Reference Voltage Adjustment Strategies for Dynamic Voltage Compensator

Ehsan Kazemi-Robati
Center of Power & Energy Systems
INESC TEC
Porto, Portugal
ehsan.kazemi@inesctec.pt

Hossein Hafezi
Faculty of Information Technology and Communication Sciences
Tampere University
Tampere, Finland
hossein.hafezi@tuni.fi

Roberto Faranda
Department of Energy
Politecnico di Milano
Milano, Italy
roberto.faranda@polimi.it

Bernardo Silva
Faculty of Engineering
University of Porto and INESC TEC
Porto, Portugal
bernardo.silva@inesctec.pt

***Abstract*—Modern electrical distribution networks are prone to more severe voltage fluctuations due to the presence of variable loads such as electrical vehicles and renewable energy generation units. These fluctuations decrease both the quality of power and hosting capability of the grid. In such a condition, a Dynamic Voltage Compensator (DVC) can be used to stabilize the voltage of the LV networks. DVC is generally designed to resolve voltage fluctuations reflected from MV systems maintaining the voltage on a constant value. However, it will more effectively improve the voltage quality in the grid if the reference voltage is dynamically adjusted based on measurements inside the LV system. On the other hand, the more complex measurement and coordination strategy may lead to the inapplicability of the methods. Hence, voltage reference adjustment strategies should be developed to conform to the availability of data and measurements inside the grid. Accordingly, in this paper, novel voltage reference adjustment strategies have been developed for DVC based on the measurements in the installation point of the device. In order to examine the proposed methods, they are applied to a LV grid with real measured data and the results are discussed. Based on the provided simulation results, the developed dynamic reference voltage adjustment strategies can successfully improve the quality of voltage and improve the hosting capacity of the LV network.**

Keywords—voltage stabilization, DVC, hosting capacity, active distribution networks.

I. INTRODUCTION

Power quality is one of the major concerns of the electrical grid operators and customers in the energy transition era [1]–[3]. Accordingly, by the increase in the share of renewable energies in the different sectors of grids in recent years, there has been a focus on the assessment and improvement of power quality in active distribution networks [4]–[6].

In LV distribution grids, the voltage quality problems can be both reflected from the MV system through the substation and due to the demand fluctuations inside the LV network; however, the energy transition can negatively affect both. Accordingly, the presence of renewable energy farms and the fast electric vehicle charging stations in the MV sector can increase the voltage fluctuations at the substation of the LV system[7], [8]. Furthermore, the high number of electric vehicle chargers connected at the LV level as well as the high penetration of rooftop PV units can have a considerably negative effect on the voltage quality inside the network due to the strong differences between night loads and daytime generations [9]–[11].

Altogether, if the voltage in a modern distribution network is not successfully stabilized, it will have a limitation in hosting more loads and generation units even if a high share of the cables is unoccupied. However, it is very important for modern electrical grids to have a high capacity of hosting the new elements both in terms of load/generation levels. [12]–[14]. On the other hand, by the successful stabilization of the voltage in the different loading and generation conditions that may happen in the LV network, the hosting capacity of the grid can reach the nominal capacity of the installed cable.

In order to improve the quality of volage in LV networks, different devices and strategies have been developed by researchers in the literature [15]–[17]. As a promising method, a device called Dynamic Voltage Compensator (DVC) has been developed and tested in [18]. The applicability of this device for voltage stabilization has also been tested in a real LV network in [19].

The capability of DVC for the stabilization of voltage in the pure-reactive mode is highly affected by its nominal capacity [20]. In other words, the higher capacity of the DVC can assure the DSO for successful voltage stabilization at the substation and compensation of the fluctuations reflected from MV side. However, the constant setpoint of the DVC on the nominal voltage value may limit load and generation increment inside the LV feeder due to the different loading conditions that may happen and the voltage violations inside the feeder. In other words, the DVC will be able to provide a more effective improvement in voltage profile by lowering or increasing the reference for the excess of generation and load demand, respectively.

The process of adjusting the reference voltage of DVC is preferred to be done automatically using the measurements in the grid. It is obvious that the more detailed data of the systems and the measurements inside the grid can provide the more effective voltage improvement in the network. However, due to the costs and complexities of the measurements, coordination, and communication, it is preferrable to have alternative solutions for DVC reference voltage adjustment using less data and measurements available close to the DVC installation point.

Accordingly, in this paper, two different dynamic reference-voltage adjustment strategies have been developed for DVC based on the measurements of the current in the substation. For the first method, the only supplementary data needed to adjust the voltage reference of DVC is the capacity of the cable while the second strategy applies the impedance of the feeder. Altogether, both of them can be attractive when the voltage regulation is expected to be done with the limited local measurements in the substation.

The rest of the paper is organized as follows. DVC device is shortly described in Section II. The dynamic reference-voltage adjustment strategies for DVC have been described in

Section III. Simulation results for the proposed strategies are provided in Section IV. Finally, the study is concluded in Section V.

