Study of the Reactive Power Side Effects for Tariff and Compensation Purpose at the Transmission Networks'Users

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Abstract - **The reactive power flows affect voltages, losses and transmission capacities. Thus MVAR flows are a matter of increasing concern for the grid operators and the Romanian Regulatory Authority for Energy has established their importance into a specific Order. The latest corresponding regulation for Romania allows the grid operator to exonerate of payment those injections of reactive which affect in a positive manner positively the voltages in the network. Such exemption is difficult to apply since the influence of MVARs on voltages is locational and time dependent. This paper deals with the assessment of reactive powers related to network users for payment and compensation purposes. The drawbacks are evaluated and compared with the benefits for voltage regulation, according to Romanian regulations. Theoretical skills are combined into one organic methodology, and an in-house software package for reactive power assessment is built. This is based on sensitivities of voltage, loss and transmission capacity to reactive injections into nodes. A case study consisting of a real 110kV network of about 2000 nodes was adopted. The survey was conducted for 6000 hours and outlines voltage to sink's MVARs. The results were used to evaluate the opportunities to compensate and/or to discharge payments the MVARs with positive contribution to voltage regulation. This paper proposes a sensitivity based analysis for a real 110kV network.**

Keywords: *sensitivity; compensation; reactive; loss; optimal; regulation.*

I. INTRODUCTION

Reactive power is a topic of constant concern in modern electric network operation. Nowadays everyone agrees on the drawbacks of reactive power: it affects voltage magnitude [1], increases losses [2], reduces the available transmission capacity (ATC) of the network [3] etc. Transmission and distribution companies are interested in reducing reactive power flows [4], mainly by compensation or reciprocal cancelling [5].

The synchronous generator is the most common source of reactive power. It can deliver MVARs at opportunity costs. Another traditional reactive power, spinning too, is the synchronous compensator. It can have no active load and produce more expensive MVARs. The new generation of reactive power sources, employed for compensation purposes as well as for system control, consists of flexible AC transmission devices (FACTS): thyristor controlled reactors (TCR), static VAR compensators (SVC), shunt static synchronous compensator (SSSC) and static compensators (STATCOM), [6], [7].

The features and capabilities of the reactive power sources become crucial in a competitive market environment. The cost characteristics of the solutions able to supply the required reactive powers in secure steady state and dynamic operational conditions also weigh heavily. These elements will be referred in conjunction with the sensitivities of individual elements, depending mainly on their location in the network [8].

The compensation of the reactive power is mainly directed towards voltage control. Optimal voltage control through V/Q ancillary service also aims at loss reduction and capacity relief so as to host additional flows.

The reactive power problem is rather local: one inductive flow seeks to pair with the leading reactive power of the nearest capacitive element. In most cases the consumers are inductive and they shall be compensated either by neighboring under loaded lines or by a specific compensator.

However, transformers and the transmission line exhibit their own reactive powers, which depend on the system load. Nobody pays for these reactive powers, either beneficial or not for the network operation.

In Section II of this paper the authors present the Romanian regulations with regard to reactive power matters and payment settlement. Specific exemption conditions, provided by this regulation, are pointed out in order to be further analyzed in section V.

Section III describes the reactive powers of the network components: transformers and transmission lines. Computing equations and influence factors are outlined.

Section IV outlines the methods available for evaluating the effect of reactive power flows.

Section V presents the proposed methodology and the toolkit developed in order to emphasize the impact of the reactive power on the network voltage, power losses and transmission capacity use.

The results of a case study are delivered and analyzed in section VI and section VII concludes this work.

II. ROMANIAN REGULATION FOR REACTIVE ENERGY

ANRE, the Romanian Regulatory Authority for Energy, has established the importance of reactive power matter into a specific Order [9]. This order defines all the elements, definitions, formulas and computing methodology for the reactive energy payments.

In accordance with it, the inductive reactive energy (lagging) and capacitive reactive energy (leading) aren't cancelled any more but entitle to separate payments. The tariff for reactive energy at power factors bellow 0.65 is three times higher than for power factors between 0.65 and 0.92. These methodology and tariffs are meant to discourage sinks to exchange intensive reactive powers with the network.

