Coordinated Reactive Power Control to Ensure Fairness in Active Distribution Grids

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***Abstract*-This paper deals with the influence of a large share of dispersed generation (DG) in the medium-voltage distribution networks. Distribution networks traditionally operate in a way that they don't predict the influence of DG and the voltage drop is assumed to be increasing with the distance from the substation. A large share of DG can cause that at the local level the voltage upper limits are reached. This problem can be solved in many ways. In the paper a coordinated voltage control is presented which on the basis of time dependent power factor of DG determines the amount of reactive power they have to produce. Development of the control is based on the fact that in the near future the new technologies will allow bidirectional data flow in real time. This will allow more active participation of the users in the network. With reactive power dispatching the voltages can be correlated and furthermore losses can be minimized. The paper deals with the fact that DG will have to produce different amounts of reactive power. That is why the options of fair contribution of reactive power are investigated.**

Different solutions were evaluated by means of computer simulations. The simulated network was a part of medium-voltage distribution system in Slovenia. The network was modified by increasing the number of DG as their growth is very fast in Slovenia.

Keywords-voltage control; loss minimization; reactive power, Smart Grids

I. INTRODUCTION

Distribution utilities have to maintain network voltages between tight statutory defined limits. During past decades the operation of distribution networks has thoroughly improved, the network losses are small, there are little blackouts and the voltage control is simple [1]-[4]. The system is dimensioned in a way that the voltages are always within the limits, which is achieved by oversizing the cables and transformers. The only real-time measurement point in the network is at the secondary of the on-load tap changer (OLTC) transformer [5]. Unfortunately such a control cannot detect a local voltage rise which occurs due to high penetration of active power from DG. The voltage rise usually occurs during high DG production and low consumption, for example:

- a strong wind at night in case of a large number of wind farms and
- high output from photovoltaic sources at the midday in the urban places.

This problem can be traditionally solved by increasing the cross-sections of the conductors and replacement of distribution transformers with bigger ones. This is unfortunately environmentally unacceptable and economically costly solution. To mitigate the voltage rise problem, some countries around the world have already prescribed static *Q*(*U*) characteristic for DG to participate in the voltage control (for example Slovenia [12]). On the basis of local voltage measurement and current active power output of DG, its necessary reactive power is determined. That kind of control allows reducing the voltage at connection point by consuming reactive power and increasing the voltage by injecting it. The upgrade to this control presents introduction of smart grids. Smart grids are electrical power networks with operating communication infrastructure which allows real time data to be transmitted in two way direction and thus allow new control possibilities. Static *Q*(*U*) characteristics are only temporary solutions. Once the smart grid technologies will be fully implemented the static characteristics won't be needed anymore.

Fig. 1. Example of static *Q*(*U*) characteristic for DG prescribed in Slovenia [12].

Smart grids have opened a whole new field in planning and management of distribution networks. New technologies enable us to develop new control mechanisms which were not possible till recent. The network operation can be optimized by many objectives [6] - [11]:

- obtain voltages in the statutory defined limits,
- minimize the network losses,
- postpone the network investments,

- minimize the operation costs,
- reducing the operators' burden,
- improve reliability,
- minimize the reactive power production,
- improve the safe operation for the people etc.

The presented work discusses two objections; voltage rise and loss minimization with different approaches of voltage control. Firstly, the usage of static $Q(U)$ characteristic was investigated. This approach has a positive impact on the voltage profile, but unfortunately, that kind of local control requires from some DG to consume or inject bigger amounts of reactive power than others. This seems unfair as the retail customers typically have no choice where they are located along the feeder [1]. In this paper a coordinated control is presented, which enables more uniformly reactive power dispatching.

II. FAIR CONTRIBUTION OF REACTIVE POWER

DG usually worked with constant power factor (cosφ = 1) which means that they did not participate in the voltage control. By using static $Q(U)$ characteristics the voltage rise can be minimized to some extent, unfortunately this results in increased network losses and uneven reactive power dispatched by the generators. The customers usually have no choice where to place their power plants. Usually they install it on the roof of their houses (photovoltaic power plants). This means that some customers who live far away from the main substation, where the voltage deviations are more frequent, will have to inject or consume more reactive power than those located in areas where the voltage deviations are minor. This means that they will have to take all the burden and responsibility for the voltage rise and that some DG will be privileged [1], [2]. It is not their fault that they live in electrical meaning far away from the substation. This can result in increased aging of inverters and, more important, their necessary oversizing.

