Coordinated voltage control scheme for Flemish LV distribution grids utilizing OLTC transformers and D-STATCOM's

Nikolaos Efkarpidis, Thomas Wijnhoven*, Carlos Gonzalez*, Tom De Rybel*, and Johan Driesen**

**ESAT/ELECTA, KU Leuven, Belgium, Nikolaos.Efkarpidis@esat.kuleuven.be*

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Abstract

The incorporation of on-load tap changers (OLTC) in secondary distribution transformers has been proposed as alternative technology to prevent the violation of the voltage statutory limits in Flemish LV distribution grids. Under high penetration levels of distributed generation (DG), this device can partly eliminate those violations increasing the voltage unbalances when independent tap-changing control per phase is applied. The paper describes a coordinative scheme for the regulation of positive and negative sequence voltages utilizing OLTC transformers and distributed static synchronous compensator (D-STATCOM) devices. From the results, it was concluded that the proposed scheme can fully remediate the over-voltage violations via active power control and decrease the voltage unbalances considerably via reactive power management.

1 Introduction

At present, voltage regulation in LV distribution grids is performed through the use of manual, off-load tap changers, whose positions are calibrated and changed only in case of network extension or modification, including seasonal variations in some cases. Considering the move towards active network management (ANM) strategies and technologies, several utilities have already implemented prototypes of distribution transformers with an on-load tap-changer (OLTC) [1, 2]. In accordance to the voltage control method, various control strategies have been reported in the literature for the active voltage regulator (AVR) of the OLTC [3–5]. As concluded in [5], the proposed control technique can deteriorate the voltage unbalances in the grid because of the independent OLTC control of every phase. In addition, the OLTC can only partly decrease the violations of the over-voltage limit (1.1 p.u) due to the finite response of the devices. Hence, the proposed voltage control algorithm is required to be combined with additional ANM technologies which aim to solve the identified issues.

FACTS devices have been widely used throughout the world and as such are fairly mature technologies, however, they are most commonly used at the transmission level achieving a

myriad of control functions including voltage regulation, system damping and power flow control. Their use at the LV level has been virtually non-existent due to their cost, perceived complexity and possibly some apprehensions about their reliability and the state of development of the technology. The concept of distributed FACTS (D-FACTS) has been recently proposed as an alternative approach for realizing the functionality of FACTS devices removing the above barriers. D-FACTS devices are attached directly to distribution lines controlling dynamically the effective line impedance, unlike the traditional capacitive compensators such as static var compensators (SVCs), switched capacitors or other fixed impedance devices. Thanks to the advancement of power electronics technology, D-FACTS devices, such as distributed static synchronous compensator (D-STATCOM), dynamic voltage restorer (DVR) and distributed power flow controller (DPFC) can become viable in real applications. D-STATCOM is suitable for power quality improvement of the distribution power systems mitigating various problems such as voltage fluctuation and flicker, voltage unbalances and current distortion. Compared to SVCs, D-STATCOM's allow more flexibility and the reactive power is more independent of the actual voltage on the connection point. Furthermore, it can also be used to mitigate current harmonics, whereas SVCs introduce harmonic currents and voltage flicker [6]. As for DVR, it is connected in series with the feeder and usually protects sensitive loads from all supply-side interruptions. Although DVR has a much smaller rating, DSTATCOM has been proven to be more efficient for voltage profile improvement and voltage unbalance reduction compared to DVR [7]. Combining DSTATCOM with DVR, the DPFC device is derived with the capability of varying the transmission angle, the bus voltage and the line impedance simultaneously. Even though the active and reactive power flow through the line can be controlled independently with the main advantages of load compensation and voltage control, its utilization has been limited due to high costs and reliability concerns.

Considering the above observations for the FACTS devices, a coordinative voltage control scheme utilizing D-STATCOM's and a distribution transformer with OLTC is introduced in this paper. Two different distributed static synchronous compensator (D-STATCOM) devices are incorporated in a LV distribution grid in order to eliminate the violations of both the over-voltage and the voltage unbalance limits. Although, in real-

ity, both operations can be combined in one D-STATCOM device, two devices were used due to modelling constraints of the simulation software. The paper is organized in four sections. The voltage constraints that are exceeded due to the anticipated high penetration levels of distributed energy resources (DER) and modern appliances is the topic tackled in section 2. The complete proposed methodology for the control of both the over-voltages and the voltage unbalances is discussed in section 3. Two case studies and the simulation results are demonstrated in section 4. These results are illustrated to prove the efficiency of the proposed control methodology for the elimination of the over-voltages and the voltage unbalances. Finally, the paper's proposal is concluded.

