 MHPs are planed for construction and connection, to same distribution network. Distribution network with constructed 11 MHPs is characterized by: higher generation than consumption, outstanding variation of generated energy during a year, permanent increase of number of constructed and connected MHPs and significant space dispersion of MHPs. In such network the power flow is directed from low voltage to medium voltage level of network. Number of MHPs, that are planed for construction and connection to distribution network, increases and it is necessary to determine the way of voltage regulation during yearly generation change and during increase of MHPs number. The area which includes 11 MHPs and corresponding network, are presented in Figure 1 and 2, respectively. The planed MHPs in this area are presented in Figure 1.

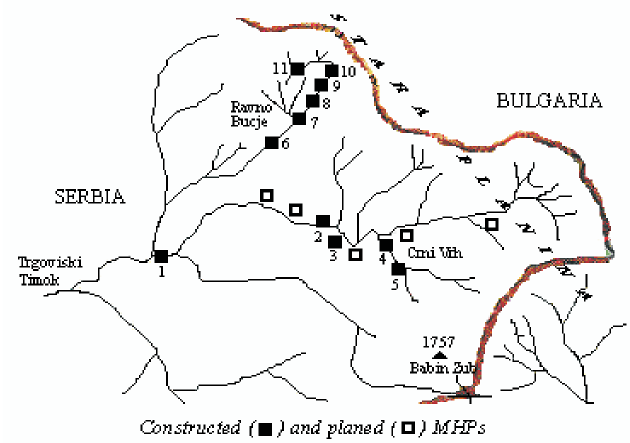


Fig. 1. Constructed (□) and planed (■) MHPs in catchment area of little river Trgoviski Timok at mountain Stara Planina.

The annual power curves of MHPs for 2007 year are presented in Figure 3. The basic data for constructed MHPs are given in Table 1. The data of MHPs induction generators, lines, transformers and loads are given in tables A1–A4 of Appendix.

The aim of paper is to develop a procedure for optimal seasonal voltage regulation of rural distribution network with distributed generation and to apply the procedure in this particular network. Use of procedure for seasonal voltage regu-

Table 1. Basic data for MHPs

MHP	Maximal head H_l^{max} (m)		Turbine Type	Turbine R_1 (kW)	Average value of generated energy in 2005, 2006 and 2007 years, W (kWh)
MHP1	17	0.40	Crossflow	40	236 546
MHP2	4.25	0.40	Crossflow	12.5	53 602
MHP3	12.5	0.65	Crossflow	40	148 700
MHP4	13	0.13	Crossflow	16	41 947
MHP5	17.5	0.15	Crossflow	10	32 495
MHP6	13	0.10	Crossflow	10	20 920
MHP7	32	0.10	Crossflow	20	102 670
MHP8	30	0.10	Crossflow	20	59 750
MHP9	35	0.07	Francis	16	44 120
MHP10	20	0.04	Pelton	10	32 500
MHP11	12.5	0.04	Crossflow	10	22 356

lation will enable to generate the energy of higher quality and will help in optimal planning of new network part with planned MHPs in this area. This procedure can be applied in future similar rural networks with MHPs that will be constructed in West Balkan countries after acceptance of EU directives about renewable energy sources. The procedure includes calculation and setting of optimal off- voltage tap changer positions at transformers, twice in year, i.e. in season with higher generation and in season with lower generation. After application of this procedure, at outlying nodes (near outlying MHPs) voltages can stay out of standard limits. In this case, voltage regulation of outlying nodes can be performed by two autotransformers (ATs) of 0.95/0.4 kV with tapes, that will be placed in line which supplies these nodes.

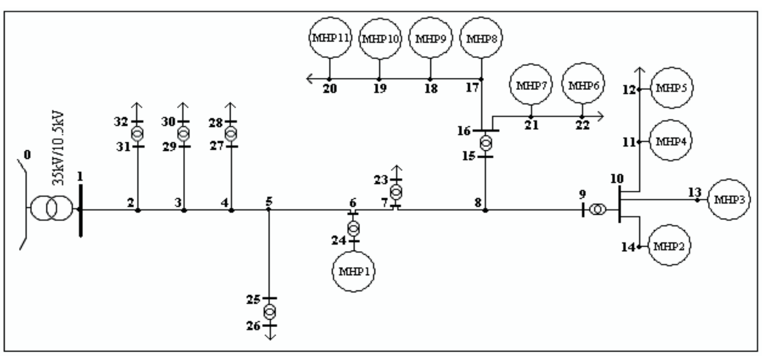


Fig. 2. Distribution network with 11 MHPs.

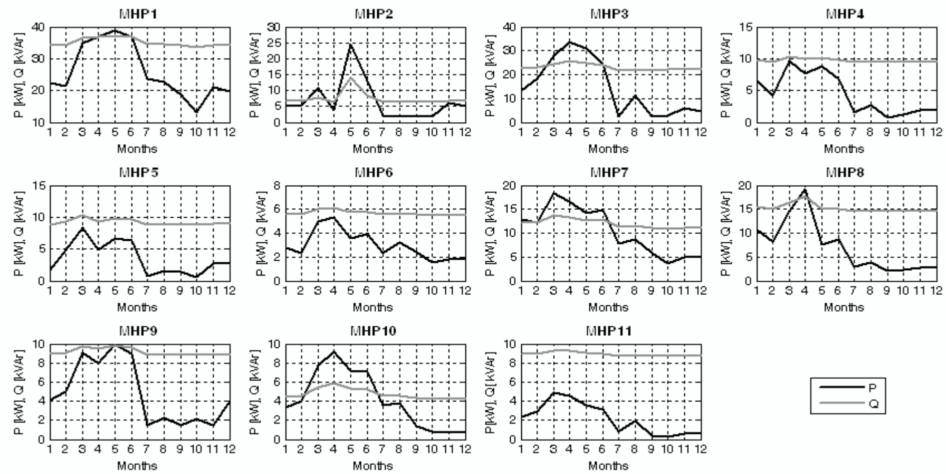


Fig. 3. Annual power curves of MHPs for 2007 year.

