Optimized Reactive Power Characteristics for Distributed Generation Sources in the Low Voltage Network

Dejan Matvoz, Rok Leskovec, Miloš Maksić
Elektroinstitut Milan Vidmar (EIMV)
Ljubljana, Slovenia
dejan.matvoz@eimv.si, rok.leskovec@eimv.si, milos.maksic@eimv.si

***Abstract*— Reactive power regulation of distributed generation sources in the low voltage network is by many professionals still considered as unnecessary, especially in the cable type networks. In this paper we show, that this is not true. We present optimized reactive power regulation characteristics of the distributed sources for the low voltage network. Characteristic is active power as well as voltage dependent with the aim of maintaining voltage in the low voltage network as constant as possible and at the same time minimizing network losses. Voltage ranges, reactive power regulation, distributed generation curtailments and reactive power characteristics comparison are analyzed and compared. Results clearly show that with proposed optimized reactive power characteristics of distributed generation sources in the low voltage network distributed generation active power curtailments are minimized, in majority of cases network losses are lowered and in the vast majority of cases voltage variations are smaller.**

***Index Terms* - Distributed generation sources, Network integration, Reactive power regulation, Network losses**

I. INTRODUCTION

With distributed generation sources (DG) becoming an increasingly important factor in the active power production in the network, reactive power regulation of DGs is still often considered as unnecessary, even by the professionals who operate the distribution network. This opinion is even more present when they talk about DGs which operate in the low voltage networks, especially in the cable type networks. But this opinion is not true, as will be presented in this paper.

More and more distribution network operators (DSO) across Europe define reactive power characteristics even for the smallest DGs in their networks. Latest version of the European standard EN 50438 [1] defines the minimum capability for reactive power of DGs to be up to PF = 0.9 leading and lagging. Several articles have shown that there are benefits in targeted reactive power regulation of DGs [2] - [4]. Starting from 2011, Slovenian DSOs are also demanding reactive power regulation even for the smallest DG units [5].

IEEE standard 1547 - 2003 [6] did not allow any reactive power regulation of the DGs. But this standard was amended in 2014 with the Amendment 1 [7]. And in this amendment regulation of reactive power of the DGs is allowed, but not before coordination with and approval of the area Electric Power System and DG operators.

In this paper, we present optimized reactive power regulation characteristics for the DGs in the low voltage network, which is in compliance with the Slovenian rules for operation of DGs in the distribution network.

II. OPTIMISED REACTIVE POWER CHARACTERISTICS FOR THE DGS IN THE LOW VOLTAGE NETWORK

Proposed optimized reactive power characteristic for the low voltage network is active power and at the same time voltage dependent with the aim of maintaining voltage in the low voltage network as constant as possible while at the same time minimizing network losses. The characteristic is depicted in Figure 1.

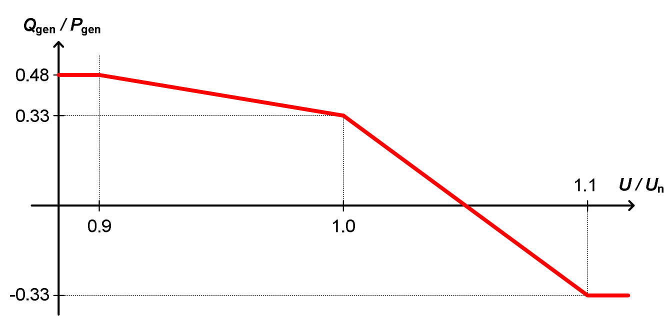

Figure 1. Proposed optimized reactive power characteristic $Q_{GEN} = f(P_{GEN}, U)$ of DGs in the LV network

This characteristic is conformant with the allowed area of operation regarding reactive power, as demanded in the Slovenian rules for the operation of DGs in the LV network.

