ACTIVE POWER CURTAILMENT FOR MV NETWORK OPERATIONAL PLANNING IN AN INDUSTRIAL ENVIRONMENT

Mathilde HASQUENOPH
EDF R&D - France
mathilde.hasquenoph@edf.fr

Soufien HOURRIG
EDF R&D - France
soufien.hourrig@edf.fr

Olivier CARRÉ
Enedis - France
olivier.carre@enedis.fr

ABSTRACT

The massive integration of Distributed Energy Resources on the MV network not only triggers bidirectional power flow but also increases variability. To be able to better anticipate their impact on the grid as well as tackle the constraints induced, new network management tools are needed. This paper presents an algorithm for MV production active power curtailment, along with the contractual context set by the French DSO, Enedis. This new tool is integrated within Enedis' industrial environment for operational planning purposes.

INTRODUCTION

The growing number of Distributed Energy Resources (DER) connected to the MV network is inducing significant changes. While the grid was initially designed for downstream energy flow from conventional Generation Plants to end users, bidirectional power flow is now experienced as a result of DER integration. Moreover, the fluctuating nature of renewable energy sources (wind, solar) involves an increased variability on the MV network. Therefore, new network management tools need to be developed to better anticipate the impact of DER on the grid and be able to overcome the potential constraints triggered, such as high voltages or reverse power flows in lines and/or transformers. In this context, EDF R&D has designed and developed a new tool for MV production active power curtailment in operational planning, which is integrated into Enedis' operational Distribution Management System (DMS). This tool is exclusively focused on the MV network management.

GLOBAL ARCHITECTURE OF THE NEW NETWORK MANAGEMENT TOOL

Figure 1 sketches the global architecture of the tool developed, which is used in an **operational planning process**.

From the Distribution Control Center (DCC), an operator launches a calculation to analyse the network on a given period (e.g the coming day): based on load and production forecasts and on the current network topology, a Load Flow calculation is performed to detect potentially coming constraints (1). If constraints are detected, the MV production curtailment algorithm (2) is launched to **calculate the active power limits of each relevant MV producer in order to solve the predicted constraints while maximising the energy delivery**. This calculation enables the network operator to **anticipate** the time slots when a limitation will be needed. The set point values, however, will be re-evaluated closer to real time (3) based on the most up-to-date forecasts and topology, to improve accuracy.

