TECHNICAL AND ECONOMIC ASSESSMENT OF CENTRALISED VOLTAGE CONTROL FUNCTIONS IN PRESENCE OF DG IN THE FRENCH MV NETWORK

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ABSTRACT

To improve the integration of Distributed Generation (DG) in the French MV and LV networks, EDF R&D and ERDF have investigated different Voltage and VAr control approaches with the aim of developing and field testing the most appropriate solution in the near future. The new functions are based on a centralised and coordinated solution that could be included in ERDF's remote control system SIT-R.

This paper presents the different Volt and Var functions which have been studied: their implementation cost as well as their respective advantages and drawbacks are described. The final choice to be experimented is then justified.

INTRODUCTION

The penetration of wind power in the French electric system has increased from 350MW in 2005 to more than 4.5GW in 2010. A large share of these wind farms is connected to ERDF's (the French DNO) network at the Medium Voltage level. Some large Photovoltaic (PV) panels (4-5 MW) are also expected to be connected to the MV network in the near future. The number of LV connected PV panels (in the range of 3kVA to 250kVA) has increased over the past couple of years leading in some regions to voltage rise issues in the MV network.

Most of the large distributed generators (>7MW) are today directly connected to the HV/MV substations by dedicated feeders,. For smaller size distributed generators, a connection to existing feeders could be envisaged. However, such connections may lead to voltage rise issues in rural networks dominated by overhead lines and low consumption levels. Nowadays, network reinforcement is the sole orientation applied by ERDF to overcome voltage rise issues. However, this solution shows its limits (technically and financially) and the French DNO searches for more efficient and performing voltage control alternatives in view to increase the MV network hosting capacity as well as its monitoring efficiency

This paper describes the possible voltage control options that could be applied to the French MV network and their corresponding instrumentation requirements. Three different centralised and coordinated solutions have been investigated. Their advantages/drawbacks and their respective implementation costs are presented in this paper. The results discussed in the paper will drive the implementation choices of new DMS functions in ERDF's real-time distribution network control system.

DESCRIPTION OF EXISTING VOLTAGE AND VAR CONTROL FEATURES IN ERDF'S NETWORK

Existing voltage control equipment

A new centralised voltage control function must be based on both the available voltage setting devices in the distribution system and on an improved observability of the MV network. In ERDF's network, voltages must be kept within the range 20kV +/- 5% in the MV network and 400V +/- 10% in the LV network. To do so, HV/MV substations are equipped with automatic voltage controller which sets the on-load tap changer in a position which corresponds to the imposed voltage value at the MV busbar of the HV/MV substation. In some cases, a compound factor is used in order to take into account the loading of the HV/MV transformer: instead of controlling the voltage at the MV busbar, such scheme controls the voltage at a pre-defined pilot node in the MV network. However, the compound factor is being removed from automatic voltage controller due to the presence of Distributed Generation in the network.

MV/LV substations are equipped with off-load tap changer allowing for the fine tuning of the LV side according to the transformer location along the MV feeder.

Existing VAr control equipment

The VAr control function is designed for the control of MV capacitor banks located at the HV/MV substations. This local function (integrated in the HV/MV substation control system) has been developed in order to reduce the reactive power flow from the transmission network into the MV system. These capacitor banks are not used to directly control voltages in the distribution network. However, switching on or off capacitor banks influences the voltage amplitude at the MV busbar of the HV/MV substation. Moreover, the presence of DGs with reactive power control capabilities in the MV system could interfere with this existing VAr control.

When investigating new solutions to improve the existing hosting capacity through a better voltage control in presence of DG in the MV and LV networks, it is therefore essential to keep a coordination between the voltage control function and the reactive power compensation function.

INTEGRATING VOLT AND VAR FUNCTION IN THE EXISTING DMS ARCHITECTURE

ERDF's Distribution Management System is an open remote control architecture which has been developed in order to easily add new external real-time functions [1]. The architecture consists of a SCADA module, a software data bus and a data concentrator. The software data bus allows the algorithms of the automation functions to access the network's static and dynamic data. It makes the connection of new advanced functions modular.