According to this characteristic, if the voltage in the network is nominal, DG provides reactive power with the power factor of 0.95 in addition to its active power injection. In this case, active and reactive power from DGs and average low voltage (LV) loads in the network should compensate.

When voltage in the LV network is low (as in abnormal network operation or in heavily loaded networks), DGs help raise the voltage by injecting reactive power into network. If the voltage increases towards its highest allowed limit (+ 10 % U_n) according to the standard EN 50160 [8], DG starts to lower its reactive power output and begins to consume reactive power from the network and thus helps lower the voltage in the network.

Limit for injection of reactive power by the DG into the distribution network is at power factor 0.9 ($\tan \varphi = Q_{GEN} / P_{GEN} = 0.48$) and limit for consumption of reactive power by the DG from the distribution network is at power factor 0.95 ($Q_{GEN} / P_{GEN} = 0.33$).

III. Simulation Network Model

In order to be able to perform analysis of the effect of reactive power regulation, simulations were performed on a test LV network depicted in Figure 2. Nominal line to line voltage of the MV and LV network is 20 kV and 400 V, respectively.

Simulation network model consists of a standard three-phase MV/LV transformer (TR) with S_n = 160 kVA and a LV network. TR data is presented in Table I. LV network is represented with three segments of LV lines (Line 1 – Line 3), their total length is 450 m. After each 150 m long segment a load and a generator are connected to the busbars LV 1 – LV 3. Load data for each scenario is presented in Table IV and generator data in Table V. Lines 1 – 3 are in half of the scenario cases overhead lines (OHL) with the cross-sectional area of 70 mm^2 and in the other half of the cases cable lines with the same cross-sectional area. Data for the OHL and cable lines are presented in Tables II and III respectively.

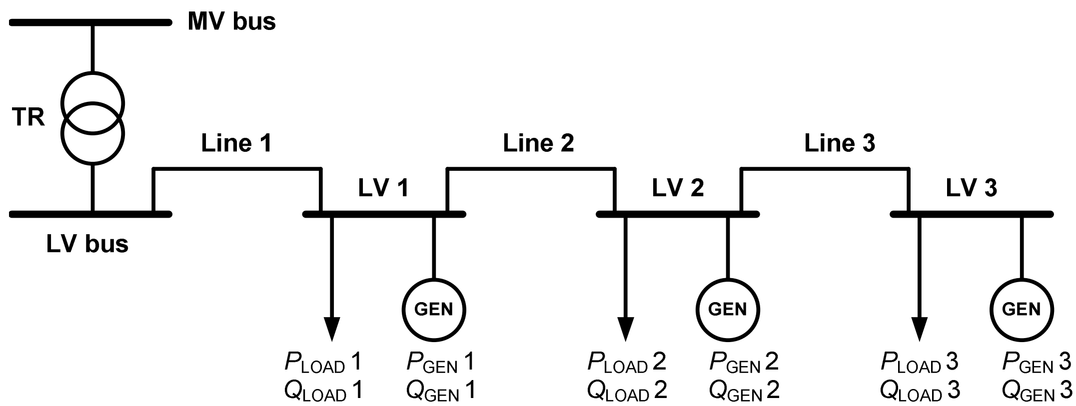

Figure 2. Network model for simulations

TABLE I. MV/LV TRANSFORMER DATA

Parameter	Value
S_N	160 kVA
u_{SC}	0.04 pu
P_{Fe}	300 W
P_{Cu}	2.35 kW

TABLE II. OVERHEAD LINE DATA

Parameter	Value
r'	$0.433 \cdot 10^{-3}$ Ω/m
x'	$0.357 \cdot 10^{-3}$ Ω/m
c'	319 MΩ·m
l	150 m

TABLE III. CABLE LINE DATA

Parameter	Value
r'	$0.433 \cdot 10^{-3}$ Ω/m
x'	$0.139 \cdot 10^{-3}$ Ω/m
c'	15.915 MΩ·m
l	150 m