2 Unit Energy Cost of MHPs

The analysis gives the calculated costs of MHPs and unit energy costs. The capital costs of MHPs construction usually consist of two main costs: turbine cost and other capital cost [1,2]. The cost of turbine, C_t, can be presented as function of the shaft power rating, R_t, [2]:

$$C_t(R_t) = b_0 + b_1 R_t + b_2 R_t^2 \tag{1}$$

These values are within two limits

$$C_t(R_t)^{min} \le C_t(R_t) \le C_t(R_t)^{max} \tag{2}$$

where is $b_0 = C_t^{min}$. The values of constants b_0, b_1 and b_2 for different turbines, are calculated by fitting of function $C_t(R_t)$, for values of (R_t) and corresponding values of (C_t), that are given in [1].

The capital cost expressed as an annual cost, can be calculated:

$$C_A = k_t(H_t^{max}) C_t(R_t) \frac{r(1+r)^T}{(1+r)^T - 1} \tag{3}$$

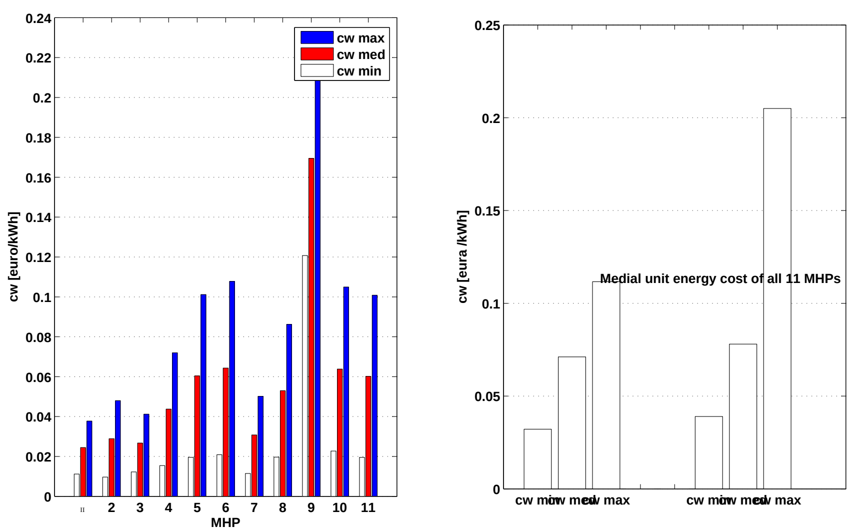
where r is real discount rate, T is number of MHP year life, H_t^{max} is head installation, $k_t(H_t^{max})$ is factor which includes the cost difference for low-head installations ($H_t^{max} = 15$ m or less) and high- and mediumhead installations (H_t^{max} higher than about 15 m) [2]:

$$k_t(H_t^{max}) = \begin{cases} \dfrac{100}{35}, & \text{for} \quad H_t^{max} < 15\text{m} \\ \dfrac{100}{24}, & \text{for} \quad H_t^{max} \geq 15\text{m} \end{cases} \tag{4}$$

Annual running cost (operation and maintenance costs (O+M)), are about 10% of total annual costs [1, 2]. Unit energy cost, c_w (/kWh) can be calculated:

$$c_w = \frac{C_A + (O+M)}{W} \tag{5}$$

where W is yearly generated energy (kWh), which is given as average value for three years 2005, 2006 and 2007 (Table 1). It was assumed that yearly generated energy during T years of MHP life, have approximately this average value. From formulas (3) and (5) it follows that unit energy cost which can put back the capital and running costs, depends on T and r values. Figure 4(a) shows the unit energy costs calculated from formulas (3) and (5) for $T = 15$ years and $r = 6.5\%$. In figure 4(b) the medial value of unit energy cost is compared with values given in [3] for small-scale hydro (where are used same values of T and r). As it is shown in Figure 4, the unit energy costs of 11 MHPs are lower than usual values (90% of the cost of small-scale hydro in EU [3]).



(b) (b)

Fig. 4. Unit energy costs of MHPs.

3 Power Flow Calculations

For computation of voltage values and power flow the backward-forward method [4, 5] was used. The network is presented as one-line scheme which contains numerated nodes as connecting points of MHPs and consumers. The branches are presented by serial impedance $\underline{Z}_{\ell}$. The two-winding transformers are modeled by impedance Z_T and by variable voltage ratio, $t = 1 + n\Delta t$, where n is position number of tap changer on voltage taps in the higher-voltage winding. Consumers and capacitors for reactive power compensation are modeled by PQ nodes and constant power. Induction generators (IGs) are presented by PQ nodes as "negative consumers".

