RISKS OF DETERMINING THE OPTIMAL TECHNICAL SOLUTION OF POWER PLANT CONNECTION TO DISTRIBUTION NETWORK

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ABSTRACT

Growing share of power plants in the distribution system and efforts to increase utilization of network reduce the margin of error thus increasing the share of uncertainty in determination of the optimal technical solution for connection of power plant to the network. The paper describes different sources of uncertainty, elaborates implemented margins of safety and correlation with the additional risks taken over solely by the distribution system operator.

The paper gives possible methods of reducing the identified risks and means of risk-sharing among all involved energy entities and other responsible parties.

INTRODUCTION

While there was a relatively small share of power plants (DG) in the distribution network, the new DG could be connected to an existing network with a large margin of safety. Nowadays, the use of usual margin of safety makes impossible to "squeeze in" a single new DG in an already DG-saturated power network. In absence of specific regulations for preserving the necessary minimal safety margins, distribution system operator (DSO) is forced to minimize the margin of safety, thereby taking over a significant additional risk with the possible long-term consequences.

Unlike the customer's connection fee, in Republic of Croatia the producer's connection fee is based exclusively on 100% of actual connection cost (deep integration connection fee) [2].

Cost of DG connection consists of two components:

a) cost of connection facilities - electrical link of electricity meter (delivery point) to the existing distribution network
b) cost of upgrading the existing network to the extent necessary for the connection of the power plant.

Distribution network in Croatia includes medium voltage (MV) and low voltage (LV) network (35 kV and lower).

In Croatia DSO has to carry out a study (EOTRP) before issuing preliminary connection approvals (PEES) for MV network user [2], [6].

EOTRP is a comprehensive network analysis aiming to determine the optimal technical solution of network user connection to network and to elaborate and explain the necessary connection costs (the connection fee).

EOTRP is a power flow network analysis based on the network models, load models (consumption model and production model) and the network user models. The risk of determining the optimal technical solution of connection is based on the fact that the input data of the study brings a level of uncertainty into the network model and the load model. Those models are analysed to determine all extreme network conditions that may occur during normal network operation. If the study of extreme conditions in normal operation results in network parameters outside the permitted range, network reinforcement is necessary to enable DG connection.

Since the DG connection fee consists of real cost of connection, necessary reinforcement of existing network increases the connection fee. The DSO should take into account a possible error of the network model and load models. Therefore DSO should define reasonable margin of safety to prevent possible incorrect conclusions in EOTRP. The existence of safety margin will result in additional cost of necessary network reinforcement (which is necessary as soon as the results of the network power flow analysis enter the safety margin). Therefore the DG investors oppose any margin of safety, accusing DSO for enforcing the risk of possible uncertainties of network and load models exclusively to investors.

It is indisputable that some uncertainties in models exist. Too narrow margins will result in failure to perceive the necessity of network reinforcement / upgrade. This will cause problems in normal network operation, as well as problems in network use (DG outages etc.). The moment problem occur, DSO must upgrade the network at its own expense to enable normal network operation and normal network use for all users. Otherwise DSO will face numerous network user complaints.

Thus, the DSO is exposed to complaints or lawsuits either by DG investors for the excessive connection fee, or by network users for inadequate network operation or network unavailability.

There is only one solution acceptable for all parties: the optimal technical solution of connection. The only way to determine the optimal technical solution is to find the optimal margin of safety for each source of uncertainty for each network component, load and network user modelled in EOTRP.

The paper elaborates sources of uncertainty, problems encountered and implemented solutions. The paper gives technical argumentation for the logic of network elements modelling and associated safety margins, as well as load modelling (production and consumption) and necessary model adjustments to specific categories of network users, network configuration or network load.

The paper is based on over 400 studies (EOTRPs) carried out by DSO since 2010. DSO continuously improves implemented models. Models are continuously verified in practice by DSO's supervision of the power plant's trial operation and by monitoring of ongoing parallel operation of DGs in the network.

THE SCOPE OF THE NETWORK ANALYSIS

In the beginning of DG integration in EOTRP there was a simple network analysis "before and after connecting of analysed DG" based on the model of existing network (model "before") and the model "after" (model "before" upgraded with the analysed DG and associated connection). Nowadays EOTRP is turning into a complex network analysis with a complicated description of many possible network model variations.

This phenomenon is caused by numerous DGs (and associated connections) in various stages of completion of the project. DSO has to "preserve" the network resources (connection availability) for all DGs having valid PEES, regardless of probability of completion.