TABLE IV. ACTIVE AND REACTIVE POWER DATA FOR LOADS AT DIFFERENT CASES

Case	None	Near	Equal	Far
P_{LOAD} 1 (kW)	0	60	20	0
Q_{LOAD} 1 (kvar)	0	20	6.67	0
P_{LOAD} 2 (kW)	0	0	20	0
Q_{LOAD} 2 (kvar)	0	0	6.67	0
P_{LOAD} 3 (kW)	0	0	20	60
Q_{LOAD} 3 (kvar)	0	0	6.67	20

TABLE V. ACTIVE POWER DATA FOR DGS AT DIFFERENT CASES

Case	None	Near	Equal	Far
P_{GEN} 1 (kW)	0	60	20	0
P_{GEN} 2 (kW)	0	0	20	0
P_{GEN} 3 (kW)	0	0	20	60

In Tables IV and V "*None*" refers to no load or no generator was used (0 W). "*Near*" means that full active power (60 kW in case of loads and 60 kW in case of DGs) was connected to the busbar which is the nearest to the MV/LV transformer (busbar LV 1). "*Equal*" means that active power was equally distributed through the LV network (20 kW on each of the busbars LV 1 – 3) in case of loads and in separately also in the case of DGs. "*Far*" means that full active power (60 kW for the case of loads and also for the case of DGs respectively) was located at the farthest busbar from the MV/LV transformer (busbar LV 3).

IV. Simulated Cases

Two sets of simulations were done, one set with the OHLs and the other with the cable lines. Each set consisted of simulating the loads and DGs separately in different network cases. In all the cases voltage on the MV side of the transformer was set to 104 % U_n as could be the case in the real network. In this state 104 % U_n is also the target voltage for the unloaded LV network. This assured equal conditions for all the cases.

First a simulation was done using the loads only. Case "*Far*" was used to determine minimum voltages in the network and its compliance with the network rules. According to the operational rules, network should be able to provide such voltage conditions to assure at least 92 % U_n at all the busbars in the network when loaded to its maximum (worst case in our case is at the busbar LV 3). With the OHL the lowest voltage is $U_{LV}\,3 = 92.3$ % and with the cable lines $U_{LV}\,3 = 93.9$ %.

Then DGs were placed into the network and all possible scenarios according to the Tables IV and V were simulated. Regarding reactive power regulation of the DGs, two separate simulation packs were performed. One pack using the $Q_{GEN} = 0$ in all the cases and the other using $Q_{GEN} = f(P_{GEN}, U)$ regulation in all the cases with regard to the characteristic depicted in Figure 1.

The following was simulated:

- Simple comparison of voltage profiles on all LV nodes for the most diametric scenarios.
- Avoidance of DG's active power curtailment by using the proposed reactive power regulation.
- Comparison of voltage levels in the network for all different scenarios.
- Comparison of cumulative losses in the network for all different scenarios.

V. Results

By using simulation results several aspects were observed and compared.

A. Simple comparison of voltage profiles on all LV nodes for the most diametric scenarios

Effect of different reactive power regulation on voltage profile in the LV network can be easily seen on Figure 3 where voltages on all LV nodes (LV bus – LV 3) are depicted for both types of reactive power regulation of DGs and using cable lines.

Firstly, scenarios P_{GEN} ("*Far*") from the Table V and P_{LOAD} ("*Far*") from the Table IV were simulated. Loads and DGs are all connected at the LV 3 busbars. The result of that are the **lower red and blue lines** in Figure 3 (both lines have dots as markers). Red line represents scenario with $Q_{GEN} = 0$. Blue line represents scenario with $Q_{GEN} = f(P_{GEN}, U)$ according to the Figure 1.