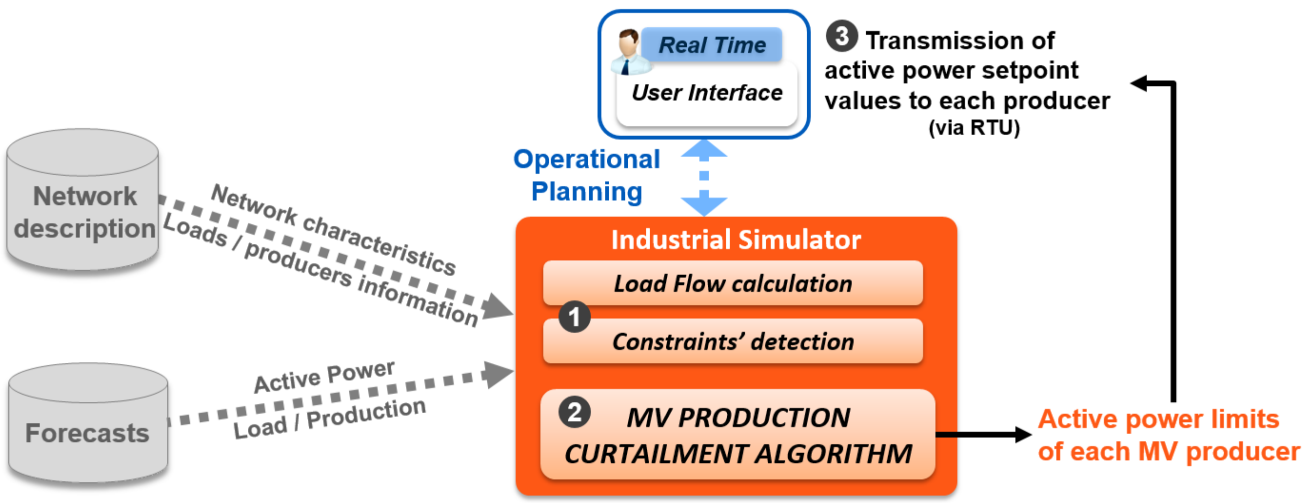

Figure 1: Global architecture of the active power limitation tool

This paper describes each step of this process, from the constraints' detection in operational planning to the real time commands sent to producers. After introducing the contractual rules and hypothesis, the MV production curtailment algorithm is explained more thoroughly.

CONSTRAINTS' DETECTION

Different types of technical constraints can occur on the grid, as a result of a local imbalance between load and production. The constraints addressed by the tool are the followings:

- Power overflow in HV/MV transformers:
$$S_i > S_{\max i}$$
- Current overflow in MV lines and cables:
$$I_i > I_{\max i}$$
- MV voltage out of contractual boundaries:
$$U_i > U_{max\ i}$$

S_i	*Apparent power in HV/MV transformer i*
$S_{max\ i}$	*Maximum apparent power in transformer i*
I_i	*Current in line i*
$I_{max\ i}$	*Maximum current in line i*
U_i	*Voltage at bus i*
$U_{max\ i}$	*Maximum voltage allowed at bus i to comply with contractual requirements*

Enedis' operational Distribution Management System encompasses a **constraints' detection tool**, developed by EDF R&D. Using load and production forecasts and network description data (topology, lines and transformers, capacitor banks, loads and producers' characteristics …), a Load Flow calculation is performed in order to determine the power flows in each line and transformer and the voltage at each MV bus. Constraints are detected based on those results and displayed on the operator's interface.
NB: forecast's errors are not taken into account in this process. Load and production forecasts are taken as determinist.

Due to a local excess of production compared to consumption, **reverse power flows and high voltages can appear: with the rapid development of DER, those types of constraints will be observed more and more often on the grid**. The advanced function for MV production curtailment, based on the opportunity to send active power limits to MV producers, aims at addressing this issue.

ACTIVE POWER LIMITATION

Contractual rules and hypothesis

To facilitate the integration of DER, Enedis intends to launch a **new type of contract for the connection of MV producers to the network**. The objective of this new connection offer, called "*Alternative Technical Solution*" (ATS, as opposed to the *Reference Technical Solution*, RTS) is to **reduce the global *societal supported costs* related to DER integration while increasing their energy delivery** (cf. [1], [2]). On one hand, the DSO reduces the DER connection costs and delays while on the other, the producer accepts a contractual power curtailment. This contract thus provides more flexibility for the network operation.

The conditions of the **ATS apply to producers connected through a "usual network topology"** stated in their contract. The "usual network topology" (UNT) refers to both the feeder to which the producer is usually connected **and** the HV/MV transformer through which this feeder is usually supplied. If constraints appear in this topology, the DSO is entitled to ask producers connected under an ATS to reduce their production under a given active power limit. This limit is calculated by the tool developed by EDF R&D, which principles are explained below, in order to **solve the predicted constraints while maximising the production**.

When a producer is not connected through its usual network topology, e.g. as a result of a reconfiguration due to works undertaken on the network, two different cases are distinguished:

- The producer is not connected to its usual feeder: for the time being, the producer is not allowed to inject in that situation and is thus considered disconnected;
- The producer is connected to its usual feeder, but this feeder is supplied via a different HV/MV transformer than its usual one: the producer is allowed to inject but will be curtailed first if constraints appear. This applies to **all** MV producers, regardless of their connection contract (RTS or ATS).