2 Voltage Statutory Limits on LV Grids

The electricity distributors have the obligation to design the supply system in order to keep the voltage characteristics within the statutory limits. These limits are chosen as a compromise between the objective of providing the majority of the customers a satisfactory service and the aim of keeping the cost of supply as low as possible. In this section, the customer voltage rise/drop and the voltage unbalance are described.

2.1 Customer voltage rise/drop

Under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed the specified limits of 230 V +10%/-10% for LV distribution networks. According to the standard EN-50160 [8], "Voltage characteristics of electricity supplied by public electricity networks," the 10 minutes mean r.m.s voltage shall be within the range of 230 V +10%/-10% (253 V; 207 V), during 95% of the week. In addition, all 10 minutes mean r.m.s voltages shall not exceed the range of the 230+10% and 230-15% (253 V; 195,5 V).

2.2 Voltage unbalance

Voltage unbalance in three-phase distribution systems is a condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120° phase relationship or both [9]. The major cause of voltage unbalances in LV networks is the distribution of single- and double- phase loads along the network and their continuously changing instantaneous demand values. In addition, small-scale embedded generators (SSEGs) with maximum capacity equal or less than 5 kVA are normally single-phase generation units and are installed disproportionately on a single-phase along with the fact that their growth is consumer-driven and not centrally planned.

Voltage unbalance in percent is defined as the maximum deviation from the average of the three phase voltages or currents, divided by the average of the three-phase voltages or currents [9]. Another index used in European standards to indicate the acceptable level of unbalance is the percentage

voltage unbalance factor (VUF) and is calculated by (1)

$$VUF(\%) = \frac{|\vec{V}_2|}{|\vec{V}_1|} \times 100\% \quad (1)$$

where V_1 , V_2 are the positive and the negative sequence components of the voltage respectively. According to the standard EN-50160 [8], under normal operating conditions the measured VUF at any node must remain below 2% during each period of one week for at least 95% of the week.

3 Coordinated Control Strategy of OLTC and D-STATCOM's

Considering that the OLTC has much slower response than the D-STATCOM, in this work the bus voltage is controlled by D-STATCOM's until they reach their maximum limit. Then the OLTC is activated to eliminate the rest of the voltage violations. In this section, the proposed control algorithms of both the OLTC and the D-STATCOM's are discussed in detail.

3.1 OLTC Control Algorithm

The traditional line drop compensation (LDC) function measures the voltage and load current, estimates the voltage at a remote point without using any communication link and triggers the tap-changer when the estimated voltage is out of bounds. This method monitors the voltage at the secondary side of the transformer, using the secondary side transformer current, to estimate the voltage drop between the transformer and the load at any point. Though the conventional voltage control represents the most straightforward method, high DG penetration and gradual load modification increase the difficulty of current prediction leading to possible failures. Using conventional OLTC control could save investment and operational costs for additional information and communication technologies (ICT), but may have other technical drawbacks like unintended tap settings due to misinterpretations of non-measured values.

In this paper, the OLTC control methodology, which was proposed in [5], is applied. Instead of maintaining the substation secondary voltage in a preset tolerance band, the applied control strategy utilizes remote voltage measurement values from all the points of common coupling (PCC's) and is applied to each OLTC phase individually. One unit calculates the minimum U_{min} and the maximum U_{max} value of the n PCCs voltage magnitudes $U_1, U_2, \dots, U_n$ over a period of time, as illustrated in Fig. 1. A tap changer event is triggered, if one of the following conditions becomes true:

$$\Delta tap = \begin{cases} +1, & \text{if } (U_{min} < U_L) \cup (U_{max} < U_H) \\ -1, & \text{if } (U_{min} > U_L) \cup (U_{max} > U_H) \\ -1, & \text{if } (U_{min} < U_L) \cup (U_{max} > U_H) \\ & \cup (\Delta U_{max} - \Delta U_{min} > U_{step}) \\ +1, & \text{if } (U_{min} < U_L) \cup (U_{max} > U_H) \\ & \cup (\Delta U_{min} - \Delta U_{max} > U_{step}) \end{cases} \quad (2)$$