II. Dynamic Voltage Compensator

The simplified per-phase topology of the DVC installed in a LV distribution system is illustrated in Fig. 1 [19]. Connected in series at the beginning of the LV feeder, the device can deal with the fluctuations of the PCC voltage and stabilize it at the desired while V_s represents the per-phase voltage at connection point inside MV/LV substation, V_x is the injected voltage by DVC and V_{PCC} is the voltage at PCC after the device.

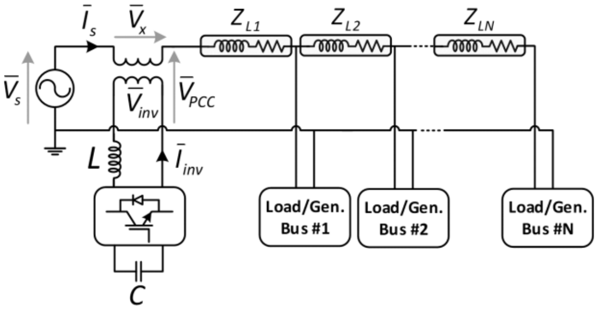

Fig. 1. The diagram of a LV distribution network with a DVC

According to Fig. 1, the voltage at the PCC in the presence of the DVC can be calculated using (1).

$$\bar{V}_{PCC} = \bar{V}_s + \bar{V}_x \tag{1}$$

Hence, by the online adjustment of $\bar{V}_x$, the voltage at the PCC is maintained constant regardless of the $\bar{V}_s$ value as the substation voltage. It should be emphasized that the device is managed to inject $\bar{V}_x$ perpendicular to the current in order to work in non-active mode [19].

According to [21], this device can successfully improve the power quality and hosting capacity of the distribution networks. However, as stated, the conventional control algorithm of the device is designed to maintain the voltage at the PCC on nominal voltage regardless of the loading condition of the grid. Accordingly, implementation of reference voltage adjustment strategies is suggested in this paper to improve the quality of voltage regarding the different loading conditions in the presence of DVC. In this way, the higher levels of the hosting capacity can be provided up to the nominal capacity of the cable. These dynamic reference voltage adjustment strategies are described in Section III.

III. Dynamic Referece Voltage Adjustment Strategies for DVC

In this Section, two dynamic reference voltage adjustment strategies developed for DVC are proposed and described. The strategies are then applied to the grid in Section III and the results are compared with each other.

A. *DR1: Reference adjustment based on the real component of the current in the substation*

In this strategy, the real part of the current in the substation of the LV network is calculated and applied for DVC reference voltage adjustment. The diagram for the implementation of this method is given in Fig. 2 in which V_{ref} is the reference voltage adjusted for the DVC and I^r_{sub} is the real part of the current in the substation calculated by (2).

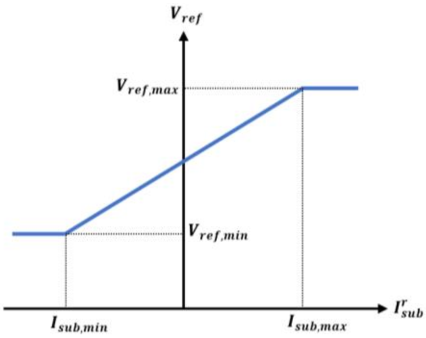

Fig. 2. Voltage adjustment in DVC based on the real component of the current measured at the MV/LV substation of the feeder

$$I^r_{sub} = I_{sub} \times cos(\varphi) \tag{2}$$

where I_{sub} is the RMS current of the substation and φ is the angle of the current. It should be emphasized that $I_{sub,min}$ in Fig. 2 is a negative value as the representative of the high PV generation condition in the LV grid. Accordingly, when the active power generation level is very high, the reference voltage is decreased to prevent overvoltage in the busses of the feeder. On the other hand, for the high loading conditions with considerable positive real current at the substation, the reference voltage is set to the maximum value to obtain the maximum compensation of the voltage drop in the feeder.

For the sake of the simplicity and increasing the applicability of the method in all LV grids regardless of the detailed grid data, the parameters represented in Fig. 2 are adjusted using (3).

$$\begin{bmatrix} V_{ref,min} \\ V_{ref,max} \\ I_{sub,min} \\ I_{sub,max} \end{bmatrix} = \begin{bmatrix} 0.9 \times V_n \\ 1.1 \times V_n \\ -I_n \\ I_n \end{bmatrix} \tag{3}$$

where $V_n = 230\,V$ is the nominal RMS voltage of the LV network and I_n is the rated current of the cable in the substation.

As it is clear, reference voltage adjustment in this method only necessitates the current measurement in the substation and the availability of the cable nominal capacity data. Accordingly, the simplicity of the implementation is the most important characteristic of this method; in other words, this method can be easily implemented in any LV distribution network regardless of having any detailed data about loading conditions.