Moreover, the algorithm currently **does not take into account a guaranteed level of power injection**: if needed, producers can be asked a full curtailment of their forecast production.

Main principles of the algorithm

The algorithm aims at calculating the active power limits to be sent to MV producers on a given time period in order to solve constraints predicted on the network (reverse power flow in lines or transformers, high voltages) while maximising their energy delivery.

Calculation on a time period

To address constraints on a given time period, the algorithm handles each of its constituent time steps independently, in the chronologic order. On each time step, an active power limit is calculated for each MV producer in order to solve the predicted constraints. A post-treatment is performed at the end of the calculation to handle the case of producers who do not have a Remote Terminal Unit (RTU) installed, in order to minimise the number of different set points to be sent (cf. Figure 2).

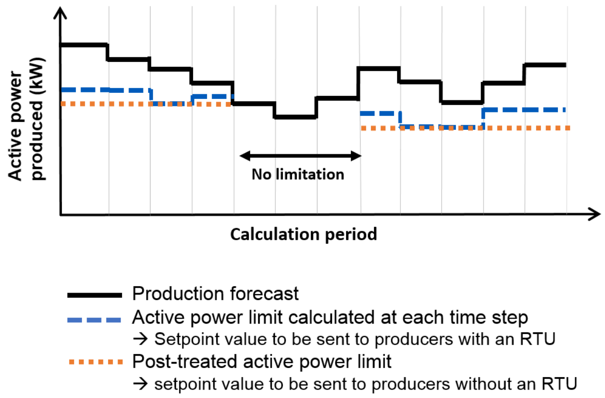

Figure 2: Results' overview on a calculation period

Handling several constraints at a given time step
When several constraints are anticipated on the same time step, they are ranked and addressed one after another, based on the number of producers responsible for each constraint.
The producers responsible for a constraint are:

- For a constraint in a line or a transformer: producers located **downstream** from the constraint.
- For a voltage constraint: all producers connected to the **feeder** on which the voltage constraint is observed.

Figure 3 shows an example of the constraints' processing order. The three different constraints detected are ranked in the following order:

1. Reverse flow constraint in line (a): 2 producers located downstream.
2. Voltage constraint on bus (b)'s feeder: 3 producers located on that feeder.
3. Reverse flow constraint in HV/MV transformer (c): 4 producers located downstream.

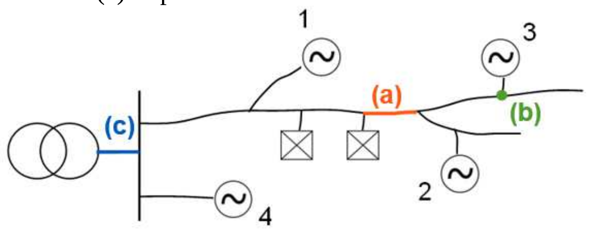

Figure 3: Constraints' processing order

This processing order, combined with the "allocation rule" (see page 4) between producers, ensures that **a producer is all the more limited that it is responsible for more constraints.**

Limitation rules to solve a given constraint at a given time step
The limitation of each MV producer responsible for the constraint depends on:

- The network topology (UNT or not)
- The producer's contract (ATS or RTS)

To solve a given constraint, **producers responsible for it are limited in the following order** (see page 4 for details regarding active power limits calculation):

1. Producers not currently connected via their usual network topology, regardless of their connection contract.
2. Producers benefitting from an ATS and currently connected via their UNT.
3. Producers with a regular contract (RTS) and currently connected via their UNT.
   NB: the limitation of those producers should never be needed, due to the network's planning rules.

Reminder: producers connected to a different feeder than their usual one are considered disconnected.