Fig. 1: OLTC control methodology

where:

$$\begin{aligned} \Delta U_{max} &= U_{max} - U_H \\ \Delta U_{min} &= U_L - U_{min} \\ U_L &\text{ minimum allowable voltage} \\ U_H &\text{ maximum allowable voltage} \\ U_{step} &\text{ step voltage per tap-change} \\ tap &\text{ position of the tap-changer} \end{aligned}$$

More information on the range of the transformer ratio, the number of tap-change steps and the additional voltage step per tap is given in [5]. Finally, the voltage measurement data are retrieved from the remote units every 2 sec according to the integration time constant of the simulation.

3.2 DSTATCOM Control Algorithm

In [10], the proposed D-STATCOM controller realizes positive-sequence admittance (or inductance) and negative-sequence conductance (or resistance) to regulate positive-sequence voltage as well as suppress negative-sequence voltage. From the evaluation of the method in a radial line rated at 23 kV and 100 MVA, the compensation of positive-sequence voltages seems not to affect the VUF, while the compensation of negative-sequence voltages is deactivated. Considering the high R/L ratio in the LV distribution grids, the above methodology cannot be applied due to the high required currents for the positive-sequence voltage regulation. Hence, this work proposes the compensation of the positive-sequence voltage via active power management, while the negative-sequence voltage can be regulated via reactive power management. Two D-STATCOM devices with different control algorithms are incorporated in a LV distribution grid in order to eliminate the violations of both the over-voltage and the voltage unbalance limits. Both devices are implemented by the conventional three-phase voltage source inverter (VSI) and are connected to the distribution line by a step-up transformer. Fig. 2 displays the model of the D-STATCOM controller for the generation of the reference-current to accomplish regulation of the positive-sequence voltage. The comparator receives remote positive-sequence voltage values from all the PCC's and makes the following calculations determining the output voltage u and lo-

Fig. 2: D-STATCOM controller for the generation of the reference-current to accomplish regulation of the positive-sequence voltage

calizing the node with this voltage:

$$u_{min} = \min\{u_1, u_2, \dots, u_n\} \quad (3)$$

$$u_{max} = \max\{u_1, u_2, \dots, u_n\} \quad (4)$$

$$du_{max} = u_{max} - 1 \quad (5)$$

$$du_{min} = 1 - u_{min} \quad (6)$$

$$u = \begin{cases} u_{max}, & \text{if } |du_{max}| > |du_{min}| \\ u_{min}, & \text{if } |du_{min}| > |du_{max}| \end{cases} \quad (7)$$

Then a PI regulator is realized to generate the positive-sequence conductance G_p to maintain u at the nominal value u_{ref}^* . As for the gain K_V of the PI regulator, its optimal value depends on the position of the node with the voltage u , the characteristics of the distribution line, the consumed power of the households and the generated power of the generation units. Considering the complexity of defining the gain K_V in function of those parameters, the optimal value of the gain is determined taking into account the voltage u and the current that is generated by the multiplication of G_p with u . On the other side, the current i_q^* is equal to zero due to the non-usage of reactive power for the compensation of the positive-sequence voltage. Using the inverse Park transformation, the currents i_d^* and i_q^* are transformed from the dq synchronous frame to the reference currents i_a^* , i_b^* and i_c^* of the abc stationary frame. The phase angle γ is determined by the output of a phase-locked loop (PLL) device that is connected at the PCC of D-STATCOM. Next, the real currents are synthesized through the pulse-width modulation (PWM) method.

Fig. 3 illustrates the model of the controller for the generation of the reference current to accomplish elimination of the voltage unbalances. In this case, the comparator receives remote VUF values from all the PCC's and calculates the maximum values of both VUF and V^- . Additionally, the phase angle ϕ of the maximum V^- is measured and its value defines the variable sign as follows:

$$sign = \begin{cases} 1, & \text{if } \sin\phi > 0 \\ -1, & \text{if } \sin\phi < 0 \end{cases} \quad (8)$$

Fig. 3: D-STATCOM controller for the generation of the reference current to accomplish elimination of the voltage unbalances

Similarly with the controller for the positive-sequence voltage, the PI regulator generates the negative-sequence admittance Y_n to maintain VUF at the nominal value VUF_{ref}^* . The gain K_{VUF} is also determined considering the maximum VUF , and the generated current by the multiplication of the signed Y_n with V^- represents the current i_q^* . In this instance, this current is non-zero, because the reactive power control is utilized for the regulation of the negative-sequence voltages. In both controllers, the current that represents the losses of the capacitor on the DC side is included in the current i_d^* . Finally, magnitude limiters are used for the protection of the distribution grid from high injected/absorbed currents.