One principle almost obvious in theory has become rather controversial in practice: the possibility to exempt some network users of the payment due for the reactive energy. This exemption is limited to prosumers that:

- participate to the V/Q regulation, under the command of the network operator, for the energy exchanged, injected in/drawn from the network during this service;
- contribute to the improvement of the voltage level by injecting or drawing reactive power.

The last case lacks accuracy in defining the benefits for the voltage regulation service. This opportunity could entitle a prosumer having sometimes fortunate V/Q sensitivity to wait to be exempted for the reactive energy exchanges with the network. In order to characterize the true contribution to this service over a time period, an in-depth analysis, as presented in section VI, is required.

After enforcing this Order in the last 18 months, ANRE has published some global outcomes and decided to continue applying it with minor changes and updates [10]. The results run as follows:

- the inductive energy billed raised by 15% for power factors ranging between 0.65 and 0.92, and by 25% for users operating at power factors bellow 0.65;
- the capacitive energy payments have increased by 12% for power factors ranging between 0.65 and 0.92, and by 200% for users operating at power factors bellow 0.65.

The last case corresponds to situations where the capacitive power is injected in an underloaded network area and has to be discouraged. Al these results entitled the Regulatory Authority for Energy in Romania to maintain these rules and amend some descriptions. Moreover, the network operators where asked to approve of exemptions solely based on an in-depth analysis and measurements. Thus, only beneficial reactive powers have to be rewarded. All the others have to be penalized according to their disruptive effect.

Further in this paper the opportunity of ANRE regulation regarding the reactive power tariff is analyzed by considering a set of operation regimes for a 110 kV distribution network. The presented study cases outline the influence of reactive power on the voltage level by using multiple analysis approaches.

III. REACTIVE POWER OF NETWORK COMPONENTS

The operation principle of most consumers involves reactive powers in correlation with the active one. These reactive powers are not delivered by some reactive sources, as for the real ones, but exchanged with neighboring branches.

The network components, transformers and lines have their own reactive powers, which depend on the operation regime. Thus, the reactive power of transformers can be estimated by computing with:

$$Q_T = B_T \cdot V^2 + X_T \cdot I^2 \qquad (1)$$

or

$$Q_T = \frac{I_0\%}{100} S_N + \frac{V_{sc}\%}{100}\left(\frac{S}{S_N}\right)^2\left(\frac{V_N}{V}\right)^2 \qquad (2)$$

where:

B_T - the shunt susceptance of transformers – inductive (S);

X_T - the longitudinal reactance of the transformer (Ω);

V - the operation voltage of the transformer (kV);

I - the current through the transformer (A);

$I_0\%$ - the no-load current of the transformer (%);

S_N - the rated power of the transformer (MVA);

V_N - the rated voltage of the transformer (kV);

$V_{sc}\%$ - the short-circuit voltage of the transformer (%).

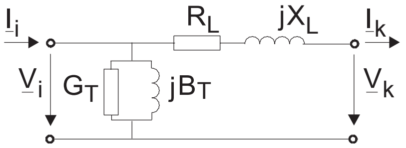


Fig. 1. Model - Γ of the transformer

This reactive power always lags and exhibits a quadratic flow dependency of the power delivered by the transformer. On the other hand, the transmission lines lead when no-load and become lagging when the line flow increases above the surge impedance loading, SIL:

$$SIL = \frac{V_L^2}{Z_0} \qquad (3)$$

where:

Z_0 is the surge impedance (Ω):

$$Z_0 = \sqrt{\frac{X_L}{B_L}} = \sqrt{\frac{L}{C}} \qquad (4)$$

L the serial inductance of the line (H)

C the shunt capacity of the line (F)

The reactive power loss of the transmission line can be evaluated using the formula:

$$Q_L = \frac{P_i^2 + Q_i^2}{V_i^2} X_L - \frac{V_i^2 + V_k^2}{2} B_L \qquad (5)$$

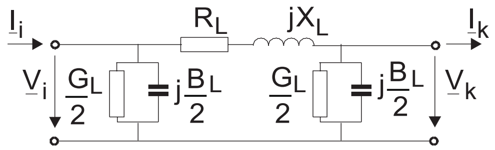


Fig. 2. Model - Π of the transmission line

The balance at the network level points out to the reactive power of the whole network. This amount can reach significant values and varies heavily with the operation regime. It can be either positive or negative. Nothing is to be paid for these reactive powers whatever the case.