The reactive power dispatching can be seen as a sanction for producing the active power or as a tax system. If the output of active power is higher, the higher the amount of reactive power has to be [13]. The amount of necessary reactive power compared to currently producing active power determines the tgφ:

$$tg\varphi = \frac{Q_{DG}}{P_{DG}}. \tag{1}$$

Every generator in the network according to static $Q(U)$ characteristic operates with different tgφ. The idea behind the coordinated control presented in the paper is: what if the generators work with uniform tgφ. This means that their participation in the voltage control is no longer based on their location (to which they have no influence) but on their size. If their active power is higher, they will have to produce/consume more reactive power, so their participation is based only on their size, like in the business world, the richer stakeholders have to pay higher taxes. Bear in mind that the voltage conditions have to be meet first. If the voltages are within the limits, the network can be additionally optimized by different criterions; in our option uniform tgφ operation to minimize losses.

III. DESIGN OF THE OPTIMIZATION

The control system has implemented load-flow simulation tool which on the basis of modeled network estimates the voltage drop. The dataflow is presented in Fig. 2. The smart meters in the network are broadcasting the power measurements to the central control system. Then the simulations are carried out. The outputs of the algorithm are new set-points for DG, which are then broadcasted back to the network.

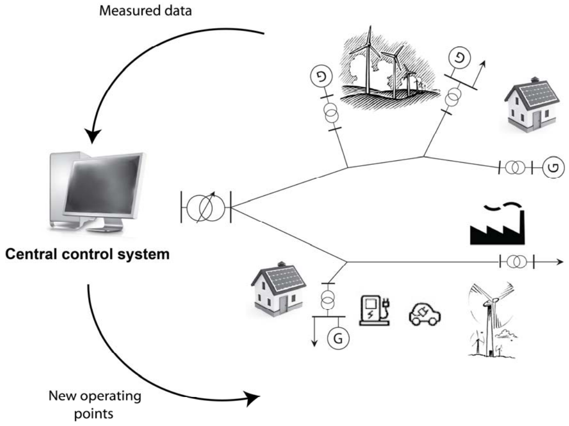

Fig. 2. Smart grid data flow [13].

The development of a good voltage control must take into account different parameters. The OLTC's tap position has to be controlled; DG reactive power and in some cases even active power has to be controlled; OLTC can be connected to many diverse feeders whose power consumption or production can differ widely. Nevertheless, the main condition that has to be assured regardless anything else is the voltage condition. The voltages in the network have to be always within the limits:

$$0.95 \le U \le 1.05 \tag{2}$$

Additionally other conditions can be minimized, like:

$$losses \rightarrow \min. \tag{3}$$

$$DG\ reactive\ power\ generation \rightarrow \min. \tag{4}$$

$$OLTC\ \ operations \rightarrow \min. \tag{5}$$

Taking into account the statutory defined voltage conditions, different set-points for tgφ can be given. The graphical representation of optimization problem is presented in Fig 3. If tgφ of all generators is variable, there always exists some point at which the losses are minimal. Furthermore, for participation in the voltage control, not only utilities but also the DG owners must gain financial benefit. Higher tgφ higher are the ancillary services costs. The sum of losses costs and ancillary services costs determine the optimal uniform tgφ. If at this desired operating point the voltages are within the limits, this tgφ is sent to the generators.

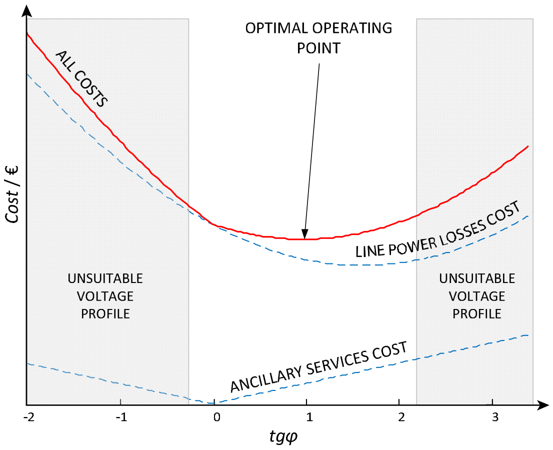

Fig. 3. Graphical representation of the optimization problem [13].

IV. STUDY CASE

The main questions arising when simulating this kind of coordinated control is: is it reasonable not to differentiate between positions of retail customers on electrical location? Is it even logical to make such a control? That is why the operation of the algorithm was evaluated by the means of simulations. As said in the introduction, this is only one of the possible control solutions in smart grids.