By now (the end of 2016) DSO has made 402 EOTRPs for DGs. EOTRPs analysed the possibility of connection to distribution MV network for a total of 881 MW of production (27.6% of the maximum load of entire Croatian power system, or 24% of total installed capacity of electricity production of the national electricity production company: HEP-Production ltd.)

Now in Croatia there are 5815 DG valid PEESs for DSO's DGs. By these PEES the DSO made a commitment to connect the total of 858 MW in DG connected power. Now in the DSO's network in permanent operation are only 1577 DGs (184 MW connected power).

The completion of DG projects in Croatia is low (21% of connecting power, 27% of DGs). Therefore DSO is compelled by regulations to count as booked (due to valid PEES) five times more network resources than necessary.

The phenomenon of never-ending validity of the preliminary connection approval (PEES)

In Croatia PEES is valid 2 years upon its issuance. The validation can be prolonged by DSO for further 2 years on request [1]. But, if PEES is issued in the process of obtaining a location or building permit for the network user, the validity of the PEES is determined by the validity of the location and/or building permit [4], [5]. Furthermore, validity of PEES lasts forever if the construction of network user has already started [5] (building permit is considered to be consumed as soon as construction started). This non-technical legal request creates enormous technical problems for DSO.

How to model a network having many unbuilt (unconnected) power plants with valid PEES (DG_{PEES})? To model all DG_{PEES} as already in operation, with associated connection and network upgrade? In that case EOTRP should treat such a network model as initial network and evaluate if the network resources are sufficient for connection of new DG. What if the conclusion of EOTRP is based on the assumption that there are sufficient network resources due to the network upgrade demanded for connection of DG_{PEES} that actually will never be built (neither will it's connection and the network upgrade)? Problem escalates by increasing the density of $DG_{PEES.}$, Network may change considerably due to the every DG_{PEES} connection (topology in normal operation, voltage level, feeding point etc.).

The solution is: more than one network model for "before the new DG connection". At least there are two models: network without any DG_{PEES} (existing network model) and network with all DG_{PEES} (initial network model).

In case of significant network changes due to influential DG_{PEES} connection there are two options: a) additional initial network model has to be created (to model option what if the new DG is connected prior to influential DG_{PEES}), or b) the new DG has to have the network upgrade as determined by PEES for influential DG_{PEES} connection. If two or more DGs have the same network upgrade required, cost will pay the first DG connected.

The distribution network in Croatia will eventually become too crowded by DG_{PEES} thus network modelling in EOTRP will become impossible if the legislator do not intervene and repeal DG_{PEES} with expired prescribed validity (2 + 2 years). Until that moment DSO has to perform complicated and technically senseless network analysis in accordance with present regulations.

Basic terms

Analysed network is the part of electric power system influenced by the new network user; it is part of the network that is analysed in EOTRP.

Zero state network – existing network in normal operation with network users already connected to the network; network model based on input data of existing network topology and of the existing (measured) loads.

Initial network = existing network + all "PEES network users"

Future network = initial network + new network user + all "future network users"

Simplified network - network model having one or more simplified DGs

PEES network user (DG_{PEES} or $Consumer_{PEES}$) - model of future (not yet connected) network user having valid PEES, combined with its connection and associated network upgrade (determined by PEES)

"Existing" network user – network user connected to the network or PEES network user

New network user (new DG, new consumer) – the subject of EOTRP (combined with its connection and associated network upgrade)

Future network user - network user having EOTRP (but not yet requested PEES) combined with its connection and associated network upgrade (determined by EOTRP)

Simplified DG – model of individual DG connected deep in network substituted by DG connected on the busbars of the feeding substation - this is permitted only if the new DG has no influence on the conditions at location of the DG aiming to be simplified.

The network models

Calculations in EOTRP follow the series of scenarios:

1. **Zero state network**
2. **Initial network**
3. **Future network**
4. **Future network + new DG -** case of new DG connected after "existing" and future users
5. **Initial network + new DG -** case of new DG connected after "existing" users, but prior to future users - additional scenario in case of necessary network upgrade in model 3.

For each scenario two extreme situations are analysed:

a) maximum consumption with no production,
b) minimum consumption with maximal production.