IV. METHODS FOR REACTIVE POWER EVALUATION

Various methods are available for evaluating the effect on voltage control of reactive power injections on voltage control [11, 12, 13].

A. *Marginal sink variation method*

This outlines IQ contributions to voltage upholding for marginal sink variations. The sensitivity of IQ at bus i to the marginal variation of sink from bus j is:

$$SQ_{ij} = \frac{dQ_i}{dS_j} = \frac{dQ_i}{dU} \cdot \left(\frac{dS_j}{dU} \right)^{-1} \tag{6}$$

where

dQ_i - the IQ at bus i which maintains voltage if sink at bus j varies of dS_j.

The overall sensitivity of IQ at bus i is the sum of equations (6) for all sinks:

$$SQ_i = \sum_{j=1}^{c} SQ_{ij} \tag{7}$$

with c – no. of consumers.

The IQ sensitivity of all the g reactive “sources” to a marginal variation of the sink from node j is:

$$S\Sigma Q_j = \sum_{i=1}^{g} SQ_{ij} \tag{8}$$

Full IQ sensitivity to all sink marginal variations becomes:

$$S\Sigma Q = \sum_{i=1}^{g} \sum_{j=1}^{c} SQ_{ij} = \frac{\sum_{i=1}^{g} dQ_i}{dV} \cdot \left(\frac{\sum_{j=1}^{c} dS_j}{dV} \right)^{-1} \tag{9}$$

Sensitivities from (6) … (9) allow to compare technical efficacy of As-V/Q service provider bids. However, these sensitivities deliver no systematic way for ranking bids.

B. *P/V curves method*

In this method the loads are increased not by a marginal value, as in the previous section, but until the system reaches the stability limit. The scenario is chosen to fulfill the purpose of the analysis (e.g. we can increase only the consumption from a region, at various quotas, at constant/variable power factor).

The issues aren’t wide-ranging. Moreover, the selection of the scenario can be critical.

By simulating a consumption ($\Delta S_j \big|_{j=1,\dots,c}$) increase up to the stability limit, balanced by AGC units (all others remaining PV buses at constant specified voltages and powers) we get the IQ variations, ΔQ_j. Various specified voltages can be utilized.

The appraisal of different IQ, reveals the efficacy of each reactive power “sources”. The conclusions are useful rather for security analysis than for assessing As-V/Q tariffs.

C. *Fictitious compensators method*

When the IQs change, voltages alter. Fictitious compensators at each PQ bus can restore system voltages.

We denote by $Q_j^{(x)}$ the IQ of the As-V/Q service provider from bus j in regime x and $Q_j^{(\min)}$ its IQ minima (lower edge of secondary range for voltage regulation). For synchronous compensators and static „sources” we let $Q_j^{(\min)} = 0$.

By simulating a variation $\Delta Q_j^{(S)}$:

$$\Delta Q_j^{(S)} = Q_j^{(x)} - Q_j^{(\min)} \tag{10}$$

we determine the IQs of the fictitious compensators which “replace” the missing injection. For a load at bus i, the resulting fictitious IQ, $\Delta Q_i^{(C)}$, defines its “duty” for the $\Delta Q_j^{(S)}$ service. Because $\Delta Q_j \neq \sum_i \Delta Q_i^{(C)}$, the “duties” aren’t normalized and must be shared (e.g. pro-rata: load i pays to provider j matching to: $\left(\Delta Q_i^{(C)} \Big/ \sum_i \Delta Q_i^{(C)} \right) \cdot \Delta Q_j^{(s)}$).