Calculation was carried out for two different cases. First case is when the sum of coincidental MHPs power is maximal and second case is when the sum of coincidental MHPs power is minimal.

The consumption is much lower than generation and it is assumed that it is approximately constant in both cases. The Figure 3 shows the maximal coincidental power is in May and minimal coincidental power is in October. These power values are used for calculation. The compensation of induction generators reactive power is carried out by capacitors whose nominal powers are given in Table A.I. At the beginning of calculation the tap changer position of all transformers is assumed $n = 0$. The calculation results are given in Figures 5, 6 and 7. Treatment of the voltage limits: values of upper and lower voltage limits in MV and LV networks are specified in engineering standards (e.g. 105 and 95%) [6].

Figure 5 shows the voltage values in some of nodes diverges from regular values. During the minimal generation from MHPs, the voltage values in 11-th and 12-th nodes are below of lower limit (0.95 pu). During the maximal generation from MHPs, the voltage values in nodes signed by numbers 13, 17, 18, 19 and 20, are higher than upper limit (1.05 pu). Moreover, the significant difference is between voltages in regimes of maximal and minimal MHPs generation. This difference is result of difference in active power (reactive power of induction generators and compensation capacitors are approximately constant). The power flow in network branches is presented in Figures 6 and 7. Positive power values in Figures 6 and 7 indicate the direction of power is from supply network node to nodes at network periphery. Negative power values in Figure 6 indicate inverse direction of power in network.

During maximal coincidental generation, MHPs supply the local consumers and surplus of energy is transmitted by transformers 0.4/10 kV (branches 10, 16 and 24) to 10 kV network. This energy is distributed to remaining consumers (by branches 23,26,28,30 and 32) and rest of energy is transmitted by supply transformer to 35 kV network.

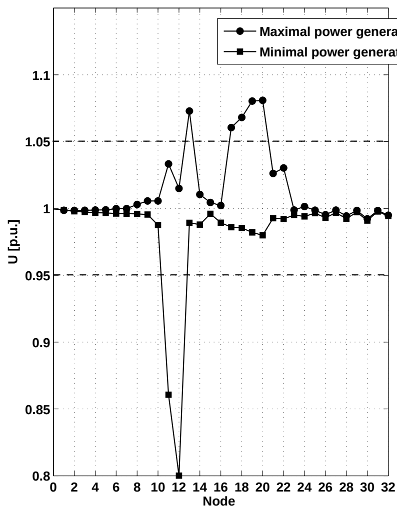


Fig. 5. Network voltage profile.

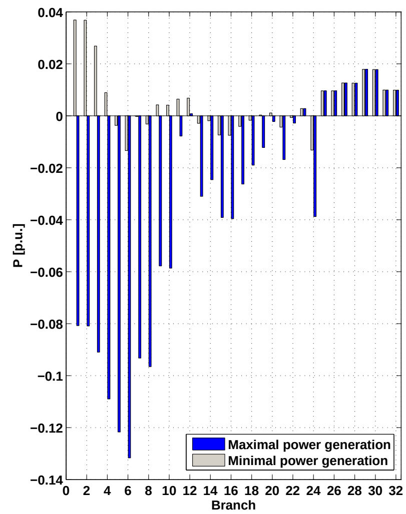


Fig. 6. Active power flow in network branches.

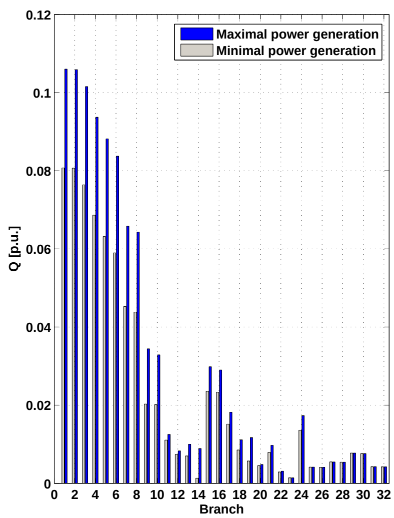


Fig. 7. Reactive power flow in network branches.

Minimal coincidental generation from MHP2 - MHP5 is not enough to supply the consumers in node 12 so that deficit of active power is imported from 10 kV network (by branch 10). Minimal coincidental power from MHP6 - MHP11 continued to be higher than local consumers power (nodes 20 and 22) so that, in this case, surplus of energy is transmitted to 10 kV network (by branch 16) and, farther, to other local consumers. However, the value of power through branch 1 (figure 6) shows the deficit of active power, which is recovered by import from 35 kV network.

In season January June, the generation from MHPs is higher then local consumption in whole network so that surplus of active power is transmitted to 35 kV network. In season July December, MHPs cant fully to supply the local consumers so that the deficit of active power is imported from 35 kV network.

The reactive power, in both cases, is directed from medium voltage network to consumers and MHPs (due to nature of induction generators) (Figure 7).

4 Seasonal Plan of Voltage Regulation

The voltage regulation in network was carried out by seasonal voltage regulation at supply 35/10 kV (MV/MV) transformer, at 10/0.4 kV (MV/LV) distribution transformers and at 0.95/0.4 kV autotransformers (ATs) that are temporary placed on outlying low voltage (LV) lines.