Table 1: Network analysis scenarios in EOTRP

Network model	Connected network user			PEES network user		EOTRP network user		Study subject
	"small" consumer	ZK	DG	ZK_{PEES}	DG_{PEES}	ZK_{EOTRP}	DG_{EOTRP}	New DG
Zero state network (0)	Linear distribution of line consumption	User's electricity meter data		- (not modelled)				
Initial network (1)	As in (0)	Model ZK	Model E	Model ZK	Model E	-		
Future network (2)	As in (1)					Model ZK	Model E+	-
Future network + new DG	As in (2)							Model E+
Initial network +new DG*	As in (1)							Model E+

In case of connection of solar DG, or if there are major solar DGs in the network, consumption and production are modelled as daily load curve for specific days (days of minimum or maximum consumption).
DSO always starts with the simplest connection first. EOTRP has to elaborate if it wasn't applicable, and moves to the analysis of next possible connection option.

The size of the analysed network

The greater the relative share of DG production is in a given area, the impact of DG on power flows and voltages in the network extends further. Thus EOTRP must cover greater part of the network.
As the analysed (covered) network expands, it includes more users (and DGs). Hence the cumulative impact of new DG with other DGs in the analysed network expands further, causing additional extension of analysed network. DG domination causes power to flow into transmission network. Then analysed network expands to transmission network. The network and load model of transmission DSO harmonizes with the network owner (TSO). The upward direction of energy opens the topic of optimal settings of automatic voltage regulation at the interface between the transmission and distribution network. The extent of this topic requires a separate paper.

CONSUMPTION/PRODUCTION MODEL

The model of existing consumption is needed as input data for the network analysis. This issue gets a new dimension if there are DGs connected to network. This fundamentally changes the perception of network, turning radial into multiple-feeder network.
It is essential to distinguish terms "load" and "consumption". In the radial line before DGs load of the line was equivalent to line consumption (plus losses in the network, which in this elaboration can be ignored). In case of the line with DGs these terms represent different values: line consumption is sum of line load and cumulative line production. The load model of line in EOTRP is based on extreme values of consumption and production of the line. The load of the MV line is measured value and usually available in DSOs SCADA. The data of consumption of the line with DGs is difficult to obtain. Line consumption can be calculated as:

a) sum of simultaneous consumption of all consumers connected to line;
b) sum of simultaneous delivery to the line (line load + production of all DG's connected to line).

Due to the lack of adequate measuring data of simultaneous consumption of all consumers, method a) is not applicable. Furthermore, due to the lack of adequate measurements of simultaneous load of substations MV/LV, substitution modelling of LV consumption as measured load of substations MV/LV is impossible.
Data of DG production (delivery to network) is available in DSO's SCADA only for the DGs connected to MV network. Data of DG production connected to LV network is measured only by the smart electricity meters, so measuring data is not available in DSO's SCADA.
In theory, one should continuously add up the simultaneous delivery to line from all feeding points (all DGs and the mains) and find the maximum/minimum of this sum. This will give the maximum/minimum of existing consumption of the line.
Caution: the power flow direction at each feeding point has to be taken into account. In some parts of the network still exists older measuring equipment unable to recognize the power flow direction. Before DGs non-recognition of power flow direction was not a problem. However, in lines with dominant DG production non-recognition of direction always results in an error of twice the amount of measured values. Such an error regularly leads to incorrect technical solution of connection detectable in late stages of EOTRP.
Furthermore, all measurements obtained during not normal line operation (or in different line configuration, or switching status) has to be identified and excluded. The majority of switching in distribution network is still performed locally, so the data available in DSO's SCADA isn't sufficient to identify changes of switching status in the line. Therefore, the calculated min/max of line consumption should be reviewed. If there are any doubts, the additional verification of the line status at the given period should be performed. If necessary, the backup lines should be checked for atypical load changes.
There is the issue of optimal level of detail in modelling of min/max MV line consumption. Is it necessary to take into account the contribution of LV DGs? There is no universal answer. Each situation is different. Constructive engineer reasoning is crucial. The relative impact of LV DGs is essential, as well as whether the results are close to the margin of safety. Incorrect assessment of irrelevance of omitted LV DGs may lead to incorrect technical solution of connection and associated incorrect connection fee (error might be huge, up to 5000% fee).
Consequently, it is not possible to assess the competence of input data used to model line consumption in EOTRP.