D. *Back-up generation method*

An IQ, $\Delta Q_j^{(S)}$, can be “replaced” not only by a fictitious compensator, but also by the IQ of another As-U/Q provider. For the provider from bus k we note:

- $\Delta Q_k^{(x)}$ IQ in the regime x;
- $\Delta Q_k^{(\to \min_j)}$ IQ in the regime having the same voltages as in *x*, and $Q_j = Q_j^{(\min)}$.

We can consider that the IQs $\Delta Q_j^{(S)}$ (at bus j) and $\Delta Q_k^{(\to \min_j)}$ (at bus k) are equivalent. This statement is very useful for assessing tariffs for As-V/Q service in the operating regime x.

E. *dV/dQ sensitivity method*

The voltage sensitivities to IQ describe a widespread tool in voltage control. The reactive power injection at bus k meant to correct the voltage at bus i of about ΔU_i is:

$$\Delta Q_k = \frac{\Delta U_i}{S(U_i, Q_k)} \tag{11}$$

where

$$S(U_i, Q_k) = \frac{\vartheta U_i}{\vartheta Q_k} \tag{12}$$

is the reverse, (= $\vartheta Q_k / \vartheta U_i$) of the corresponding element of the Jacobian.

Equation (11) exhibits that the voltage at bus i can be equally corrected by an IQ of:

$$\Delta Q_j = \Delta Q_k \cdot \frac{S(U_i, Q_j)}{S(U_i, Q_j)} \tag{13}$$

at bus j or by an injection of ΔQ_k at bus k.

For voltage regulation at bus i:

- (11) defines the required amount of challenging injections for voltage correction;
- (13) states the tariffs' ratio for two IQs at buses j and k, which are equivalent in voltage "correction": $S(U_i, Q_j) / S(U_i, Q_j)$.

V. Assessment of Reactive Power of Grid Users

The effects of reactive powers injected or drawn by a network user can be quite volatile. Thus, in certain operation regimes, some reactive power injected at specific buses could be helpful for the voltage regulation service. This does not hold true for all operation regimes and isn't true for all network users (it depends on the amount and the location of reactive).

Therefore the impact of each reactive power for all the regimes in question is to be assessed individually. This can be done either *ex-ante* or *ex-post*. In the *ex-ante* approach, the assessment is based on measured data. Hence the corresponding results are undisputable and can be used for payment purposes.

This paper proposes the sensibility-based analysis as the most suitable tool. The voltage sensitivity to nodal reactive power:

$$S_{VQ} = {\partial V_i}/{\partial Q_k} \tag{14}$$

and the loss sensitivity to MVAR injected / drawn at node k:

$$S_{LossQ} = {\partial Loss}/{\partial Q_k} \tag{15}$$

outline the impact of Q_k to voltage regulation and losses.

The contribution to the voltage regulation can be considered useful if the injections Q_k move the voltage according to the needs for the corresponding operation regime (e.g. if Q lags, as for most of the loads, than S_{VQ} should be positive off-peak and negative on-peak). The support to the voltage regulation is stronger if the grid operator lacks available reserves. Further complex analysis can be conducted based on the QV curves, known also as nose curves.

The impact of the reactive power on losses is easy to evaluate based on S_{LossQ} sensitivity. The injection of reactive power is to be considered useful (loss-friendly) if it diminishes the losses for this operation regime. The magnitude and even the sign of S_{LossQ} can change during one year.

The reactive power from one node affects the available transmission capacity in the neighborhood. The strongest effect is to be observed over the branches connected to the node. This dependency can be assessed based on direct numerical simulation. Since the nonlinear model of the network is not suitable for superposition, only the full simulation is relevant.in this case, [14].

Any exemption regarding the payments for reactive power / energy, as in [9] could be applied, ex-post, by reimbursing the prosumers for the reactive energy which help the voltage regulation. The main problem is that these quantities are not measured. Even the latest smart metering system (AMS) does not deliver such kind of data. It should be done by computing these quantities *ex-post*, based on the hourly measurements of reactive power. These measurements are to be set into categories corresponding to their effect on voltage regulation.