4.1 Voltage regulation at MV/LV distribution transformers

Voltage regulation at MV/LV distribution transformer, due to radial configuration of distribution network, influences on voltages at consumers (and at MHPs that are modeled as “negative consumers”) connected to this transformer, but do not influences on voltages at consumers connected to other transformers. This fact enables space decomposition of distribution network [6] and determination of optimal tap changer position at MV/LV transformer, independently in relation to other MV/LV transformers. For certain power of LV consumer, the voltage at corresponding transformer at MV side can be considered as constant in relation to tap changer position. Accordingly, the voltage ratio, exactly, tap changer position, can be simply determined as a function of consumer power, voltage at MV side and demand voltage at LV transformer side. The demand voltage at LV transformer side was given as an optimization criterion. The Figure 8 shows the model of distribution network part which consists of MV/LV transformer, line and consumer. The values are given in per-unit system (pu).

The voltage values at network nodes are given from power flow calculation. Relationship between modules of voltages U_1 (it is assumed that value of U_1 is approximately constant) and U_2 is:

$$\left(\frac{U_1}{t}\right)^2 = \left(U_2 + \frac{P\cdot R + Q\cdot X}{U_2}\right)^2 + \left(\frac{P\cdot X - Q\cdot R}{U_2}\right)^2 \tag{6}$$

where is $R = R_t + R_L$ and $X = X_t + X_L$.

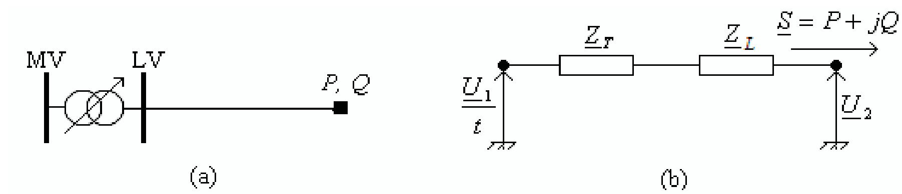


Fig. 8. One-phase model (a) and equivalent scheme (b) of simple radial system. $\underline{Z}_T = R_T + jX_T$ impedance of transformer; $\underline{Z}_L = R_L + jX_L$ - impedance of line. $\underline{U}_2$ voltage phasor of MV transformer bus; voltage phasor at consumer; $\underline{S} = P + jQ$ complex injected power; $t = 1 + n\Delta t$ variable voltage (transmission) ratio; n tap changer position; Δt step between positions (pu).

From expression (6), for constant value U_2, the expression for calculation of t value is:

$$t = \frac{U_1}{\sqrt{\left(U_2 + \dfrac{P\cdot R + Q\cdot X}{U_2}\right)^2 + \left(\dfrac{P\cdot X - Q\cdot R}{U_2}\right)^2}} \tag{7}$$

From given value of t the tap changer position n is calculated:

$$n = \frac{t-1}{\Delta t} \tag{8}$$

On the base of obtained value of n from expression (8), real tap changer position, n_r is determined as a nearly whole number from defined numbers of box positions (usually $n_r = -2, -1, 0, 1, 2$). If calculated value of n_r is higher than n_{max} value, it is carried $n_r = n_{max}$ and if $n_r < n_{min}$, it is carried $n_r = n_{min}$. As real value n_r is different from calculated value n, the real value of t from equation (8) is: $t = n_r\Delta t + 1$. The real value of voltage U_2 can be determined by solving the equation (6) per U_2 or by power flow calculation in whole network.

The consumers and MHPs power is not constant during a day, month and year. Therefore, for calculation of U_2 values, the average values of power in one period (season), is determined. The annual power diagram of each consumer and MHP can be divided per seasons. Usually, annual power diagram can be divided on two seasons. The selection of seasons is conducted according to an analysis of the annual power diagram. Seasonal power actually represents a median power of segments which account for the mentioned season. In a general case, a different number, duration, beginning and end of seasons are obtained for different power diagrams. However, since a seasonal voltage control in this work implies a simultaneous harmonization of tap changer positions of a supply transformer and final (terminal) distribution transformers, the same (coinciding) seasons for all transformers are required. The mentioned requirement is actually attainable provided the following two assumptions are applicable:

1. All consumers in rural distribution networks are alike, which means that they have approximately the same normalized annual power diagrams;
2. DG which are connected to a distribution network have similar annual power diagrams.

For use of procedure which is described above, real LV branched network is transformed in line model with consumer model at the end, as it is shown in Figure 8. For determination of line model impedance, it is used principle of voltage sag equivalence and principle of power losses equivalence, in real system and model of system. The injection power of consumer model is determined approximately as summed injection power in nodes of real LV network.

4.2 Voltage regulation at supply MV/MV transformer

For determination of tap changer position at supply transformer, the optimization criterion, by simultaneous voltage limit, is used. Selected optimization criterion is minimization of voltage deviation from reference (nominal) value [7, 8]. This criterion is expressed:

$$ObjFun = \min \Delta U = \min \sqrt{\sum_{i=1}^{N} \left(U_{ref} - U_i\right)^2} \tag{9}$$

where U_i is voltage at i-th node, U_{ref} is reference (usually, nominal) voltage value, N is number of network nodes.