Distribution of line consumption by substations MV/LV along the MV line

Consumers connected to MV are major consumers (ZK). The calculated extreme (min/max) line consumption should be reduced by the simultaneous consumption of all ZK. ZK consumption is based on data measured by electricity meter. The reduced line consumption is distributed by substations MV/LV along the MV line assuming a linear distribution of line consumption by individual substations MV/LV in proportion to installed power of transformer (cosφ=0,95ind) by formula:

$$S_{teret_i} = S_{IZVOD} \cdot \frac{S_{n_i}}{\sum_{i=1}^{N} S_{n_i}} \cdot f_g = f_{NKO} \cdot S_{n_i}$$

S_{teret_i} - calculated consumption of substation i; S_{IZVOD} - calculated reduced line consumption; S_{n_i} - rated power of transformer of individual substation; N - number of substations in line; f_g - loss factor, f_{NKO} - correction factor of equivalent consumption curve. Loss factor takes into account losses in lines and transformers depending on network configuration and voltage conditions in the network. The losses are calculated by iteration procedure used in the network analysis software.

Applied linear distribution of consumption along the line brings the unknown, but significant level of inaccuracy. However, this method is currently the only method available considering the available consumption data.

Models of major network users

Major network users are modelled individually. Major network users are: MV consumer or DG, and LV DG or group of LV DGs causing the power flow to turn upwards on MV/LV substation.

Major consumer is modelled by its extremes: zero consumption in analysis of minimal consumption and by connected power in maximum consumption analysis (table 2). The reason for this approach is possible binary (on/off) extreme status of consumer and the fact that Croatian DSO is obliged to enable each network user to use network within the connection power. Real life problems have shown this must be taken into account.

Power factor of 35 kV consumers are modelled by individually metered data, the others by cosφ=0,95ind.

Power plant (DG) model

DG's minimal production is modelled by 0 kW delivery to network and by simultaneous maximal DG's self-consumption (connecting power of DG as consumer with cosφ=0,95 ind). Maximal DG's production is modelled by connecting power (P) of DG as producer with extreme allowed $\cos\varphi_{ind}$ and by simultaneous minimal DG's consumption (0 kW).

In current situation, regulations [1], [2], [3] and [6] force DSO to provide favourable conditions in network regardless of DG operation, while DG has no regulation obligations at all. DSO's only available option is to narrow the DG's power factor range in order to reduce DG's contribution to voltage rise in network.

Prosumer is modelled as DG. Prosumer's consumption connecting power is modelled as DG's self consumption.

Table 2: Network user models in minimum and in maximum consumption network analysis

Model label	Network user		Network user modelling			
			Case of maximum consumption	Case of maximum production during minimum consumption		
				The mildest case	The most rigorous case	Alleviation of the most rigorous case (*)
ZK	Major consumer		connected power	0 kW		
E	DG	production	0 kW	connected power, cosφ=1	connected power, PEES-conditioned most ind cosφ;	As the most rigorous case
		self-consumption	connected power	0 kW	0 kW	
E^+	New DG (study subject)		as model E	as model E	connected power, legitimate most ind cosφ	connected power, reduced range of *cosφ* (less ind)
					0 kW	0 kW

(*) additional model - if necessary to narrow the *cosφ* range to avoid network upgrade due to too high voltages in network

POWER TRANSFORMER MODEL

Model of power transformer with AVR

All transformers HV/MV and some MV/MV have automatic voltage regulation (AVR). The tolerance band (TB) is modelled by ±1,5%Un. The tap changer is modelled with 21 position, and step of 1,5% (±10x1,5%). Voltage on regulated side is usually fixed on regulated value. Optionally, load dependent modification of the set point, as well as Z-compensation may be modelled.

TB is modelled to make worse the worst case scenario. In network scenarios having lowest voltage (max. consumption), voltage is modelled 1,5% lower than set value on the secondary. In minimum consumption scenario, the secondary voltage is modelled by TB (1,5%Un) higher than the set voltage value. Modelling wider TB, to take into account the error of voltage transformers, is out of the question because this parameter directly affects the possibility of connection (increases connection fee). Any widening of TB may be interpreted as imposing unnecessary costs of connection.

Model of MV/MV power transformer without AVR

Transformer with manual voltage regulation (±2x2,5%) is modelled with the existing tap changer position (determined by the needs of connected consumers in the network). Any change of tap changer position is sensitive issue and should be very critically reviewed.

Model of MV/LV power transformer

For most transformers rated secondary voltage is 0,4 kV (older types), for the newer types is 0,42 kV.

In *zero state network* and *initial network* secondary rated voltage is modelled according to real data, if available.

In *future network* and *initiall+newDG network*, secondary voltage is modelled to anticipate worst case scenario:

a) in maximum consumption scenario (low voltages in network): real data, if available; otherwise 0,40 kV,
b) in minimum consumption (high voltages): 0,42 kV, (eventually all transformers will be replaced by new type)

If real data is not available, in scenarios needing real data, secondary rated voltage is always modelled by 0,40 kV.

