DETERMINATION AND ORIGINS OF REACTIVE POWER FLOWS IN HV/MV SUBSTATIONS

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ABSTRACT

This paper analyses the evolution of reactive power flows at the interface of French transmission and distribution systems. The influence of the insertion of distributed generation (DG), the replacement of medium voltage (MV) overhead lines by underground cables as well as the evolution of the reactive part of the load are investigated. Numerical simulations are performed with a real French HV/MV substation for illustrative purpose. The technical consequences of such evolutions are investigated, e.g. the saturation of On Load Tap Changers (OLTC). The use of DGs connected to the MV network to regulate reactive power exchange between Transmission System Operator (TSO) and Distribution System Operator (DSO) is also discussed.

INTRODUCTION

The reactive power flows at the interface of French transmission and distribution networks are evolving. Several reasons can explain such a change: the replacement of MV overhead lines by underground cables, the insertion of DG and the evolution of the reactive part of the load connected to MV and LV networks. As a result, reactive power flowing from distribution network towards transmission networks can be observed in several HV/MV substations.

As a consequence, local voltage increases are likely to occur on MV and HV networks as well as difficulties to manage reactive power flows with existing equipment for both Transmission System Operator (TSO) and Distribution System Operator (DSO). On Load Tap Changers (OLTC) used in HV/MV substations are more likely to reach their technical limits. Moreover, this trend can also be an issue in the new European Grid Code development framework. According to the existing draft on Demand and Connection [1], new requirements could be imposed for new HV/MV substations when active power consumption is below 25% of the substation maximum import capacity, no reactive power should be exported to transmission networks. Analyzing the evolution of reactive power flows within distribution networks and its consequences are thus very useful for DSO. Especially with the stressed conditions of transmission systems that lead to consider the potential use of distribution systems to support transmission voltage control and reactive power management [2]–[5].

This article focuses on determining the maximum and minimum reactive power flows in a given substation. By analyzing its origins, the paper presents the evolution of these reactive power flows with the new developments of distribution networks. A real semi-urban HV/MV substation has been considered for illustrative purpose. Practical consequences e.g. saturations of OLTC are illustrated. Then, the use of DGs to regulate reactive power exchange is further discussed.

ORIGINS OF REACTIVE POWER FLOWS AT TSO – DSO INTERFACE

The reactive power flow seen by TSO at the Coupling Point (CP) comes from:

- Reactive power consumed by the load connected to the distribution network
- Reactive power losses in the distribution network feeders (overhead lines and underground cables)
- Reactive power losses in HV/MV and MV/LV transformers
- Reactive power from reactive power compensators connected to the distribution network
- Reactive power absorbed or produced by distributed generators.

The decomposition of reactive power according to the several aforementioned sources at the interface between TSO and DSO is therefore not straightforward to evaluate. Indeed, reactive power losses in transformers and feeders are highly dependent on load and production conditions.

As a consequence, a precise evaluation of reactive power capacity of a given substation should be performed by simulations, considering several operating points.

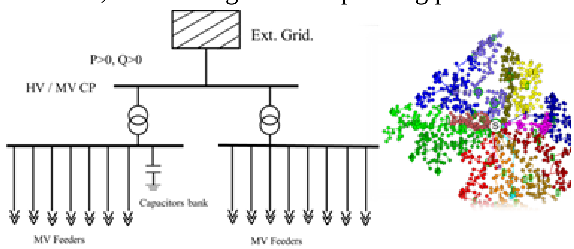


Figure 1 : Schematics of the HV/MV substation

The semi-urban substation considered for illustrative purpose is described in Figure 1 and Table I. This is a 90/20 kV substation. Three DGs are connected to this network; one is connected on a so called “dedicated feeder" (i.e. with only production) which is connected to the MV busbar of transformer 1 and two are connected to a so called "mixed feeder" (with both production and consumption) which is connected to the MV busbar of transformer 2.