The power flow calculation is carried out from each tap changer position at supply transformer. After each power flow calculation, the value of tap changer positions at MV/LV transformers are calculated using formulas (7) and (8). Minimal value of objective function (9) determines optimal tap changer positions and optimal season plan of voltage regulation. The flowchart of proposed and applied procedure is given in Figure 9. The optimal seasonal voltage regulation plan determination process is conducted:

a) On regular bases, once a year, based on updated power diagrams from the current year,
b) Extraordinarily, after certain significant changes in the distribution network have occurred, such as: adding a new DG unit, network reconstruction by building a new line, transformer etc.

MHPs power diagrams (Figure 3) show two characteristic periods: period of higher power (January Jun) and period of lower power (July December). This fact caused two changes of transformers tap changer positions during a year. Optimal voltage

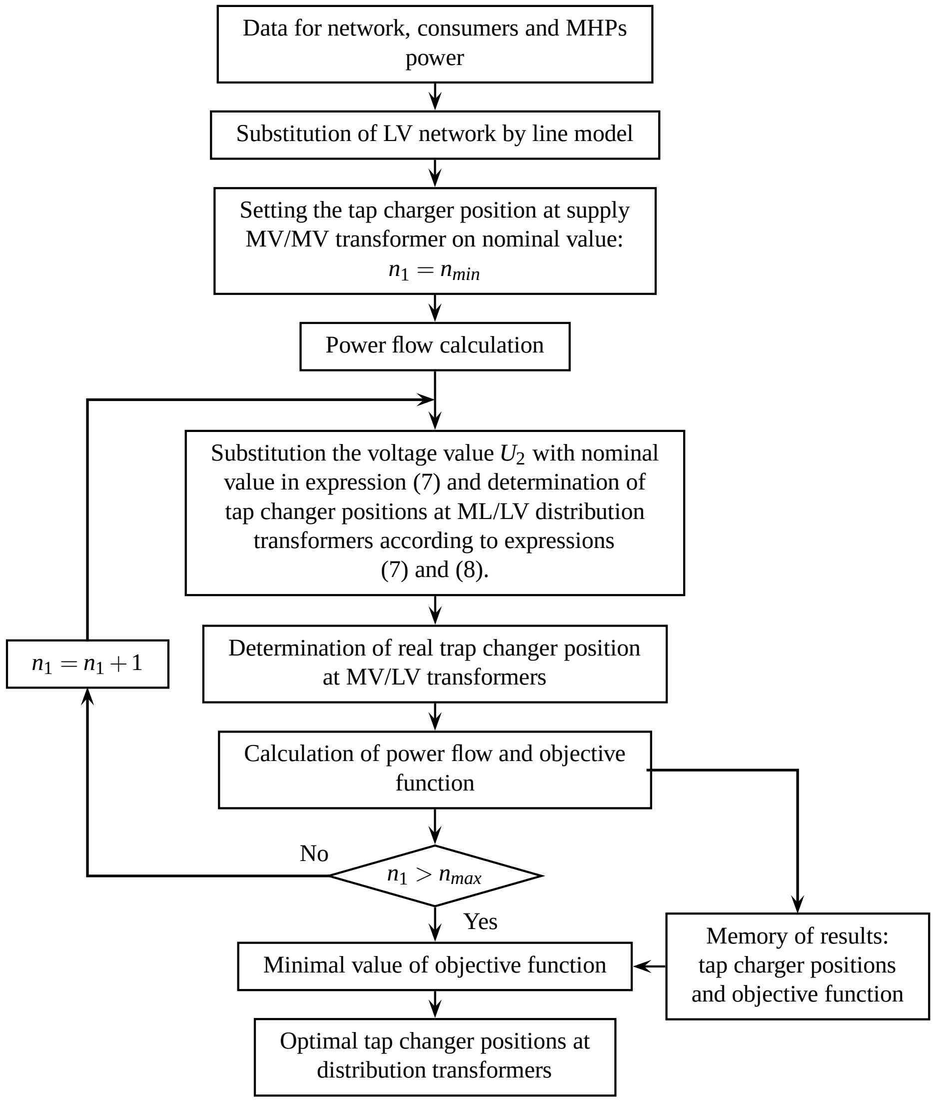
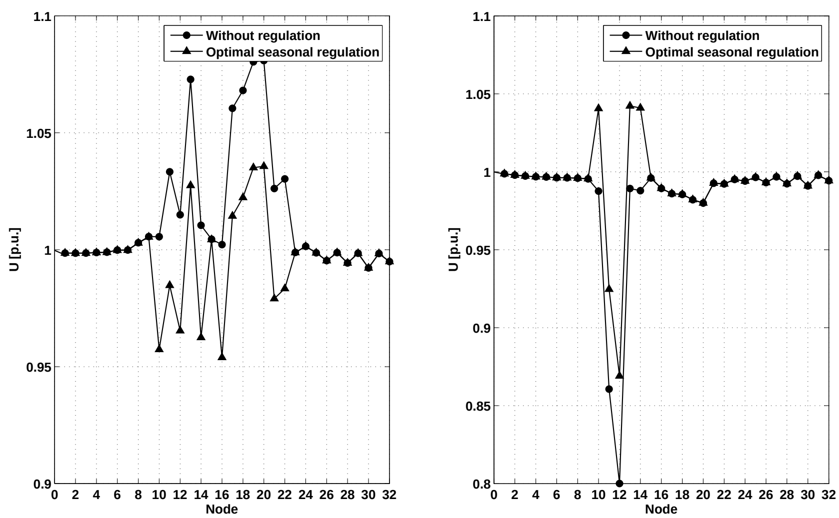


Fig. 9. Flowchart of proposed procedure for seasonal voltage regulation.

plan is applied for average powers values of MHPs in two periods. It is assumed that powers of consumers are constant. Optimal season plan of voltage regulation is given in Table 2. The network voltage profiles for maximal and minimal coincidental MHPs power, for optimal seasonal voltage regulation and without a regulation, are shown in Figure 10.