Figure 4 illustrates the limitation rules.
In the usual network situation, transformer nr.1 (resp. 2) supplies four (resp. three) feeders, with five (resp. three) MV producers located downstream. Half of those producers (nr. 1, 2, 4 and 7) benefit from an ATS.
In this example, as a result of works undertaken on transformer nr.2, all the feeders normally connected behind this transformer are transferred on transformer nr.1 which triggers a reverse flow constraint. To solve this constraint, the MV production curtailment module is launched.
NB: although the network is not in its usual topology, all producers are connected to their usual feeder and are consequently allowed to inject power on the grid.

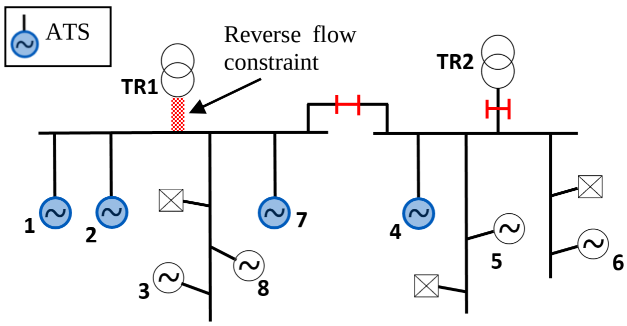

Figure 4: Limitation rules to solve a constraint – Example

The calculation takes place in the following order:

1. Producers 4, 5 and 6 are not connected behind their usual transformer: they are limited first (regardless of their connection contract).
2. If the limitation of this first set of producers does not solve the constraint, producers connected with an ATS and currently in their usual topology (1, 2 and 7) are curtailed.
3. If the limitation of both first and second sets of producers is not enough to solve the constraint, producers 3 and 8 are curtailed as well.

In the following, this order will be referred to as **three different "limitation levels".**

Active power limits calculation

At each limitation level, the limits of the relevant set of producers are calculated in order to solve the considered constraint on the considered time step t. This limit is noted $P_{\lim\ k,t}$ for each producer k.

Producers are limited proportionally to their forecast production level, or, if a producer has already been limited to solve a constraint handled before on time step t, proportionally to the previously calculated active power limit. This is called the "**allocation rule**".

$P_{\lim}(k,t)$ refers to the limit of producer k on time step t to solve **all** predicted constraints. This value is initialised with the production forecast and built up gradually as and when constraints are treated. When handling constraint i, $P_{\lim}(k,t)$ is such that all constraints treated previously are solved.

At each limitation level, the calculation mainly encompasses three steps:

1. Calculate the maximum production level $P_{\lim TOT,t}$ of all N relevant producers that can be taken in so that the considered constraint is solved:

$$P_{\lim TOT,t} = \sum_{k=1}^{N} P_{\lim k,t}$$

   For all types of constraints, the calculation of $P_{\lim TOT,t}$ is based on a Load Flow calculation performed in a "consumption only" situation. The input of producers who do not have to be limited at this stage is also accounted for: it corresponds to their production forecast **or** to their previously calculated power limit where appropriate.

   The calculation differs for a reverse flow constraint and for a high voltage constraint (see equations **(1)** and **(2)**).

2. Spread this global limitation on the N relevant producers, based on the aforementioned allocation rule :

$$P_{\lim k,t} = \frac{P_{lim}(k,t)}{\sum_{j=1}^{N} P_{lim}(j,t)} . P_{\lim TOT,t}$$

3. Update $P_{\lim}(k,t)$:
   - if $P_{\lim k,t} < P_{\lim}(k,t)$, $P_{\lim}(k,t)$ is replaced by $P_{\lim k,t}$.
   - otherwise, $P_{\lim}(k,t)$ remains unchanged.

Reverse flow constraint

In the case of a constraint in a line or a transformer, $P_{\lim TOT,t}$ is such that the maximum apparent power $S_{\max i}$ in the line or transformer is never exceeded:

- Line i: $S_{\max i} = \sqrt{3} * I_{\max i} * U_{N\ i\ upstr.\ bus}$
- Transformer i: $S_{\max i} = S_{nom\ i}$

The data needed are gathered in Table 1.