Table I : substation characteristics

MV Feeders	15
Max active load	44 MW
Max reactive load	17,68 MVAR
Max active production	17,20 MW : - 12 MW (dedicated feeder) - 4,8 MW (mixed feeder) - 2,4 MW (mixed feeder)
Load model	Constant Power (PC) + MV/LV transformer
HV/MV transformers	2x36 MVA – 90/20 kV

The presented results are obtained with simulations mainly based on load-flow calculation and performed with the software Powerfactory from Digsilent.

EVOLUTION OF REACTIVE POWER FLOWS AT CP

Description of case studies

Several cases have been conducted in order to assess the influence of each evolution. Table II describes those cases. The present network corresponds to case C.

Table II: Cases study

CASE	A	B	C
MV Underground cables	0 %	0 %	17 %
Total MV Generation (MW)	0	17,2	17,2
tan(φ) gen in mixed feeders	0	0	0
tan(φ) load (mean)	0,4	0,4	0,4
CASE	**D**	**E**	**F**
MV Underground cables	17 %	17 %	17 %
Total Generation (MW)	17,2	17,2	17,2
tan(φ) gen in mixed feeders	0	0,4	-0,35
tan(φ) load (mean)	0,2	0,4	0,4

Case B aims to illustrate the influence of distributed generation, case C the consequences of the replacement of MV overhead lines by MV underground cables, case D the evolution of the reactive part of the load. Case E and F investigate the influence of power factor in "mixed" feeders' DG. Two different power factors have been considered herein (-0.35 and +0.4), which corresponds to the current maximum French contractual limitations.
Several loading and generation conditions have also been assumed. See Table III below.
Reactive power compensators have not been considered here.

Table III : Tests conducted

tests	1	2	3	4	5
% load	100	75	50	25	100
% generation	100	100	100	100	0

Analysis of results

Figure 2 illustrates the total reactive power at the CP between TSO and DSO depending on various loading conditions and for each aforementioned case. It can be observed that reactive power flow at CP tends to diminish when load consumption decreases, and can be reversed at low loading conditions.

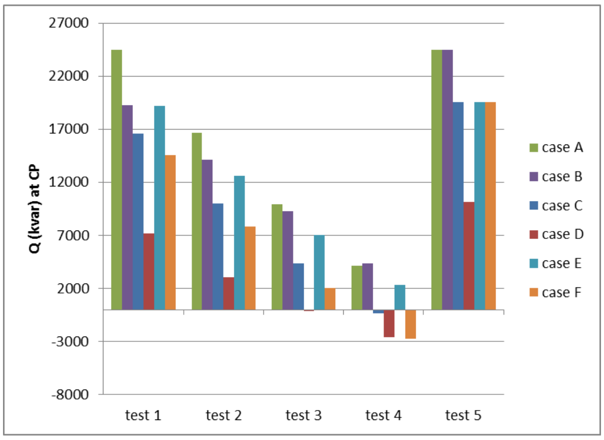


Figure 2: Reactive power at CP depending on loading and generation condition (see Table 2)

Figure 3, Table IV and V propose a detailed analysis of reactive power origins for each case and for two particular situations: at maximum loading and no production, and at low loading condition (20%) with 100% production. These situations correspond to reference situations currently in use for studies. Table VII gives the detailed analysis of reactive power origins for 100 % production and 100 % consumption.

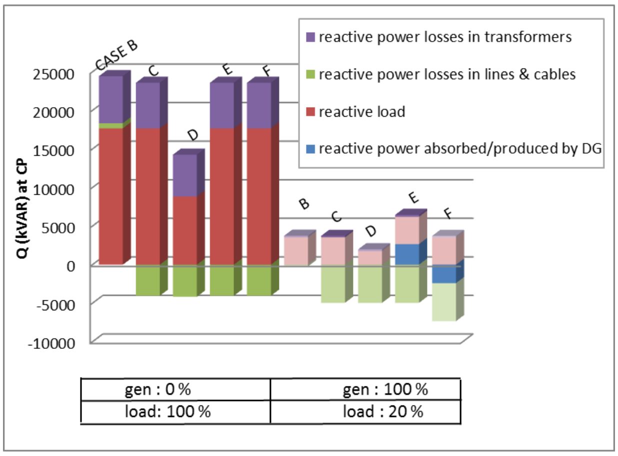


Figure 3: Origins of reactive power flows at CP

Table IV: Detailed origins of reactive power flows at CP at 100% loading and 0% production - in MVAR