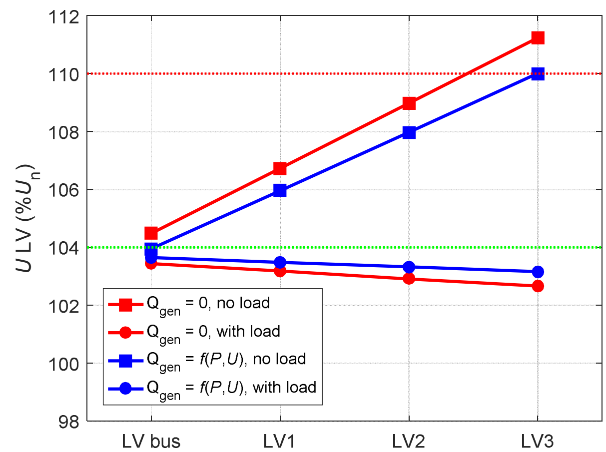

Figure 3. Effect of different reactive power regulations on the voltage profile in the LV cable network

Comparison of both these lines in the Figure 3 clearly shows that the blue line is closer to the desired voltage of 104 % (depicted as green dotted line) compared to the red line at all LV busbars.

Now we disconnect the loads in both scenarios. That yields the scenario P_{GEN} ("*Far*") and P_{LOAD} ("*None*"). The result of that are the **upper red and blue lines** on Figure 3 (both lines have rectangles as markers). Red line represents scenario with $Q_{GEN} = 0$. Blue line represents scenario with $Q_{GEN} = f(P_{GEN}, U)$ according to the Figure 1.

Comparison of both these lines clearly shows that the blue line is again closer to the desired voltage of 104 % (depicted as green dotted line) compared to the red line at all LV busbars. We can even see that without the proposed reactive power regulation voltage exceeds the allowed voltage level in the LV network of 110 % set by the standard EN 50160 [8] (depicted as red dotted line in Figure 3). In our case the voltage on the busbar LV3 is $U_{LV3} = 111.2$ %.

It can be clearly seen, that in all cases at the busbar LV 3, voltage level differs from the desired voltage level the most. Therefore, our attention in the next analysis will be concentrated to that node for easier comparison of the effect of both types of reactive power regulation.

B. Avoidance of DG's active power curtailment by using the proposed reactive power regulation

For the last presented scenario P_{GEN} ("*Far*") and P_{LOAD} ("*None*") a simulation was made to analyze the amount of active power curtailment that can be omitted if the proposed reactive power regulation is used. Using load-flow simulations we will determine how much additional active power can be injected into the LV and through the transformer further into the MV network when the proposed reactive power regulation is used.

Simulation shows that in order to lower the voltage from 111.2 % to the allowed value of 110 %, active power of the DGs must be lowered by 10.8 kW or 18.0 % relative to the initial 60 kW as in (1).

$$\Delta P_{\mathrm{LV}} = 60\ \mathrm{kW} - 49.2\ \mathrm{kW} = 10.8\ \mathrm{kW} \tag{1}$$

$$\Delta P_{\mathrm{LV\ relative}} = 10.8\ \mathrm{kW} / 49.2\ \mathrm{kW} = 22.0\ \% \tag{2}$$

Or to put it in another way, we can connect 22.0 % more DGs into the network if reactive power regulation $Q_{\mathrm{GEN}} = \mathrm{f}(P_{\mathrm{GEN}}, U)$ is used instead of $Q_{\mathrm{GEN}} = 0$ (see (2)). But this type of reactive power regulation increases active power losses in the LV network as well as in the MV/LV transformer, as can be seen in Table VI. A part of these losses can be attributed to higher active power flow and a part to reactive power flow.