Table 2. Optimal season plan of voltage regulation.

Season: January - Jun			
Transformers	9-10	15-16	Other transformers
Tap changer position, n	2	2	0
Season: July - December			
Transformers	9-10	Other transformers	
Tap changer position, n	-2	2	



(a) (b)

Fig. 10. The network voltage profiles for maximal (season January Jun) (a), and minimal (season July December) (b) simultaneously MHPs power with optimal seasonal voltage regulation and without regulation (all positions of tap changers are $n = 0$).

From Figure 10(a) it follows that correction of voltage ratio at transformers 9-10 and 15-16 (according to optimal seasonal plan of voltage regulation) enables to reduce voltages at nodes 13, 17, 18, 19 and 20 to standard limit (0.95 1.05 pu). However, from Figure 10(b) it follows that correction of voltage ratio at transformer 9-10, according to proposed voltage regulation, improves the voltage in nodes 11 and 12 but voltage values are continued below standard limit. For solve this problem three known variants are possible:

1. Substitute of existing conductors between nodes 10, 11 and 12 by conductors of higher cross-section;

2. Construction of new transformer substation and connection of MHP 4 and MHP 5 to this substation;
3. Construction of planed MHPs (Figure 1) near MHP 5 and their connection to LV network.

4.3 Voltage regulation at outlying nodes by use of autotransformers

It is applied one different way for voltage increase at 11-th and 12-th nodes that are farthest from supply MV/MV transformer. It is application of 2 ATs on posts, with voltage tapes in primary and secondary windings. One AT, of 0.4/0.95 kV voltage ratio, was placed on post at beginning of line 10-11, second AT of 0.95/0.4 kV was posted at 11-th node (Figure 11). This way usually applies in rural networks with outlying consumers of small power. This way is chosen because of it is temporary solution and the investment is postponed to construction of planed MHPs (Figure 1) near the nodes 11 and 12.

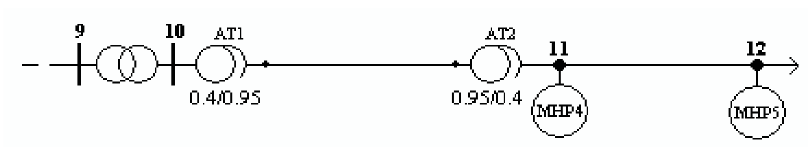


Fig. 11. Use of ATs for compensation of voltage drop on long line 10-11-12.

The optimal seasonal plan of voltage regulation in line 10-11-12, using two ATs (AT1 and AT2) (Figure 11) is given in Table 3. This plan is obtained by same procedure which is given above but for line 10-11-12 only, independently of network rest part. In this case, transformer 9-10 is given as a supply transformer for line 10-11-12. This position and this voltage plan have not influence on voltages in rest of network because of space decomposition is performed. Therefore, this plan is added to plan which is given in Table 2. Figure 12 shows the voltage profiles for line 10-11-12 after use of AT1 and AT2.

Table 3. Optimal seasonal plan of voltage regulation with ATs in line 10-11.

Season: January - Jun					
Transformers	9-10	AT1	AT2	15-16	Other transformers
Tap changer position, *n*	0	−1	0	2	0
Season: July - December					
Transformers	9-19	AT1	AT2	Other transformers	
Tap changer position, *n*	0	−2	−1	2	

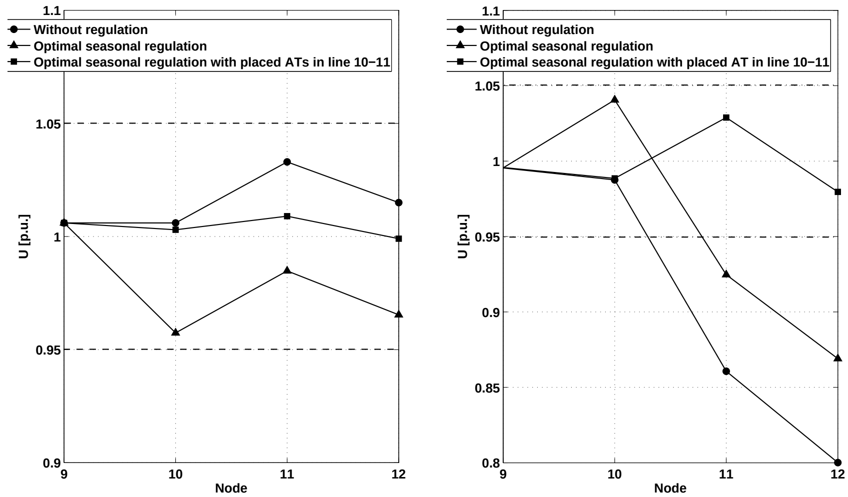


Fig. 12. The line 10-11-12 voltage profiles for maximal (season January Jun) (a), and minimal (season July December) (b) simultaneous MHPs power.