CASE	B	C, E,F	D
Total at CP	**24,45**	**19,58**	**10,13**
Q absorbed / produced by DG	0,00	0,00	0,00
Reactive load	17,68	17,68	8,84
Q losses in MV OH lines & UG cables	0,68	-4,02	-4,15
Q losses in HV/ MV transformers	5,70	5,52	5,08
Q losses in MV/ LV transformers	0,39	0,40	0,35

Table V: Detailed origins of reactive power flows at CP at 20% loading and 100 % production - in MVAR

CASE	B	C	D	E	F
Total at CP	**3,53**	**-1,20**	**-2,96**	**1,52**	**-3,58**
Q absorbed / produced by DG	0,00	0,00	0,00	2,67	-2,38
Reactive load	3,54	3,54	1,77	3,54	3,54
Q losses in MV OH lines & UG cables	-0,22	-4,94	-4,94	-4,94	-4,93
Q losses in HV / MV transformers	0,199	0,186	0,206	0,235	0,183
Q losses in MV/ LV transformers	0,013	0,014	0,012	0,013	0,013

Table VI: Detailed origins of reactive power flows at CP at 100% loading and 100 % production - in MVAR

CASE	B	C	D	E	F
Total at CP	**21,73**	**16,61**	**7,18**	**19,21**	**14,53**
Q absorbed / produced by DG	0,00	0,00	0,00	2,67	-2,38
Reactive load	17,68	17,68	8,84	17,68	17,68
Q losses in MV OH lines & UG cables	0,91	-3,91	-4,03	-3,92	-3,87
Q losses in HV / MV transformers	2,755	2,44	1,98	2,38	2,71
Q losses in MV/ LV transformers	0,39	0,40	0,39	0,40	0,39

Several conclusions can be drawn:

- The evolution of the maximum reactive power flows in the substation is mainly linked to the replacement of overhead lines (see Figure 2 and Figure 3). 100 km of underground cables can produce up to 5 MVAR at low loading conditions. Depending on loading conditions, this contribution decreases the reactive power flows in substations and can even lead to reactive power flow from distribution network up to transmission network.
- The reactive losses in transformers are proportional to XI^2 and are significant at high loading, especially for HV/MV transformers. In our simulations, U_{cc} of HV/MV transformers is about 17 % and about 3% for MV/LV transformers. The insertion of DGs and underground cables can contribute to increase or decrease these reactive losses. See Table VII.
- The reactive part of the load may slowly diminish with new equipments (based on power electronics).
- If DG connected to "mixed" feeders (i.e. with both load and generation) have a non-zero power factor (tan(φ)) or a Q=f(U) characteristic to maintain MV voltage, the real-time reactive power flows in HV/MV substations would be more erratic and therefore, more unpredictable. Indeed, the reactive power depends on the active production of DG. Comparing case E and F, a significant difference of total reactive power at CP can be observed either in Figure 3 or in Table V, Table VI and Table VII.

CONSEQUENCES: SATURATION OF OLTC

Such evolutions of reactive power are leading to higher voltage conditions on both HV and MV networks and can be responsible for OLTC to reach their technical limits. In France, the number of alerts regarding saturation of OLTC at high voltage conditions has increased over the past few years. Indeed, OLTC have traditionally been designed to deal with high loading and corresponding low voltage situations.

The tap position can be estimated according to the following formula (in per unit):

$$tap = tap_{nom} + \frac{n_{trf} - 1}{\delta V_{tap}} \quad \textbf{(1)}$$

tap_{nom} represents the tap position at nominal condition usually 0, $\delta V_{tap}$the voltage variation induced by a tap change and n_{trf} the ratio of transformer given by :

$$n_{trf} = \frac{V_{HV}}{V_{OLTC\ HV}} \Big/ \frac{V_{MV}}{V_{OLTC\ MV}} \quad \textbf{(2)}$$

Where $V_{OLTC\ HV}$ $V_{OLTC\ MV}$ are the nominal transformer's voltages, V_{HV} the HV voltage and V_{MV} the MV busbar voltage setpoint.