Transformers MV/LV have manual voltage regulation (±2x2,5%) modelled by tap changer in middle position, or in real position if real data is available (usually is not).
If the analysis with the rated secondary 0.42 kV shows too high voltages in network, tap changer may be modelled in position -2.5%Un (reducing secondary voltage). This is a risky decision, because of permitted 3%Un of relative voltage increase caused by LV DGs. By this decision transformer has no sufficient regulation capability to remediate the permitted +3%Un increase - by the last available tap changer position (Δu=2,5% Un). The special problem is if primary voltage is already high (110%Un) due to the existing DGs. By this decision DSO loses the last remaining margin of safety.

THE PHENOMENON OF VOLTAGE CONGESTION OF RADIAL NETWORK

Unlike the term "congestion" in transmission network, which indicates current overload, in distribution network term "congestion" indicates voltage problem (Figure 1).
In voltage congested network during normal operation voltage reaches both prescribed limit values (110%Un and 90%Un) [3], in the network with no any remaining upgrade or reinforcements option.

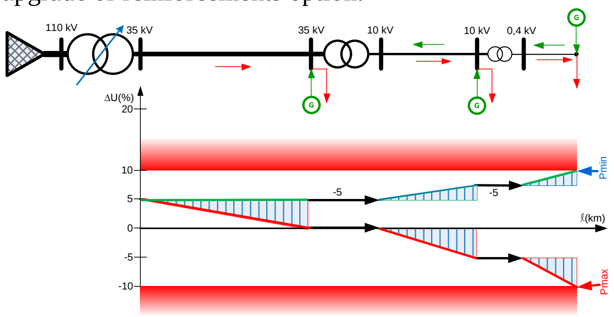

Figure 1: Voltage congestion of radial network

Congested network is "frozen" network [7] – any network extension resulting in increased network impedance is prohibited. Any reduction of minimal consumption raises the network voltage above the upper limit (110%Un) thus endangering normal operation of network and its users. Any consumption increase during the simultaneous DG outage (e.g. outage due to the isolated operation during the auto reclosure procedure in the network) lowers the voltage below the lower limit (90% Un), thus endangering the network use and disabling DG's reconnection to network. Still DSO has to take the full responsibility for the network operation outside the voltage limits.

METHODS OF REDUCING THE IDENTIFIED RISKS AND RISK SHARING METHODS

DSO should persist in eliminating the identified risk carriers. DSO should implement a load metering in every MV/LV substation, create united system of DG production monitoring implemented in DSO's SCADA, install modern metering equipment (including adequate voltage metering transformers), insist on creating complete national power network model and associated system of regular updates. DSO should issue regulations to define perceived ambiguities in existing regulations, to set up a framework for technological improvements (to encourage and direct improvements) and regulate the division of responsibilities for the normal network operation among DSO and network users.
The legislator should issue a provision to suspend further production of "eternally valid PEES" and criteria for repeal existing "eternally valid PEES" if prescribed validity (2+2 years) had expired. This action will unlock huge network resources blocked by "eternal PEES" issued for DGs that will never be built, although their construction formally started long ago.
The national energy regulator should support the DSO in defining technically substantiated margin of safety (e.g. cumulative max. influence to network voltage up to 3%Un on LV and 2%Un on MV), and start considering network user's complaints in constructive technical manner. The regulator should issue a tariff system granting important influence of connecting power to electricity costs. This will encourage network users to renounce the excessive (no longer needed) portion of connection power, causing further release of network resources.
DG should take responsibility for the possible unavailability of its production and for undelivered energy. DG should assume the liability for voltage regulation. DSO must get the authority to reduce the DG's active power delivery if needed. By this action DSO will be able to regulate the voltage in the network in the absence of voltage control by the DG.

CONCLUSION

In process of determining the optimal technical solution of DG connection, DSO faces numerous risks: nontechnical issues ("eternally valid PEES"), outdated metering concept and equipment, outdated data acquisition, uncoordinated data processing, new way of reasoning (load vs consumption) and new technical issues introduced by DG integration (voltage congestion of radial network).
Successfully connected DGs prove that DSO produces quality EOTRPs with correct conclusions despite the numerous risks. However, with an increased share of DGs in the network risks escalate. This might endanger the normal system operation, the normal network use and might prevent connection of new users. The DSO solely takes over associated risks (technical, financial and legal).
The solution is: the appropriate risk sharing, division of responsibility and the implementation of necessary measures by all involved parties: DSO, legislator, national energy regulator and network users.

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