Table 1: Data needed in the case of a reverse flow constraint

$U_{Ni\ upstr.\ bus}$	kV	*Nominal voltage at line i's upstream connection bus*
$S_{nom\ i}$	kVA	*Nominal apparent power in transformer i*
$P_{cons,t}$ (resp. $Q_{cons,t}$)	kW (resp. kVAR)	*Total active (resp. reactive) power in line or transformer i* ***due to consumption only***
$P_{fixed\ prod,t}$ (resp. $Q_{fixed\ prod,t}$)	kW (resp. kVAR)	*Total active (resp. reactive) power injected by producers who do not have to be limited at that stage*
φ_k		*Angle difference between current and voltage for producer k*

$P_{\lim TOT,t}$ is the result of the second degree equation:

$$\begin{aligned} & \boldsymbol{P_{\lim TOT,t}}^2 * (1+\alpha^2) \\ & -2 * \boldsymbol{P_{\lim TOT,t}} * \left(\boldsymbol{P_{cons,t}} - \boldsymbol{P_{fixed\ prod,t}} + \boldsymbol{\alpha} * (\boldsymbol{Q_{cons,t}} - \boldsymbol{Q_{fixed\ prod,t}})\right) \\ & + (\boldsymbol{P_{cons,t}} - \boldsymbol{P_{fixed\ prod,t}})^2 \\ & + (\boldsymbol{Q_{cons,t}} - \boldsymbol{Q_{fixed\ prod,t}})^2 - \boldsymbol{S_{max,i}}^2 = \mathbf{0} \end{aligned} \qquad \mathbf{(1)}$$

Where:

$$\alpha = \frac{\sum_{k=1}^{N} P_{lim}(k,t) * tan\varphi_k}{\sum_{j=1}^{N} P_{lim}(j,t)}$$

High voltage constraint

For voltage constraints, an approximate formula is used to link a power variation to a voltage variation.

The voltage variation ΔU_n at bus n depends on the power injected and consumed along its feeder and on the lines' characteristics:

$$\Delta U_n(pu) = \frac{U_{Nn}}{U_{MV\ BB}} \sum_{k=1}^{N_{prod}} (r_{nk} + x_{nk} \tan\varphi_k) . \frac{P_k}{S_{base}} - \frac{U_{Nn}}{U_{MV\ BB}} \sum_{k=1}^{N_{cons}} (r_{nk} + x_{nk} \tan\varphi_k) . \frac{P_k}{S_{base}}$$

All values are in per unit (pu):

$$U_n(pu) = \frac{U_n(kV)}{U_{Nn}(kV)} \qquad \Delta U_n(pu) = U_n(pu) - U_{MV\ BB}(pu)$$

$P_{\lim TOT,t}$ is such that the voltage at any MV bus on the considered feeder complies with the contractual requirements:

$$\forall\ bus\ n,\ \ U_n(pu) < U_{max\ n}(pu) = U_{C\ n}(pu) + \varepsilon_{U_c-max}$$

The data needed are gathered in Table 2.

Table 2: Data needed to solve a voltage constraint

$U_{MV\ BB}$	kV	*Voltage at the MV busbar*
U_{Nn}	kV	*Nominal voltage at bus n*
$U_{n\ cons,\ t}$	kV	*Voltage at bus n* ***due to consumption only***
$U_{c\ n}$	kV	*Contractual voltage at bus n*
ε_{U_c-max}		*Maximum authorised difference to contractual voltage (default value for MV networks: 5%)*
r_{ij} (resp. x_{ij})	pu	*Total resistance (resp. reactance) of the lines common to routes {MV busbar to bus i} and {MV busbar to bus j}*
P_k	MW	*Active power of producer or consumer k*
N_{prod}		*Number of producers on the feeder*
N_{cons}		*Number of consumers on the feeder*
S_{base}	MVA	*"Base" apparent power (for per unit calculation)*