Three functions are currently integrated in this architecture in order to reduce the overall outage time after the occurrence of a permanent fault in the MV network:

- The ESF (Event Synthesis function) which aims at reducing the number of events displayed in the logging function and at providing a diagnosis of the cause of main outages
- The FLF (Fault Location Function) which uses fault passage indicators to locate the fault.
- The NRF (Network Reconfiguration Function) which calculates a set of restoration plans in order to resupply as many customers as fast as possible.

Figure 1 describes how this existing architecture could be used to integrate new automation functions such as Distribution State Estimation (DSE) which results would feed in a Volt and VAr control function in order to better integrate DG in ERDF's MV and LV network.

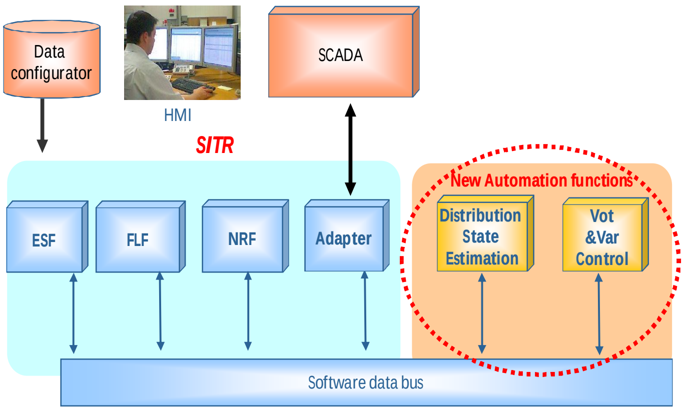

Figure 1 Integration of new functions in the existing DMS architecture

Three different centralised voltage control options have been studied for ERDF's network: they differ in the instrumentation required and in the control actions. They all use the results of a Distribution State Estimation function as input data (this DSE function is described in [2]). These three possible solutions are described in the next sections. Their respective algorithms have been modelled with Matlab in order to assess their functional performances and their economic impact for different network situations [3].

SOLUTION N°1: VOLTAGE CONTROL WITH ON LOAD TAP CHANGER

The first voltage control solution uses the assessment of voltage profiles along each MV feeder of a given HV/MV substation. The Distribution State Estimation function requires only between three to four MV voltage sensors (with an accuracy of 1%) along each MV feeder and a P/Q/V sensor at the HV/MV substation for each MV feeder and at DGs' connection nodes. Figure 2 depicts how the voltage estimation is improved with the number of sensors in the network. MV voltage sensors could therefore be installed at the existing remote controlled switches in order to share existing RTUs and telecommunication system (there is an average of 3 to 4 remote controlled switches in MV rural feeders).

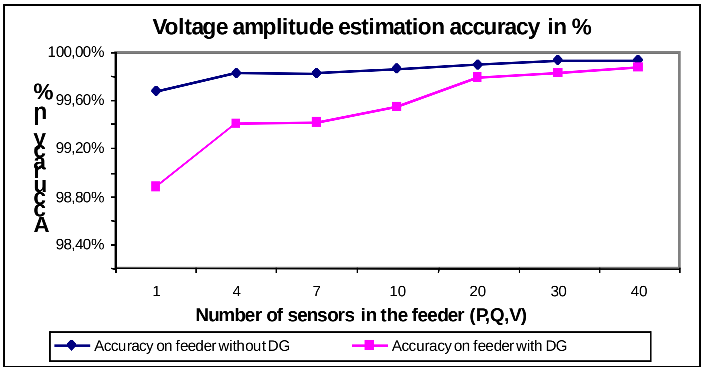

Figure 2 Impact of the number of voltage sensors on voltage amplitude estimation accuracy

This voltage amplitude assessment gives both the maximum voltage in the network (generally due to the connection of DG) and the lowest voltage in the network as described in Figure 3 by the dotted voltage profiles. The voltage control algorithm of solution 1 can then find the optimised voltage reference (V_{ref}) at the HV/MV busbar in order to keep all voltages within voltage limits as illustrated in Figure 3.