TABLE VI. SUMMARY OF ACTIVE POWER YIELD AT THE MV BUSBARS FROM THE DGS IN THE LV NETWORK

	$Q_{\mathrm{GEN}} = 0$	$Q_{\mathrm{GEN}} = \mathrm{f}(P_{\mathrm{GEN}}, U)$
$U_{\mathrm{LV\,3}}$	110 %	110 %
Q_{GEN}	0 kvar	-19.7 kvar
P_{GEN}	49.2 kW	60 kW
$P_{\mathrm{losses\ TR + LV\ network}}$	3.0 kW	4.7 kW
$P_{\mathrm{GEN}} - P_{\mathrm{losses}}$	46.2 kW	55.3 kW

Equation (3) shows calculated difference of injected active power into the MV network.

$$\Delta P_{\mathrm{MV}} = 55.3\ \mathrm{kW} - 46.2\ \mathrm{kW} = 9.1\ \mathrm{kW} \tag{3}$$

$$\Delta P_{\mathrm{MV\ relative}} = 9.1\ \mathrm{kW} / 46.2\ \mathrm{kW} = 19.7\ \% \tag{4}$$

Taking into account all the losses in the LV network and at the transformer MV/LV for the case P_{GEN} ("*Far*") and P_{LOAD} ("*None*"), active power yield at the MV side of the transformer from the DGs at the LV level is 19.7 % higher if proposed reactive power regulation is used instead of the $Q_{\mathrm{GEN}} = 0$ regulation.

C. Comparison of voltage levels in the network for all different scenarios

In this section voltage deviations from the desired voltage are analyzed for different combination of cases (different scenarios) and for different types of LV network (OHL and cable lines).

Figure 4 shows the difference of voltages in node LV 3 for both types of regulation of DGs reactive power for different cases of loads and DGs and with the overhead lines used. Figure 5 shows the same situation but with the cable lines used. Methodology used is the same as in Figure 4 as follows.

If the value is positive, then the proposed reactive voltage regulation is closer to the desired voltage level than with $Q_{\mathrm{GEN}} = 0$ regulation. The value shows the difference of both relative values (all values are normalized to U_{N}).

For example: (see Figure 4) for the scenario P_{GEN} ("*Far*") and P_{LOAD} ("*None*") difference is 2.0 % and is obtained as it is shown in (5).

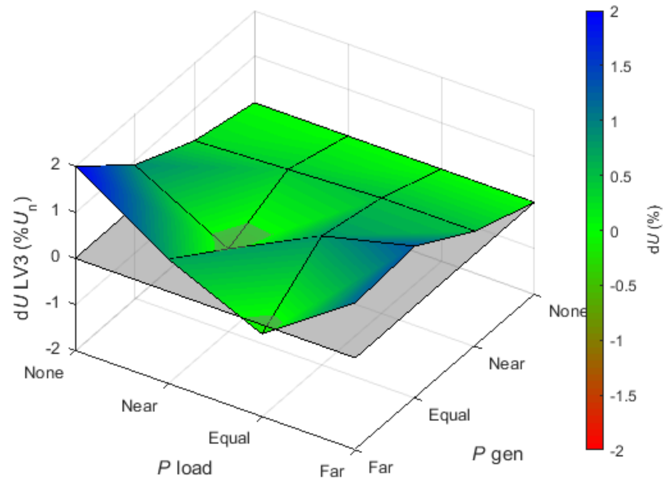

Figure 4. Difference of relative voltage changes at node LV3 between $Q_{\mathrm{GEN}} = 0$ and $Q_{\mathrm{GEN}} = \mathrm{f}(P_{\mathrm{GEN}}, U)$ reactive power reguation regarding the desired voltage in LV network with overhead lines