5 Short Circuits

Unlike synchronous generators, induction generators do not have their own source of driving reactive power. They get the necessary power from a distributive network and a compensation capacitor. The abruption of reactive power occurs if there is a symmetrical (three-phase) short circuit close to an IG. Therefore, IGs are capable of influencing the fault current only over a very short period after the failure (during a subtransient period) i.e. until the accumulated reactive power of the IG has been consumed. At non-symmetrical (one-phase and two-phase) short circuits the drive of the IG is not interrupted, so in this case it also contributes to the permanent fault current. Since the stator coils are most likely to be coupled in a triangle or an ungrounded star, the IG can only influence the direct and inverse component of the fault currents (at non-symmetrical failures).

A calculation of the short circuits has been performed based on Shirmohammadi's hybrid compensation algorithm [9].

The equivalent impedances of the IG have been calculated according to the following formula:

$$Z_G'' = \frac{1}{\frac{I_k}{I_n}} \frac{U_n}{\sqrt{3}},$$

using the relations $X_G'' = 0.922 Z_G''$ and $R_G/X_G'' = 0.42$. The IG nominal parameters are given in Table A.I. Only three-phase short circuits have been analysed. The calculation has been performed for the cases of failures at the MV and LV network elements. The obtained results are shown in Table 4 and illustrated by Figure 13.

Table 4. Fault current during the sub-transcient period at a three-phase short circuit in the network.

	Without MHPs		With MHPs		Increase of fault current
Failure spot	$\underline{I}''_k$ (p.u.)	$\lvert\underline{I}''_k\rvert$ (p.u.)	$\underline{I}''_k$ (p.u.)	$\lvert\underline{I}''_k\rvert$ (p.u.)	due to influence of MHP (%)
node 8	$8.2128 - j5.9338$	10.13	$8.7856 - j6.4920$	10.93	7.9
node 10	$1.1759 - j1.4705$	1.88	$1.4393 - j1.7538$	2.27	20.7
node 13	$0.2877 - j0.1197$	0.31	$0.4462 - j0.4860$	0.66	112.9
node 16	$1.1750 - j1.4945$	1.90	$1.4332 - j1.7516$	2.26	18.9

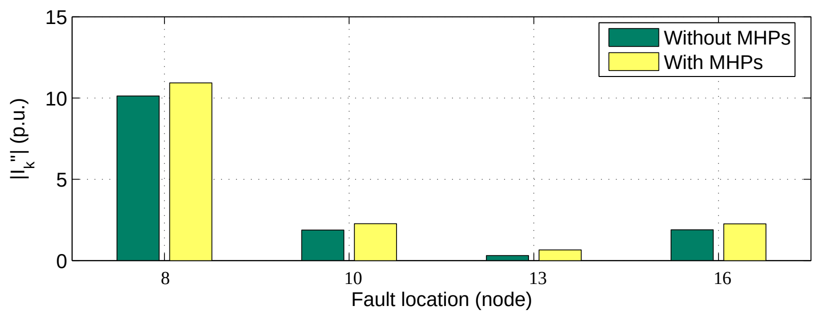


Fig. 13. Fault currents during the sub-transient period at three-phase short circuits in the network.

When a short circuit occurs in the MV network element (node 8), the influence of the IG on the fault current is relatively small and can be neglected. When a failure occurs closer to the IG, for instance in the LV transformer buses (nodes 10 and 16), the IG accounts for a significant share in the total fault current. The short circuit in node 13 is a failure at connection points of the IG in MHP 3, therefore the difference in fault currents is significantly.

A failure at node 13 has been analysed with the aim to examine the influence of the MHP on the fault current through the circuit fuses at transformer legs. The current supplied by the IG from MHP 3 is (0.1540 - j0.3666) p.u, whilst the current coming to the failure spot through the line is 10-13 is: (0.2922 - j0.1194) p.u. The current coming to the failure spot through the line 10-13 arises from the MV network and all other MHPs (except from MHP 3). The distribution of the fault current through line 10-13 to the MHP and MV networks is shown in Table V.

Table 5. Distribution of the fault current through the fuses on line 10-13 at 3ks in node 13.

Line 10-13	Line 11-10 (MHP4, MHP5)	Line 14-10 (MHP 2)	Line 15-8 (MHP 6 MHP11)	Line 24-6 (MHP 1)	Line 1-2 (MV Network)
0.2922 $-j$ 0.1194	0.0104 $-j$ 0.0002	0.0129 $-j$ 0.0096	0.0071 $-j$ 0.0043	0.0059 $-j$ 0.0045	0.2559 $-j$ 0.1008
0.03157	0.0104	0.0161	0.0083	0.0074	0.2750
	(3.2%)	(5%)	(2.6%)	(2.2%)	(87%)

The share of the current provided by the MHPs in the total amount of the fault current occurring through line 10-13 at a three-phase short circuit in node 13 is only 13%. It is obvious that their influence on the fault current through the line protection device (fuse) is practically negligible.