Such function can increase the MV network hosting capacity for DG technologies having a full output at times of low consumption: it could therefore be useful for large PV penetrations in regions with low load during daytime.

The required instrumentation for this solution leads to an implementation cost of 150k€ per HV/MV transformer with 10 MV feeders (this economic assessment is based on commercial solutions currently proposed by several manufacturers). This cost is made of:

- Sensors cost (purchase, installation, maintenance)
- Associated Telecom cost to retrieve data with the existing SCADA

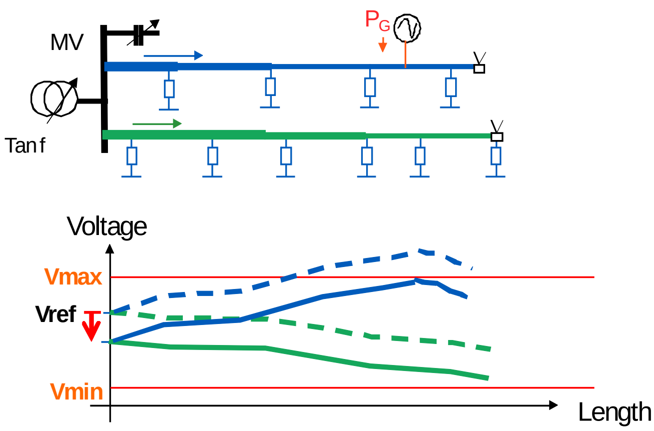

Figure 3 Illustration of solution 1

The simulations performed to evaluate the performances of this solution have demonstrated that it only very slightly makes more use of the on-load tap changer.

For VAr control at the HV/MV substation, existing capacitor banks can be used as well as the reactive power capabilities of large DGs connected through dedicated feeders to the primary substation, since they do not impact voltages on existing feeders.

SOLUTION N°2: VOLTAGE CONTROL WITH REACTIVE POWER OF DG AND ON LOAD TAP CHANGER

The second centralised solution investigated uses both the on-load tap changers and the reactive power capabilities of DGs connected to the MV network as control actions. The hosting capacity is therefore increased when compared with the performances of solution 1. It is important to note that such function is suitable for overhead lines as DG reactive power consumption is only a suitable control parameter in circuits with high X/R ratio. For underground networks, DG active power curtailment could be envisaged if not applied too often.

In order to be able to ask for a reactive power absorption of DGs at times of high voltages in the network, the algorithm of this second solution is based on load flow calculations for the two following reasons:

- Find the reactive power value of DGs that maintains voltages within limits through load flow trials
- Verify that currents are below the maximum permissible capacity values of cables and overhead lines

As load flow calculations use active and reactive power consumed/injected at each MV/LV substation as input data, this solution requires more instrumentation than for solution 1. On average three to four more sensors are required as P/Q sensors must be installed in the largest secondary substations: this solution leads to an implementation cost of 450-500k€ per HV/MV transformer with 10 MV feeders. A direct communication means must be installed between control centers and MV connected DGs in order to send them reactive power control values.

Some utilities choose local voltage control functions instead of centralized voltage control solutions: in this case, simple Q=f(U) or Q=f(P) functions are directly implemented in the control tools of MV connected DGs. It is advantageous in the sense that no communication and no instrumentation are required. However, for large penetrations of DGs, interactions between these regulations and interactions between them and existing volt and VAr control in HV/MV substations could occur. In such cases, the centralized solution 2 could avoid these interactions by setting a fixed reactive power contribution to each DG in a coordinated way.

For the VAr control with solution 2, one can use the existing capacitor banks, as well as the reactive power capabilities of all DGs connected to the MV network.