To ensure that high voltage constraints are solved all along the feeder, a calculation is performed at each production node of the feeder: $P_{limTOT,t}{}^{n}$ corresponds to the total production allowed on the feeder so that no constraint appears at bus n.
$P_{limTOT,t}$ is then set to the minimum value calculated :

$$P_{lim\,TOT,t}{}^{n} = S_{base} * \frac{\sum_{j=1}^{N_{lim}} P_{lim}(j,t)}{\sum_{k=1}^{N_{lim}} (r_{nk} + x_{nk}\tan\varphi_k) * P_{lim}(k,t)} * \left[U_{MV\,BB}(pu) * \left(U_{max\,n}(pu) - U_{MV\,BB}(pu) - \Delta U_{n\,cons,t}(pu) \right) - \sum_{k=1}^{N_{fixed}} (r_{nk} + x_{nk}\tan\varphi_k) . \frac{P_{lim}(k,t)}{S_{base}} \right] \quad (2)$$

$$P_{lim\,TOT,t} = \min_{n} P_{lim\,TOT,t}{}^{n}$$

N_{lim}	*Number of producers to limit*
N_{fixed}	*Number of "fixed" producers (producers who do not have to be limited at this stage)*

FROM THE OPERATIONAL PLANNING TO THE REAL TIME

The calculation performed in operational planning (e.g. for the day ahead) enables the DSO to anticipate the time slots when a limitation will be needed, and thus inform MV producers that they may be curtailed. However, **the set point values are not sent to producers at this stage: a new calculation will be performed closer to real time** in order to reassess the need for a production limitation, and, if this need is confirmed, re-evaluate the set point values based on the most up-to-date forecasts as well as network topology.

In order to do this, the tool memorises the start time of the next anticipated limitation period and automatically launches a constraints' detection near real-time. If the limitation is still needed, new set point values are calculated and sent to producers. The end time of the limitation period is memorised and a new calculation is launched close before this time, to determine if the limitation can be released or if the limitation period has to be extended.

NB: When a new calculation is launched, currently ongoing limitations are taken into account for constraints' detection as well as set point values calculation.

The tool thus always records as automatic launch times:

- The start time of the next anticipated limitation period.
- End times of all ongoing limitation periods.

CONCLUSION AND PERSPECTIVES

This article describes the main principles for MV production curtailment in operational planning.
The tool developed by EDF R&D is integrated into Enedis' operational Distribution Management System (DMS) to be used in a fully automated process, from the day-ahead constraints prediction and producers' limitation calculation until the real time commands sent to producers.

An experiment will take place in 2017 on a real MV network within the *Smart Grid Vendée* demonstrator project. This experiment will allow the DSO to field test the tool and assess its suitability to solve constraints on the MV network. The feedback will also help better size future connection offers, by highlighting potential improvements, especially regarding contractual rules.

Further work to be carried out involves taking into account a contractual reserve, allowing curtailment up to a maximum level per producer, as well as a guaranteed power to secure a minimum authorised injection for each producer. The tool could also be used in other contexts, for example as part of works preparation.
Moreover, while currently focused on the MV network, this work paves the way for the development of LV network management tools. More and more production means, such as PV panels, are indeed being connected to the LV network, bringing out new opportunities which are already being investigated in several studies and demonstrator projects.

REFERENCES

[1] F. Beauné, O. Carré, S. Levaufre, L. Karsenti, 2015, "New solutions for a better distributed generation integration to MV and LV networks", *Proceedings CIRED Workshop Helsinki 2016, paper 0369.*

[2] M.-A. Lafittau, G. Pelton, F. Gorgette, O. Carré, "New options for connecting generation on distribution networks and required network control preparation", *Proceedings CIRED Conference Lyon 2015, paper 0746.*

[3] A. Pagnetti, J. Fournel, C. Santander, A. Minaud, "A comparison of different curtailment strategies for distributed generation", *Proceedings CIRED Conference Lyon 2015, paper 1026.*