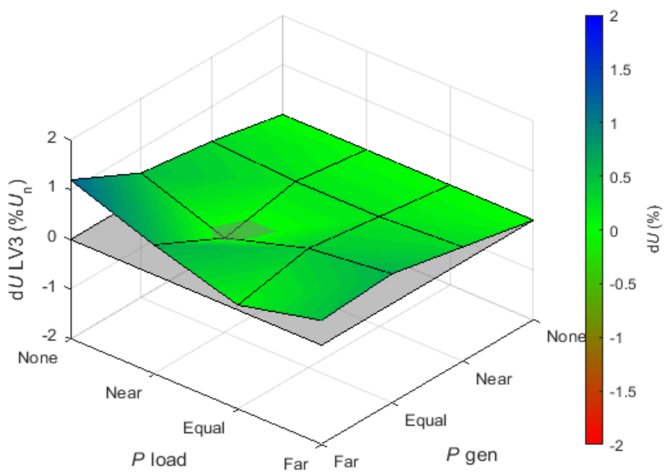

Figure 5. Difference of relative voltage changes at node LV3 between $Q_{\mathrm{GEN}} = 0$ and $Q_{\mathrm{GEN}} = \mathrm{f}(P_{\mathrm{GEN}}, U)$ reactive power reguation regarding the desired voltage in LV network with cable lines

$$\Delta U = U_{\mathrm{Q=0}} - U_{\mathrm{Q=f(P,U)}} = 111.2\ \% - 109.2\ \% = 2.0\ \% \tag{5}$$

But for the scenario P_{GEN} ("*Far*") and P_{LOAD} ("*Far*"), both values are below the desired voltage and $U_{\mathrm{Q=0}}$ is lower than $U_{\mathrm{Q=f(P,U)}}$ and thus farther from the targeted value of 104 %. Therefore, the difference is again positive (in favor of the proposed regulation) and is calculated as it is shown in (6).

$$\Delta U = U_{\mathrm{Q=f(P,U)}} - U_{\mathrm{Q=0}} = 102.7\ \% - 101.5\ \% = 1.2\ \% \tag{6}$$

As can be seen from Figures 4 and 5, in the majority of cases proposed reactive power regulation yields much better results than $Q_{\mathrm{GEN}} = 0$ regulation. Difference is bigger in the LV network with the overhead lines than in the network with the cable lines. Biggest difference is for the cases P_{GEN} ("*Far*") and P_{LOAD} ("*None*") or P_{LOAD} ("*Far*").

Detailed analysis is shown in Table VII, where scenarios which feature cases where DGs are not operating P_{GEN} (“*None*”) are not shown because the results in those cases are always 0.

TABLE VII. DIFFERENCE OF RELATIVE VOLTAGE CHANGES BETWEEN BOTH REACTIVE POWER REGULATION TYPES AT THE BUS LV3 REGARDING THE DESIRED VOLTAGE LEVEL IN THE LV NETWORK

Scenario	P_{GEN}					
	Overhead line (OHL)			**Cable line**		
P_{LOAD}	**Near**	**Equal**	**Far**	**Near**	**Equal**	**Far**
	d*U* (% U_N)			**d*U* (% U_N)**		
None	0.3	0.9	2.0	0.3	0.5	1.2
Near	0.4	-0.2	0.7	0.2	-0.1	0.6
Equal	0.5	0.8	-0.2	0.2	0.4	0.1
Far	0.5	1.3	1.2	0.3	0.6	0.5

D. Comparison of cumulative losses in the network for all different scenarios

In this section comparison of complete (cumulative) network losses (MV/LV transformer and all LV lines) for different cases and network lines is presented.

Figure 6 shows difference of cumulative network losses for both types of regulation of DGs’ reactive power for different cases of loads and DGs and with overhead lines used. Figure 7 shows the same situation but with cable lines used. Methodology used is the same as in Figure 6.

If the value is positive, then proposed reactive power regulation yields smaller network losses than $Q_{GEN} = 0$ regulation. The difference in losses is indicated in kW in Figures 6 and 7.

As can be seen from the Figures 6 and 7 in most cases proposed reactive power regulation yields much better results than $Q_{GEN} = 0$ regulation. Differences are approximately the same in the networks with overhead lines and in the networks with the cable lines. Biggest difference is for the cases P_{GEN} (“*Far*”) and P_{LOAD} (“*None*”) or P_{LOAD} (“*Far*”).