A. *Simulated Network Description*

To illustrate the effect of presented control algorithm, the operation is demonstrated on a real medium-voltage Slovenian distribution network model. The selected distribution network is quite big; it covers 483 MV/LV transformer stations, which are presented as loads. Because in Slovenia the penetration of photovoltaic power plants is increasing rapidly (see Fig. 4), the network was modified by increasing the number of photovoltaic (PV). The amount of PV in the network was set to a level at which it was still manageable only with OLTC operation.

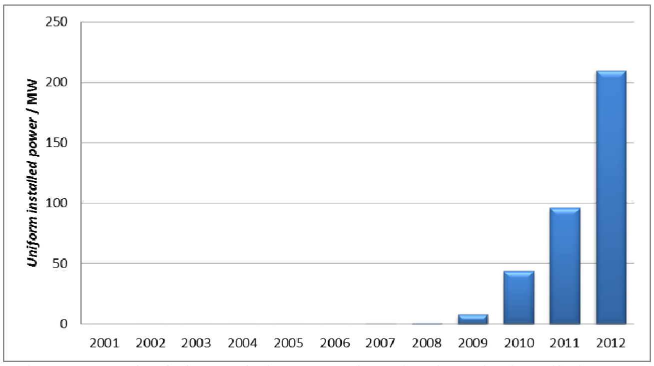

Fig. 4. Growth of photovoltaic power plants in Slovenia (installed power) [16].

Taking into account that the voltage drop on a MV/LV transformer feeding loads and LV feeder can reach 5 % and that the voltage control step is 1.33 %, the MV voltage limits were set to +5/-5 %. The voltage control technique therefore kept the MV within these limits, and consequently that should enable the maintenance of LV within the defined range.

The 20 kV network is connected to the HV level at 110 kV, which is presented as external grid, through a 63 MVA OLTC transformer. The maximal peak consumption is cca. 43 MW and maximal peak generation from DG is cca. 62 MW.

The loads were modeled as voltage dependent *R-X* impedances. A power factor cos$\varphi \approx 0.95$ was presumed. Few typical daily load patterns were developed (residential, commercial and industrial loads).

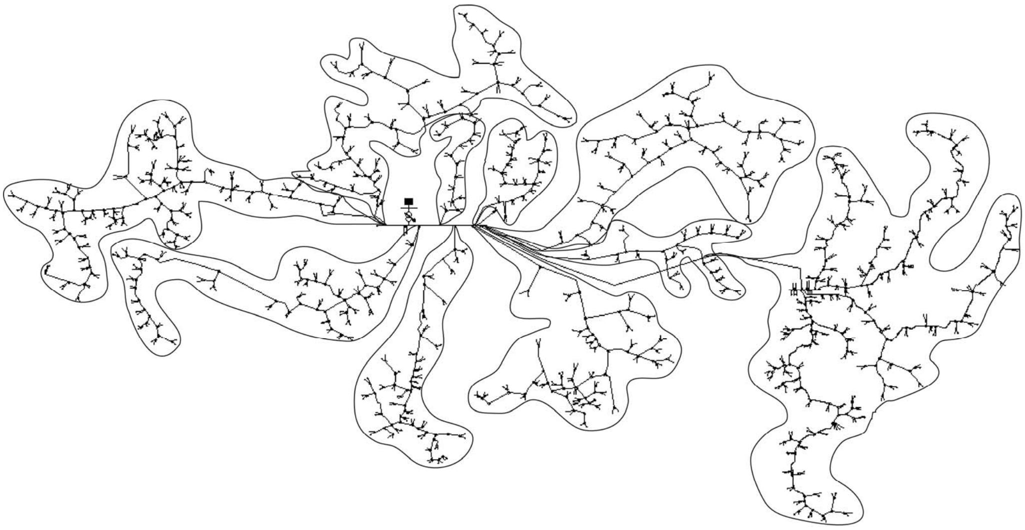

Fig. 5. Medium-voltage distribution system under study.

The network was modeled in the Matpower 4.1, which is a package of Matlab m-files for solving power flow and optimal power flow problems [14].