The chart flow of the methodology for assessing reactive power impact is presented in Fig. 3. Proprietary software packages, as well as in-house software tools are interfaced in order to reach measurement data, adjust them in a proper format and supply them in order to perform this analysis.

Besides the tariff and payments issues, the main problem is that the reactive power has to be compensated in order to avoid drawbacks. The bills for reactive energy can pay off for the investment in compensators and their operation. The opportunity to invest is based on the analysis cost benefit for each possible scenario. The tariffs for reactive energy from [9] do not generate enough income to pay for compensation at the HV level, where the specific capacity costs (€/MVAR) are more than 10 times higher than at LV.

Moreover, the losses could be decomposed into two components: one depending on the real power flow and the other under the responsiveness of reactive power. This second component can be reduced by proper compensation. Time-dependent performance indexes, "Q/loss", were defined in [15] at the branch level and for entire network.

These indexes could be useful for ranking grid operators as well as for tariff settlement purposes. Thus, the loss component which corresponds to the MVAR flows could be allocated to the grid owner, as an avoidable share of loss. Moreover, this loss share can be carried over the ancillary service dealing with the reactive support to the voltage control - V/Q service.

VI. Case Study

In order to evaluate the influence of the reactive power flows on the voltages in a studied network the authors propose basically three approaches:

- direct comparison of two simulation cases (the real operation of the test network vs. the suggested compensated configuration);
- using an interpretation of sensitivity based analysis in the buses of the test network;
- analyzing the information given by QV curves.

The analysis was carried out for a real operating 110kV network, consisting of 1994 buses and 2228 branches. The time frame was of 5855 running hours in 2015.

Voltages, real and reactive powers from 481 electric meters were collected during that time.

After undergoing a state estimation process, the data corresponding to each state were processed with an in-house software package, REANS_CONT, [16][16].