Since the ratio X/R is usually high – about 35 for the HV/MV transformers considered herein– the resistance can be neglected and the reactance approximated in per unit by the short-circuit voltage U_{cc}. The transformer internal drop is related to reactive power flow Q, the short-circuit voltage U_{cc} and the transformer nominal power S_{nom}:

$$\frac{du}{u} = R_{pu}\frac{P}{S_{nom}} + X_{pu}\frac{Q}{S_{nom}} \approx U_{cc}\,\frac{Q}{S_{nom}} \quad (3)$$

Then, depending on the voltage and transformer parameters, the maximum reactive power that can flow from distribution network to transmission network can be derived:

$$Q_{max} = \frac{S_{nom}}{U_{cc}}\left(V_{MV\,ref} - \frac{V_{HV\,ref}\,V_{OLTC\,MV}}{n_{trf\,max}\,V_{OLTC\,HV}}\right) \quad (4)$$

The maximum ratio can be obtained with (1) and (2).
Figure 4 illustrates the maximal amount of reactive power flowing from MV to HV network before saturation of OLTC depending on the HV voltage and several parameters of transformer. These parameters are given in Table VII.

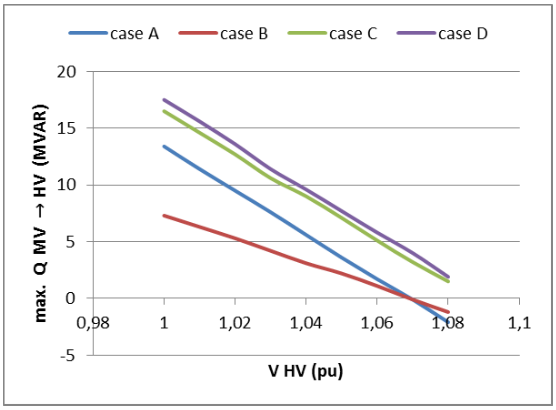


Figure 4 : Maximum reactive power from MV to HV networks before saturation of OLTC

Table VII : Detailed parameters of transformer

CASE	A	B	C	D
U_{cc} (%)	17	17	17	17
S_{nom} (MVA)	36	**20**	36	36
$V_{OLTC\,HV}$ / $V_{OLTC\,MV}$ (kV)	89/21	89/21	89/21	89/21
δV_{tap} (pu)	0.015	0.015	0.015	0.015
Number of tap	17	17	17	17
Amplitude (%)	12	12	**14**	12
$V_{MV\,ref}$ (pu)	1,02	1,02	1,02	**1,04**

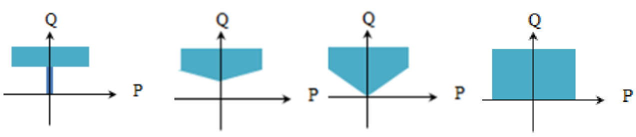
The worst situation occurs when HV voltage is at 1.08 (maximal contractual value) whereas the MV OLTC reference is low –typically 1.02 pu for French distribution network. These calculations have been validated in simulations and give an assessment of the potential risk of OLTC to saturate. This risk is higher when HV voltage rises. Other parameters have some minor influence such as the nominal power of the transformer or the amplitude of OLTC.

THEORITICAL INVESTIGATION OF THE USE OF DGS TO CONTRIBUTE TO REACTIVE POWER EXCHANGE CONTROL AT THE TSO/DSO INTERFACE

General concerns

Given the current trend of reactive power flows between TSO and DSO, there is a real need to investigate potential solutions to regulate these exchanges and insure safe operating conditions for both TSO and DSO. As previously explained, there will be new needs to contribute to handle high voltage conditions. Therefore, one can wonder what is the existing equipment connected to MV grids that can absorb reactive power at high voltage condition? In French distribution networks, there are no solutions based on power electronics or inductance. For the moment, only DGs may have the potential to absorb reactive power. In what extent distributed generation can modify the reactive power capacity of a given MV network? In some papers [2]–[5], the use of distribution networks to support transmission system regarding both voltage and reactive power control is considered. They argue that the large amount of DGs connected to MV network can provide such a service.