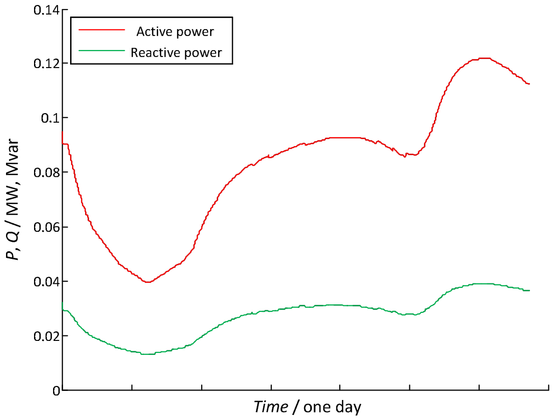

Fig. 6. Typical load pattern for residential area.

B. *Impact of Errors in the Network Modelling*

One of the questions which may be raised when modelling the network is: what is the influence on the network performance if the modelled network in the central control system has too many errors? To simulate also the errors, the simulation was carried out with two distribution models build in Matlab. Firstly the load flow was performed on the model which represented the real network. The input data were load and generation diagrams. Then the measured quantities (*P*, *Q*, *U*) were used as an input for new load flow, which presented network model in the central control system. The results of this load flow are new operating points for generators which were then "transmitted" back to the "real" network. The power quantities which are transmitted to the central control system have to be transformed back to 1 p.u. as the loads in the "real" network are already voltage dependent. This means that the voltages have to be also measured, not only powers. This transformation was made using well known polynomal equations [15] for voltage dependent loads. The equation consists of constant power and constant impedance part:

$$P_0 = \frac{P}{a_1 + a_2\left(\frac{U}{U_0}\right)^2}. \tag{6}$$

In the above equation, the *P* presents measured real power, *U* measured voltage, U_0 nominal voltage, P_0 real power at nominal voltage, coefficient a_1 share of constant power and a_2 share of constant impedance of the load. After the transformation, the power measurements are used as inputs for load flow optimization algorithm in the central control system. Flow chart of the simulation is presented in Fig 7.

Fig. 8 presents the load diagrams of one particular load. The red line presents the input data for "real" network. As this network has the loads modelled as constant impedance, the measured voltages will be different (green line). The blue line presents the transformation back to 1 p.u. The modelled network has loads which reflect constant power. It can be seen that due to error in load modeling the transformation is not the same as it should be. If the loads were modelled exactly the same as the real ones, the blue line would be the same as red line.

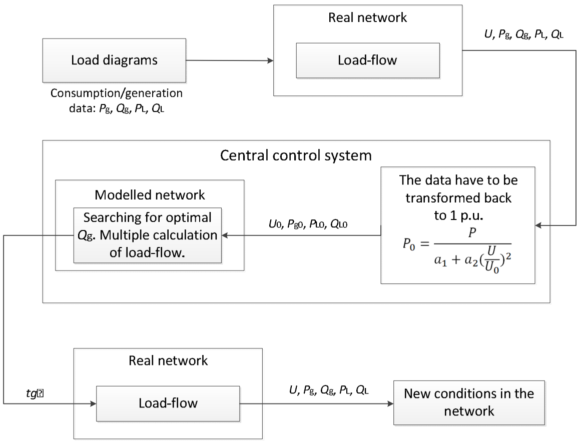

Fig. 7. Flow chart of the simulated system.

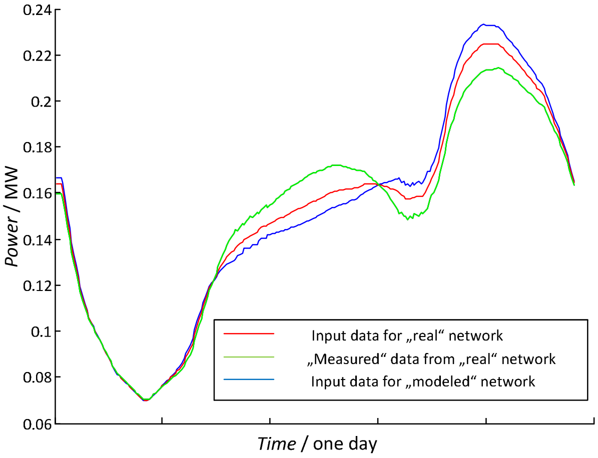

Fig. 8. Impact of errors in the load modeling. If the "real" and "modelled" network are exactly the same, the input load diagrams for the "modelled" network is the same as for the "real" network.