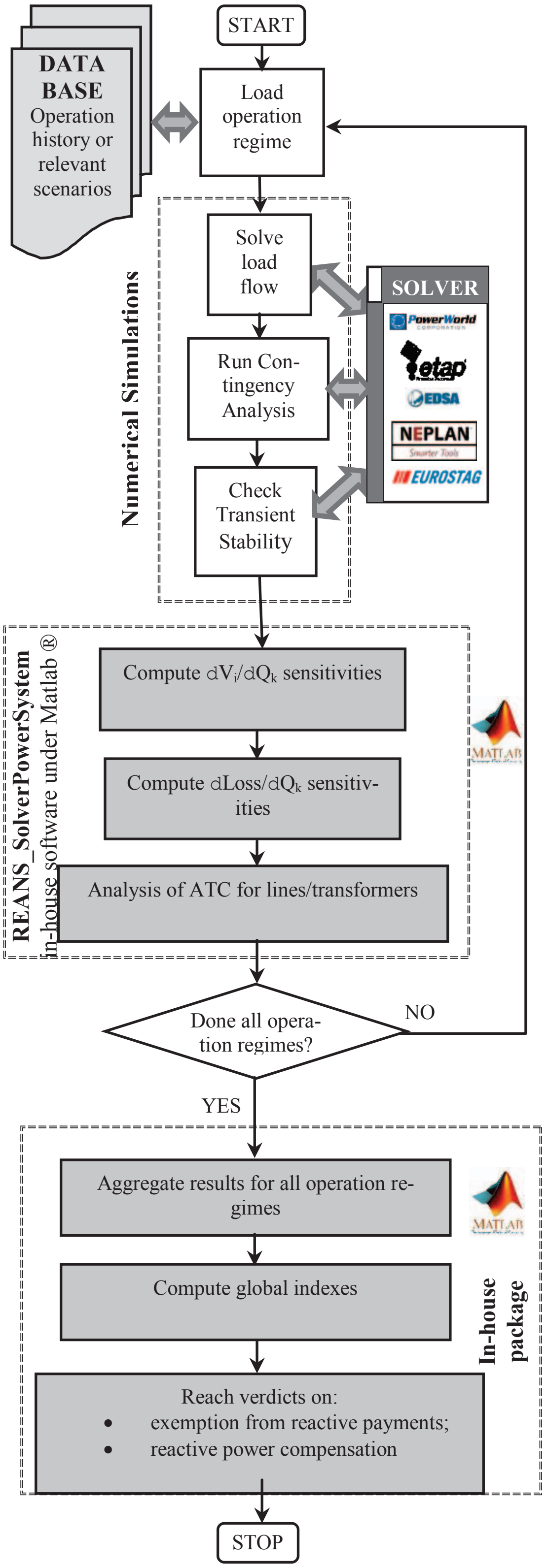


Figure 3: Chart flow of the methodology for assessing reactive power impact.

The generation and load level are presented in Fig. 4 and Fig. 5.

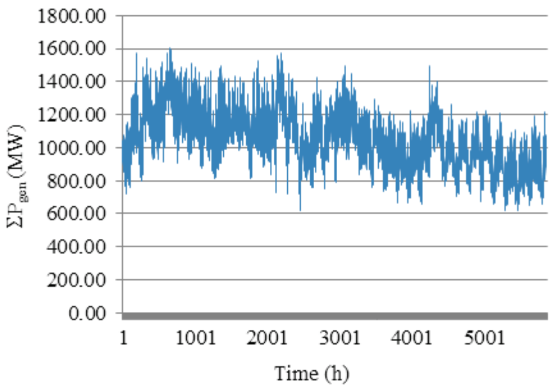


Fig. 4. Generation progression in the time frame.

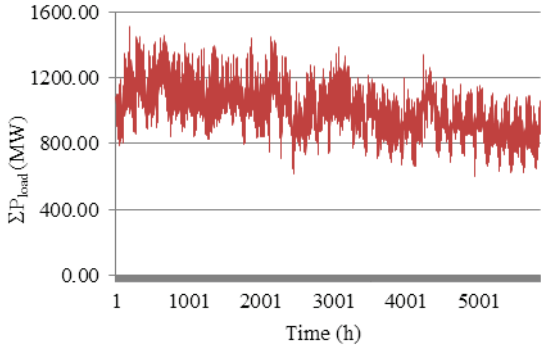


Fig. 5. Consumption progression in the timeframe.

A. *Voltage sensitivity to MVARs*

Using the REANS_SolverPowerSystem (in-house software – Matlab ® code) – see Fig. 3, the sensitivity of the voltage to MVAR was calculated.

The results for 1/10 of nodes are illustrated in 3D in Fig. 6 and in 2D in Fig. 7.

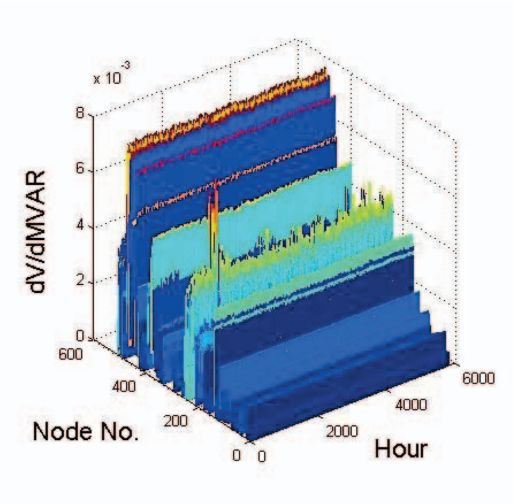
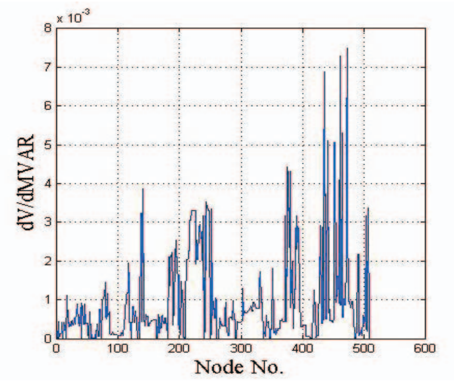
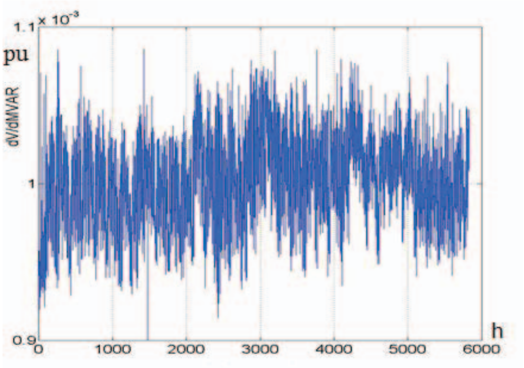