4 RESULTS

All the simulations are performed on a typical Flemish LV urban grid provided by the Belgian utilities, displayed in Fig. 4. More information about the topology, the technical characteristics of the OLTC and the power profiles of the households and the generation units are given in [5]. According to [11], in Flanders the actual load base for the year 2020 can either increase up to 103.78% or decrease till 96%, thus, the set of scenarios includes both possible changes, as well as the actual load base 100%. Regarding the PV units, they are randomly located among the grid taking into account their penetration level, which is expressed as the percentage of the transformer capacity. As for the investigated scenarios, the three load bases (96%, 100% and 103.78%) are combined with different PV penetration levels that are displayed in Table 1. This results in 12 different cases considering the initial scenario with 0% penetration level. For each scenario, the annual load flow is simulated via the power systems analysis software DlgSILENT PowerFactory, first without the presence of the OLTC and next fitting it to the transformer. The following outputs related to voltage statutory limits are evaluated:

1. Over-voltage indicator: 100th voltage percentile (maximum voltage, during 100% of the time), which is compared with the over-voltage limit ($110\% U_n$).
2. Under-voltage indicator (1): 5th voltage percentile representing the distance to the first under-voltage limit ($90\% U_n$).

Fig. 4: Investigated LV grid

3. Under-voltage indicator (2): 0th voltage percentile (minimum voltage, during 100% of the time), which is compared with the lowest voltage limit ($85\% U_n$).
4. VUF 95th percentile, which represents the distance to the standard limit (2 %) during 95% of the time.

Concerning the under-voltage indicators, the 100th and the 95th under-voltage percentiles never exceed the statutory limits. As for the over-voltage indicators, violations of the maximum value ($110\% U_n$) occur due to PV installations and the tap-changer can partly improve its value. From the results, it was also concluded that fitting the OLTC leads to voltage unbalance problems at the LV distribution grid. More information about the above conclusions can be found in [5]. Next, two D-STATCOM devices, each of them with capacity of 70 kVA, are connected at the end of the investigated grid. Their incorporation is evaluated for the time intervals of the above scenarios when the over-voltage indicator and the VUF obtain their maximum values. According to [5], the over-voltage indicator and the VUF are maximized for the scenarios of 50% penetration level-103.78% of the load base and 40% penetration level-96% of the load base respectively.

Fig. 5 displays the over-voltage indicator, the under-voltage 100th percentile and the maximum D-STATCOM positive-sequence current in function of the gains K_V and K_{VUF} when connecting both D-STATCOM's at the end of the feeder. As can be observed in Fig. 5a, the increase of gain K_V results in the drop of the over-voltage indicator under the statutory limit ($110\% U_n$) through absorbed D-STATCOM currents of about 70 A. Nevertheless, these high loadings are imposed only for a short period of time ($\sim 3min$), therefore, a small amount of energy is lost. Simultaneously, the minimum voltage decreases, however, it remains above the under-voltage limit ($90\% U_n$). As for the influence of the gain K_{VUF} at the voltage magnitudes, slight differences can be observed for zero values of K_{VUF} (Fig. 5a). In case 2, the increase of either the gain K_{VUF} or the gain K_V leads to the drop of the

Penetration level	PV capacity	Number of PVs
+20%	50 kWp	10
+30%	75 kWp	15
+40%	100 kWp	20
+50%	125 kWp	25

Table 1: Specification of the investigated scenarios

Fig. 5: Over-voltage indicator, under-voltage indicator (2) and maximum D-STATCOM current for the control of the positive-sequence voltage in function of the gains K_V and K_{VUF} for: (a) Case 1 (b) Case 2

over-voltage indicator (Fig. 5b). On the contrary with case 1, the minimum voltage remains under the under-voltage limit ($90\% U_n$) for low values of K_{VUF} and decreases, when K_V increases. Hence, when the operation of the D-STATCOM device for the control of the positive-sequence voltage is unnecessary, this device should be disconnected, otherwise the minimum voltage can deteriorate. Regarding the current for the regulation of the positive-sequence voltage, it is unaffected by the gain K_{VUF} in case 1, while some slight drops can be noticed for specific values of K_{VUF} in case 2.