Different characteristics of loads connected to distribution feeders affect power losses significantly. This means that the character of the loads has to be carefully considered. Fig. 9 presents optimal tgφ for one feeder for different types of loads. The red line and blue line represent the optimal tgφ with loads composed of 50 % of constant power and 50 % of constant impedance and 40 % of constant power and 60 % of constant impedance, respectively. It is observed that in both the cases during strong solar radiation, the differences between the calculated tgφ are small. The differences in desired tgφ are slightly greater when there is small share of DG in the network. The greater the share of DG, the less significant the load characteristic is. This is a good advantage as if the loads are badly modeled, the voltages during the peak hours will be still the same as predicted (calculated).

Errors occur also due to delay time in transmitting the signal and calculation of optimal operating points.

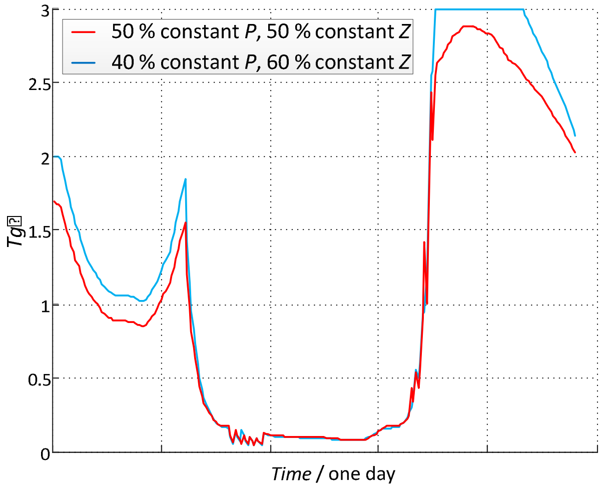

Fig. 9. Desired optimal tgφ using different load characteristics.

C. Control System Performance Evaluation

In this section the simulation results are presented and compared between different controls.

Firstly, the simulations were carried out in the case of no DG. Fig. 10 a) presents the voltage situation for one day. It can be seen that around 3 to 4 tap changer operations are needed to maintain the voltages within the prescribed limits. Fig. 10 b) presents the voltage profile after the introduction of DG into the network. In this case the DG operated with constant power factor, which is cosφ = 1. Fig. 10 c) presents the voltage profile when DG operated with static $Q(U)$ characteristic. It can be seen that this kind of control results in less tap-changer operations which means that more DG can be connected to the network. However, the generators at the end of the feeders are more burdened with reactive power dispatching as the voltage deviations are more frequent which is in conflict with our assumption of fair contribution of reactive power. Example of different contributions of generators is presented in Fig. 11, which presents tgφ of some generators at different locations on one feeder. Furthermore, with use of static $Q(U)$ characteristic the losses increase.

Every time we wanted to minimize the voltage rise the losses increased. The results of the "fair" voltage control are presented in Fig. 10 d) which presents the operation with optimal uniform tgφ. It can be seen that in this case the voltage conditions have deteriorated, but the losses have decreased.

The results for different voltage controls are gathered in Table I, which presents the situations when the loads reflected constant power voltage dependency and constant current in Table II, respectively. In the case of the time-dependent optimal power factor, the losses can be reduced by about 6.5 % compared to the static $Q(U)$ characteristic. It has been observed that with uniform tgφ, up to 40 % more DG can be integrated into the network compared to the static $Q(U)$ characteristic. If this share is higher, the uniform tgφ can no longer be obtained.