Fig. 6. Voltage sensitivity to MVAR (3D plot)



a) dV/dQ vs. Node. No at instant t



b) dV/dQ vs. time for node no. 659

Fig. 7. Voltage sensitivity to MVAR (2D plot).

The QV curves, known also as nose curves could also be useful for describing the impact of one reactive power on the voltage of the node where it is injected.

A sample of such curve for node no. 659 (a high voltage industrial consumer), as delivered by PowerWorld ® simulator, [17], is presented in Fig. 8.

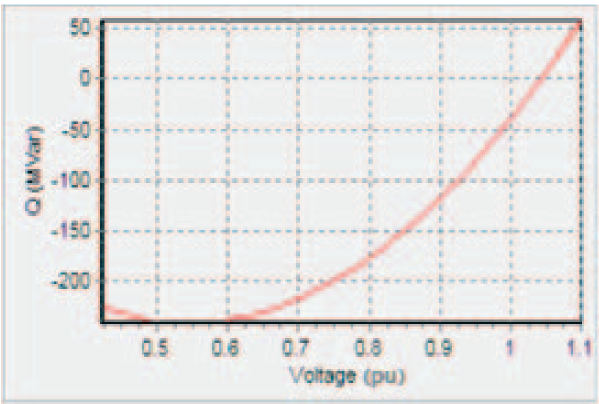


Fig. 8. QV curves for one node.

B. *Loss sensitivity to MVARs*

The sensitivity of loss to MVAR was computed using the REANS_SolverPowerSystem – see Fig. 3.

The results for 1/10 of nodes are shown in 3D in Fig. 9.

The momentary values for the same instant as in Fig. 7a) are 2D, depicted in Fig. 10.

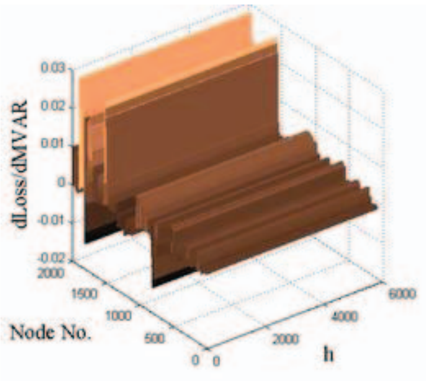


Fig. 9. Loss sensitivity to MVAR (3D plot).

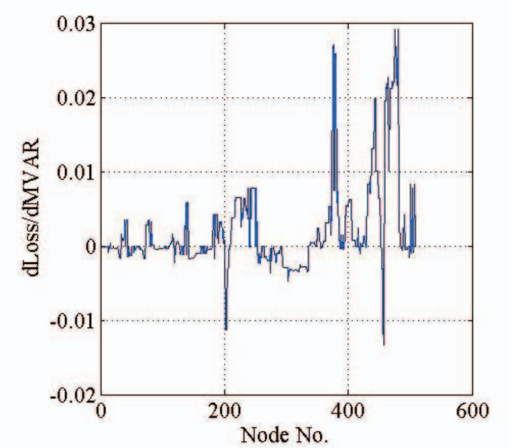


Fig. 10. Loss sensitivity to MVAR (2D plot).

C. *Impact of reactive power on ATC*

The impact of the reactive power on the available transmission capacity is outlined by numerical simulation. Thus, the difference between the simulated flows with and without the analyzed MVARs is computed.

Such an approach conducted for node no. 659 (w-w/o) outlines differences in branch loading, which go from -1% (dark blue) up to +2% (red) in Fig. 11.