Fig. 6 displays the VUF and the maximum D-STATCOM current for the control of the negative-sequence voltage in function of the gains for the investigated cases. Unlike the voltages, VUF seems to be affected by both gains as shown in Fig. 6. It is clear from Fig. 6a that increasing K_{VUF} does not always result in VUF drop, since VUF starts increasing over a critical value of K_{VUF} that depends on K_V . As for the impact of K_V , VUF follows a decreasing trend apart from a slight rise for small values of K_V ($K_V \leq 1$). On the other hand, the effects of the gains are different in case 2, when the maximum VUF exceeds the statutory limit. While the increase of K_{VUF} always causes VUF drop, the same change of K_V leads to slight VUF rise. Consequently, the D-STATCOM device for the control of the positive-sequence voltage can deteriorate

Fig. 6: VUF and maximum D-STATCOM current for the control of the negative-sequence voltage in function of the gains K_V and K_{VUF} for: (a) Case 1 (b) Case 2

the VUF and it should be disconnected, as mentioned above. Fig. 6a shows that the maximum D-STATCOM current is also affected by both gains, however, the impact of K_V is unclear. As can be seen, the current increases in function of K_{VUF} for different values of K_V except the case when it keeps a constant value ($K_V = 8$). In addition, the current reaches the maximum value for a specific K_V , and then, it drops gradually to its minimum value depending on K_V . In Fig. 6b it is clear that the current follows a decreasing trend only for small values of K_V ($K_V \leq 1$).

Furthermore, it was noticed that in case 1 for specific gains ($K_{VUF} = 403$, $K_V = 8$) VUF reaches the minimum value of 0.418% , while it obtains extreme values in some cases ($K_{VUF} \geq 10$, $K_V < 8$). Even though in case 2 VUF cannot remain below the statutory limit, D-STATCOM devices improve its value significantly, from 3.887% to 2.688% for particular gains ($K_{VUF} = 97$, $K_V = 1$). As summarized in Table 2, the incorporation of D-STATCOM devices can fully eliminate the violations of the over-voltage statutory limits and decrease the high values of the maximum VUF.

Finally, the efficiency of the coordinative scheme was evaluated in different locations of the grid. As illustrated in Table 3, the complete elimination of over-voltages demands higher injected positive sequence currents as the further away from the end of the feeder the location of the positive sequence device is. On the other hand, the reduction of the voltage unbalances fluctuates for different locations of the negative sequence device due to the diversity of both the loads and the generation units as well as the random connection of single-phase elements in the three phases.

Method	OLTC		OLTC & STATCOM	
Test case	1	2	1	2
V_{max} (pu)	1.108	1.018	1.091	1
V_{min} (pu)	0.96	0.892	0.915	0.9
VUF_{max} (pu)	1.084	3.887	0.418	2.688

Table 2: Comparison of the evaluated methods

5 Conclusions

Considering that the OLTC can partly improve the over-voltage indicators while the independent tap-changing control per phase increases the voltage unbalances this paper proposes a coordinative voltage control scheme utilizing OLTC transformers and D-STATCOM devices. It was concluded that the proposed method can fully remediate the violations of the over-voltage indicators via active power and decrease the voltage unbalances considerably via reactive power management. In future work, the proposed method will be combined with the operation of additional ANM technologies which aim to solve the identified voltage unbalance issues.

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Node	17		8	
Test case	1	2	1	2
K_V	8	1	13	1
K_{VUF}	415	133	46	130
V_{max} (pu)	1.099	1	1.098	1.001
V_{min} (pu)	0.926	0.9	0.914	0.9
I_{pos} (A)	77.192	5.067	100.971	4.356
VUF_{max} (pu)	0.415	2.659	0.504	2.712
I_{neg} (A)	7.233	39.796	5.091	37.680

Table 3: Evaluation of the Coordinative Scheme in Different Locations of the Grid

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