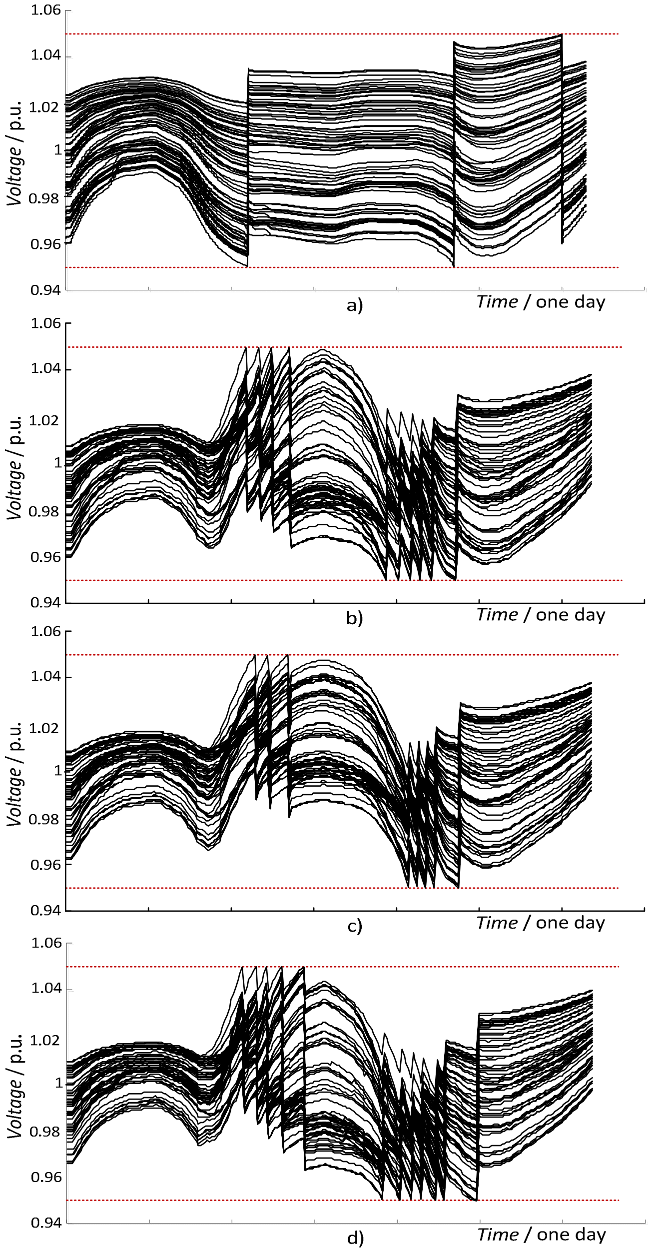

Fig. 10. Desired optimal tgφ using different load characteristics.

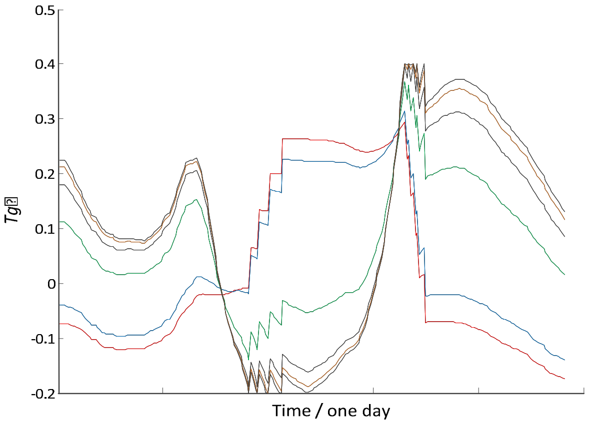

Fig. 11. Tgφ for six different generators in the same feeder. Generators have to produce different amounts of reactive power based on their location.

TABLE I
SIMULATION RESULTS FOR LOADS WITH CONSTANT POWER CHARACTERISTICS

Control	**Tap-changer Operations**	**Losses (kWh)**	**Annual savings compared to static $Q(U)$ control (€/yr)**
Without DG (Fig. 10 a))	3	37 170	/
Constant cosφ (Fig. 10 b))	10	25 467	8 541
Static $Q(U)$ characteristic from [12] (Fig. 10 c))	8	25 935	/
Optimal tgφ (Fig. 10 c))	12	24 253	30 697

TABLE II
SIMULATION RESULTS FOR LOADS WITH CONSTANT CURRENT CHARACTERISTICS

Control	**Tap-changer Operations**	**Losses (kWh)**	**Annual savings compared to static $Q(U)$ control (€/yr)**
Without DG	3	36 723	/
Constant cosφ	10	25 240	5 767
Static $Q(U)$ characteristic from [12]	8	25 556	/
Optimal tgφ	12	23 842	31 280

V. CONCLUSION

This paper deals with the problem of line loss reduction with coordinated reactive power control. Nowadays many research approaches minimize the losses or control the voltages without thinking of fair contribution of the reactive power from the generators. As the retail customers usually have no choice where they are located along the feeder it seems wrong that only some of them take all the burden and responsibility for the voltage rise or losses minimization.

In the paper one of the possible voltage control schemes in future electrical networks is presented. The main purpose of this research was a desire to minimize line losses with respect to a fair contribution of reactive power of all DG in the same feeder. To assure fairness the generators on every feeder work with the same tgφ, which can be seen as a tax rate for producing the active power. The higher the amount of active power is, the higher the amount of reactive power has to be.

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