SOLUTION N°3: VOLT AND VAR CONTROL FUNCTION OPTIMISING NETWORK LOSSES

The third solution investigated is a Volt and VAr control function based on an optimal power flow [3]. The control parameters and the implementation costs are the same as those used in solution 2. The primary objective of the algorithm is to minimize network losses (Iron and Joule losses in HV/MV substations, in MV/LV transformers and Joule losses in MV feeders) while keeping MV feeders' voltages within mandatory limits. Therefore, instead of being run at times of high voltages in the network, this function would be run continuously in order to optimise losses at all time. The algorithm can also take into account the constraint on the reactive power flow at the HV/MV substation according to the TSO's requirements.

The corresponding algorithm must be able to deal with discrete variables (tap changers at the HV/MV substation and capacitor banks) and continuous variables (reactive power production/absorption for synchronous machines and DG with modern power electronics interfaces). To do so a Mixed Decoupled Optimization (MDO) for Volt/VAR control is used: it is based on the traditional Newton-Raphson power flow calculations, Semi Quadratic Programming optimization and branch and bound algorithms

The calculations performed with this algorithm led to a slightly reduction of losses compared to solution 2. In the case of a rural network with one HV/MV transformer and its MV feeders with a single photovoltaic DER connected to the existing MV network, the following total losses were computed per year:

Photovoltaic DER	Solution n°2	Solution n°3
3 MW	985 MWh	969 MWh

5 MW	1037 MWh	1022 MWh

However this reduction in network losses is obtained with a very frequent contribution of the on-load tap changer. Since the algorithm always tries to find a compromise between Joule losses and Iron losses in the network, the voltage reference is high at times of high loading in the network (in order to minimise Joule losses) and low at times of lower consumption in the network (in order to minimise Iron losses). Therefore, when integrating on load tap changers maintenance cost in the cost-benefit analysis, this function must be rejected as it would lead to high maintenance cost or increase HV/MV substation outages. Due to this fundamental reason, this function is not being further investigated.

COMPARISON BETWEEN SOLUTIONS 1 & 2

In order to be able to make a choice between the different solutions investigated in this paper, Table 1 summarises the main advantages and drawbacks of solutions 1 and 2.

Table 1: Advantages and drawbacks of solutions 1 and 2

	Solution 1	Solution 2
Implementation cost for an HV/MV transformer	150 k€	450-500k€
Advantages	1 Low instrumentation required 2 Minimum implementation and development risk 3 No interaction with the existing VAr control in the HV/MV substation	1 Better hosting capacity 2 Better network observability (could be used for other automation functions and for asset management)
Drawbacks	1 Limited hosting capacity 2 Decreasing the voltage reference could lead to low voltages in the network	1 Installation and maintenance of a high number of sensors 2 Possible interactions with the existing VAr control function 3 Contractual framework required with DGs 4 Applicable to networks with high X/R ratio

CONCLUSIONS AND PERSPECTIVES

In order to optimize the penetration of MV and LV connected DG to the French network, several voltage control and VAr control functions have been investigated. The purpose of the study was to compare technically and economically different centralized approaches in the existing DMS architecture. Amongst the three solutions presented and described in this paper, solution n°1 has been chosen by ERDF for a field experiment. This solution has been preferred for a first experiment for the following reasons:

- Less risky to implement
- Only few sensors are required
- Most appropriate solution with existing and future DG connection rules
- Could be associated with local voltage regulation (at each MV distributed generator)
- Can deal with the impact of LV connected DG on MV voltages

The industrialization of this function is now required: it implies first the development of the distribution state estimation function followed by the development of the voltage regulation function which will look for an optimized voltage reference at the MV busbar of the HV/MV substation. These functions will then be integrated into the exiting real-time distribution tools as they will be connected to the software data bus of SIT-R.
According to the results of this first experiment, the second solution could then be envisaged in the future.

Acknowledgments

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