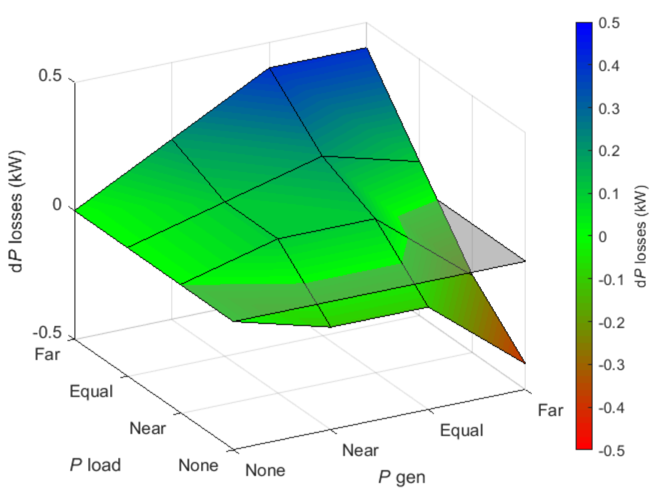

Figure 6. Difference of cumulative losses on the MV/LV transformer and LV network between $Q_{GEN} = 0$ and $Q_{GEN} = f(P_{GEN}, U)$ reactive power reguation in LV network with overhead lines

Proposed regulation shows best results when there is load in the network connected by the “*Far*” case. All in all, in most cases proposed reactive power regulation yields lower losses than $Q_{GEN} = 0$ regulation.

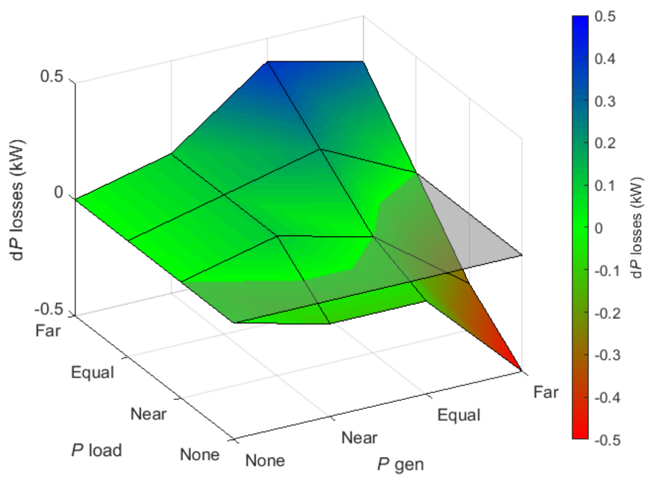

Figure 7. Difference of cumulative losses on the MV/LV transformer and LV network between $Q_{GEN} = 0$ and $Q_{GEN} = f(P_{GEN}, U)$ reactive power reguation in LV network with cable lines

CONCLUSIONS

Proposed reactive power regulation of DGs uses the philosophy of providing reactive power along with the active power at PF = 0.95 when around nominal voltage of the network. Using this philosophy loads in the LV network are supplied with the active as well as reactive power from the nearby DGs. If voltage drops to its lower limit, injected reactive power is increased up to PF = 0.90. In case of high network voltage, DG starts consuming reactive power to the limit of PF = 0.95 at the upper voltage limit.

When proposed reactive power regulation is used, voltage in the network is closer to the desired voltage level than when using $Q_{GEN} = 0$ regulation. Maximal difference is in our case 2.0 % U_N in the LV network with the overhead lines. The difference is higher in the overhead lines network than in the cable type network. Nevertheless, in the cable network maximal difference is 1.2 % U_N.

By using the proposed reactive power regulation instead of reactive power regulation $Q_{GEN} = 0$ at the DGs in the LV network, more of them can be connected to this network. Taking also losses in the MV/LV transformer and the lines into account (according to the LV network analyzed) up to 19.7 % more active power from DGs in the LV network can be injected into the MV network. And this is the case for the cable lines LV network.

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