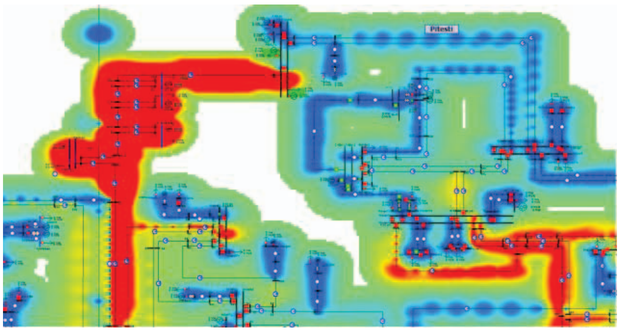


Fig. 11. ATC sensitivity to MVAR.

Information of the same nature could be extracted from the power transfer distribution factors (PTDF), as in [18]. This is faster and more general, but less precise than the method based on the difference in numerical simulation.

D. *Compensation of reactive power*

The drawback of reactive power may be avoided by compensation. The compensation presupposes an investment – capital expenditure and operation costs for the running period.

For instance, in the case of the node no. 659 considered for this analysis during the weak load time span, the full compensation of the reactive power (from 19.5 MVAR to 0 MVAR) lowers the voltage by almost 0.02 pu, as it can be seen in Fig. 12.

This MVAR variation also results in a loss reduction of 0.124 MW.

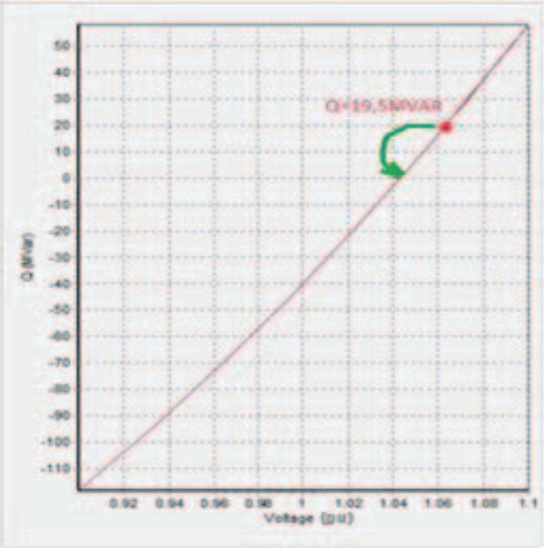


Fig. 12. Full compensation of MVARs in QV curve.

Based on data for 5855 hours, the compensator - STATCOM is to be optimally rated at 15MVAR (unremunerated part – neutral PF is avoided). The capital expenditure (CAPEX) for this compensator is 7.12 M€ and its annual operation expenditure (OPEX) is 17.8 k€. It saves losses of about 71.73 k€/year. For a discount rate of 1.05, the internal rate of return (IRR) is only -31.13 %. This lack of profitability is due to the very high CAPEX for HV compensation with SVC or STATCOM.

Once the technology will advance, the price of static compensators is expected to decrease, leading to a more cost-effective compensation.

VII. CONCLUSIONS

The paper deals with the reactive power side effect and damping tariff and payments. The drawbacks of the reactive power related to each network user (e.g., voltage drops, additional power losses and useless ATC employment) are to be avoided through compensation.

Based on a case study consisting of a real 110 kV of about 2000 buses, one can conclude that the compensation of prosumers' MVAR for reducing losses is possible but not rewarding, because of the high CAPEX at the HV level (about 5.7 €/MVARh if operating 8760 h/year, fully charged). As the grid operator does not lack providers for the voltage regulation service, new compensators are not advisable, especially at HV. Moreover, the static compensation of MVAR does not free ATC selectively – at the targeted locations.

If the MVARs injected by network users are not necessary to voltage regulation, any exemption from MVARh payments, according to [10], is to be avoided. Beneficial but volatile support under weak control may generate but not solve problems.

These conclusions are case-based. An in-depth analysis and further tests in various cases would be helpful.

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