6 Conclusions

The rural distribution network with 11 MHPs of 10 kW to 50 kW in cachment area of mountain Stara Planina (East Serbia), which is analyzed in the paper, is characterized by: higher generation than consumption, outstanding variation of generated energy during a year, continually increase of number of constructed and connected MHPs and significant spacing dispersion of MHPs. This unique distribution network on West Balkan is proposed as a model which can be applied in future similar rural networks with MHPs that will be constructed in West Balkan countries after acceptance of EU directives about renewable energy sources. Analyze showed the following:

- Unit energy costs of MHPs, that are determined on the base of medial realised generation and estimated turbine costs given in [3], are within limits: 0.04 /kWh to 0.22 €/kWh, for = 15 years and = 6.5%. The minimal, average and maximal values of MHPs unit energy costs are lower than adequate values of small-scale hydro in EU (90% of small-scale hydro in EU) [3].
- The higher generation than consumption and permanent increase of constructed MHPs number, caused the power flow from LV level to MV level of network.
- Outstanding variation of generated energy during a year and significant space dispersion of MHPs caused the voltage variation out of standard limits.
- Optimal model of seasonal voltage regulation at transformers, which is proposed in the paper and realised in the network, enables to regulate the voltage values within standard limits, except of some outlying nodes.

- At outlying nodes (near outlying MHPs), where voltage was not regulated within standard limits (using above procedure) voltage regulation is performed by two ATs of 0.95/0.4 kV that are posted on posts of outlying nodes supply line. This is temporary solution for postponing of investment to construction of planed MHPs near the outlying nodes.
- On basis the short circuit analisys the influence of MPHs on the fault current through the line protection devices (fuses) is practically negligible.

Appendix

Table A1. Data for induction generators in MHPs.

MHP	P_n (kW)	U_n (V)	f (Hz)	p	n (min^{-1})	η_n (%)	$\cos\phi_n$	I_n (A)	I_k/I_n	Q_c (kVAr)
MHP 1	55	400	50	4	761	92.5	0.81	106	6.8	2
MHP 2	11	400	50	3	1035	89	0.83	22	7	5
MHP 3	44	400	50	3	1020	92	0.85	83	6.9	15
MHP 4	15	400	50	4	780	88	0.80	34	6.4	6
MHP 5	11	400	50	4	785	84	0.72	26.5	4.4	5
MHP 6	7.5	400	50	3	1050	84	0.77	17	5.5	3
MHP 7	18.5	400	50	2	1540	88	0.82	37	6.2	6
MHP 8	22	400	50	4	765	91	0.78	45	5.9	8
MHP 9	15	400	50	3	1040	87	0.82	30.5	6	6
MHP10	7.5	400	50	2	1560	88	0.83	15	6.5	3
MHP11	11	400	50	4	785	84	0.72	26.5	4.4	5

Table A2. Data for transformers.

Transformer	S_n (kVA)	m_T (kV/kV)	R (p.u.)	X (p.u.)
0-1	4000	35/10.5	0.0021	0.0149
9-10	100	10/0.4	0.2000	0.3464
15-16	100	10/0.4	0.2000	0.3464
7-23	100	10/0.4	0.2000	0.3464
6-24	100	10/0.4	0.2000	0.3464
25-26	100	10/0.4	0.2000	0.3464
27-28	100	10/0.4	0.2000	0.3464
29-30	100	10/0.4	0.2000	0.3464
31-32	100	10/0.4	0.2000	0.3464
AT1	40	0.95/0.4	0.00	1.00
AT2	40	0.95/0.4	0.00	1.00

Table A3. Data for lines.

Line	Voltage (kV)	ConductorAl-Fe (mm^2)	Length (m)	*R* (p.u.)	*X* (p.u.)
1-2	10	70	2000	0.0083	0.0068
2-3	10	70	1600	0.0066	0.0054
3-4	10	70	1750	0.0072	0.0060
4-5	10	70	650	0.0027	0.0022
5-6	10	70	3500	0.0145	0.0119
6-7	10	70	250	0.0010	0.0009
7-8	10	16	2000	0.0376	0.0077
8-9	10	16	2750	0.0517	0.0106
10-11	0.4	25	1400	10.5262	3.2725
11-12	0.4	25	700	5.2631	1.6362
10-13	0.4	25	350	2.6316	0.8181
10-14	0.4	25	30	0.2256	0.0701
8-15	10	16	2400	0.0451	0.0093
16-17	0.4	25	420	3.1579	0.9818
17-18	0.4	25	70	0.5263	0.1636
18-19	0.4	25	210	1.5789	0.4909
19-20	0.4	25	110	0.8271	0.2571
16-21	0.4	25	240	1.8045	0.5610
21-22	0.4	25	310	2.3308	0.7246
5-25	10	50	3350	0.0199	0.0117
4-27	10	25	200	0.0024	0.00075
3-29	10	25	350	0.0042	0.0013
2-31	10	25	1000	0.0120	0.0037

Table A4. Consumers power data*.

Node	P (kW)	Q (kW)	P (p.u.)	Q (p.u.)
12	7.4	3.6	0.0074	0.0036
20	1.4	0.7	0.0014	0.0007
22	0.8	0.4	0.0008	0.0004
23	2.8	1.4	0.0028	0.0014
26	9.6	4.1	0.0096	0.0041
28	12.6	5.4	0.0126	0.0054
30	17.8	7.6	0.0178	0.0076
32	9.9	4.2	0.0099	0.0042

* Resistances, reactances and power values are given in per-unit system (p.u.) and were calculated for basis values of power 1 MVA and voltages: 10 kV and 0.4 kV.

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