However, this solution must be carefully considered. First, this capacity depends on the general condition of the network and the operating point. Then, DGs may not have the capacity to absorb reactive power at any time. That raises the concern of reactive power availability: except for generators equipped with suitable and costly power electronics interface, the reactive power capacity and availability of DG depends on their active power operating point and their technology. Especially at low active power production, absorption/production of reactive power is often not technically feasible. Figure 5 presents the constructive reactive capacity that must be complied by DG according to French regulation (a), technical requirements of French DSO (b) and the ideal case (c). The capacity b) is the more realistic. To reach an ideal diagram, costly investments are needed.



a) French law b) French DSO requirement c) ideal

Figure 5: Schematic of P,Q diagram of DG connected to MV network

Then, the respect of distribution networks operational constraints (voltage, loading, protection…) must be insured. Even if the machines of the installation have the capacity to absorb/produce reactive power it may not be possible to use these reactive power capacities at any point in time as it could impact distribution network voltage profiles, OLTC technical limits, losses, etc…

DGs in dedicated feeders to avoid saturation of OLTC ?

Since feeders with only production (dedicated feeders) have less operational constraints than feeders with both production and consumption (mixed feeders), DGs connected to dedicated feeders could be used to regulate reactive power flows.

For illustrative purpose, let's assume that the network (case C of Table II) is at 20% loading. Generators in mixed feeders are not producing, and the DG in dedicated feeders is producing 5MW. Under these circumstances, if V_{HV} is set at 1.08 pu, and the reference for the OLTC 1 is 1.02 and 1.04 pu for OLTC 2, transformer1 reaches its limit: OLTC 1 is not able to maintain the voltage. However, if the dedicated feeder's DG is able to absorb 2.7 MVAR, it is sufficient to avoid the saturation of OLTC 1.

In Table VIII, the tap position of OLTC 1 as well as the reactive power flowing from MV to HV networks is given depending on the reactive power consumed by dedicated feeders. It can be observed that one tap of OLTC roughly corresponds to -2.7 MVAR.

Table VIII : reactive power at TSO - DSO CP and tap number of OLTC 1 depending on reactive power consumed by dedicated DG

$Q_{dedicated\ DG}$ (MVAR)	0	- 2,7	- 5,5
$Q_{MV \to HV}$ (MVAR)	+ 1.63	- 1,075	- 4,052
$tap_{\ OLTC\ 1}$	8 (max)	7	6

Moreover, it should be noted that this absorption of reactive power at high HV voltage condition could also be beneficial for TSO since it can help to limit voltage rise. However it should be born in mind that reactive power losses are highly nonlinear. As a consequence the efficiency of the contribution of reactive power from MV network to HV network will vary depending on the operating point.

Reactive capacity of a MV network considering dedicated DGs

To derive the reactive capacity of a network, we recommend using the method proposed in [3]: for a given operating point of the network (loading condition) and considering the limitations of the DG (maximum rated power, P, Q diagram…) the maximum amount of reactive power that can be absorbed by DG can be evaluated through simulations. This maximum amount must insure respect of technical constraints such as voltage limits, maximum voltage deviation, loading factor, maximal currents, losses... Taking into account all of these constraints, it is possible to derive the exact reactive capacity at CP.

At last, the impact on active losses should be considered to evaluate this possibility from both technical and economical points of view.

CONCLUSION

Current evolutions in distribution networks – mainly the insertion of DG, replacement of overhead lines by underground cables – contribute to change reactive power flows at the TSO - DSO interface. These flows are more difficult to estimate, but an overall reduction is to be expected with significant variations depending on the operating point of network (loading and production level).

These changes combined with high voltage profiles at HV side can lead to saturation of OLTC and have also consequences on higher levels of voltage. There is a need to set a common strategy between TSO and DSO.

The reactive power of the DGs connected in dedicated feeders constitutes a real way to regulate the reactive power flows between TSO and DSO and they can theoretically contribute to avoid saturation of OLTC in some cases.

However, DGs may not always have the technical capacity to do so, or even the possibility depending on operational constraints.

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