B. *DR2: Two-bus model based reference adjustment*

In this method, the distribution network is transformed into a two-bus grid and the voltage deviation is calculated regarding the simplified model using (4).

$$\Delta V = I_{sub} \times \left(R \times cos(\varphi) + X \times sin(\varphi)\right) \tag{4}$$

where R and X represent the impedance between the substation and the ending bus of the feeder. Regarding the calculated voltage, the reference of the DVC is adjusted using (5).

$$V_{ref} = V_n + \frac{\Delta V}{2} \tag{5}$$

As it is clear, this method also applies the current measurements in the substation for the reference voltage adjustment. However, the impedance of the feeder is supplementary data compared to DR1 that is needed for the implementation of DR2 method. Moreover, for the more complex grids, there should be a pre-processed decision by the DSO for selecting the part of the grid with the most severe voltage problems to be applied to (4).

IV. Simulation results

In this section, the two dynamic reference voltage adjustment strategies of DVC are examined in a 4-bus LV network with real measured data. The schematic of the network is given in Fig. 3. The data of the network is given in [21] while previous assessments are also provided in [22]. However, for this study, new assessments are applied to the available yearly data to extract the less-problematic parts and ensure the correct integration of the measurement data. A summary of the other data used in the simulations is given in TABLE I.

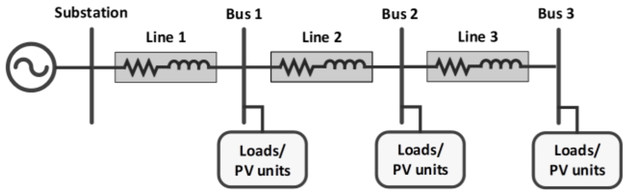

Fig. 3. Schematic of the 4-bus LV distribution system [21]

TABLE I. Summary of the data for the simulation

Parameter	Description	Value
I_n	Nominal capacity of cable	545 A
V_n	Nominal voltage of the grid	230 V
R	Resistance of the feeder	73.8 mΩ
X	Reactance of the feeder	54.5 mΩ

For the applied data, the grid assessment in the 4-bus network is implemented using load-flow analysis. Accordingly, for each individual measurement data available for the loads and the voltage in the substation, a load flow is implemented to calculate the voltage and currents of the whole branches and the buses in the grid. It should be emphasized that the loads and the generation units are modeled as constant power elements. For the case of the presence of the DVC, the measured voltage data at the substation is ignored while the reference voltage of the DVC is applied to the loadflow. This way, for each of the cases, the maximum current in the gird and the minimum-maximum voltage of the busses are identified.

A. *Voltage assessments*

In this subsection, voltage assessments are implemented on the grid for the whole year regarding the absence/existence of DVC and the reference voltage adjustment strategies.

1) *Base grid (No-DVC)*

The minimum and maximum voltage observed among all busses during the whole year as well as the maximum flow in the lines of the grid for the case of no DVC is given in TABLE II.

As it is clear, the grid is within the limits of ±10% of nominal voltage during the whole year in all the busses. Since less than 1/3 of the cable capacity is already used, there is a strong potential for hosting more loads and generation units. However, regarding the results given in TABLE II, the minimum voltage in the network is a limiting factor of this case.

TABLE II. Summary of grid assessmenT results in the whole year for the No-DVC case

Parameter	Value
Voltage range of substation (V)	210.9 - 243.3
Voltage range of network (V)	209.7 - 244.6
Max. current of the feeder(A)	178.7
Max. hosting of the feeder (%)	32.8

2) *Static Reference DVC (SR-DVC)*

In the next step, the conventional DVC with constant reference set on the nominal voltage is added to the grid to improve the quality of power; it should be emphasized that in this study, the capacity limit of the DVC is not taken into account. In other words, the device is considered capable of providing the requested reference voltage in the whole year. Accordingly, the process of updating the reference regarding [18] is out of the scope of this study. Altogether, the assessments are repeated in the whole year in the presence of the static reference DVC and the results are provided in TABLE III.

TABLE III. Effect of the static reference DVC on the voltage quality of the grid

Parameter	Value
Voltage range of network (V)	220.4 – 233.6
Max. current of the feeder(A)	174.7
Max. hosting of the feeder (%)	32.1

According to the results, the device has considerably improved the voltage quality in the grid; accordingly, the range of the voltage variations among all busses during the whole year has been decreased from 34.9 V in the No-DVC case (209.7 - 244.6) to 13.2 V in presence of the SR-DVC (220.4 - 233.6). Moreover, the minimum voltage of the grid considerably improved; hence, a potential of improving the hosting capacity has also been provided.

3) *Dynamic reference strategies for DVC*

In order to assess the effect of the two dynamic reference voltage adjustment strategies proposed for DVC in Section III, they are applied to the grid as independent cases and the assessments are repeated for the whole year. The summary of the results is given and compared with the other cases in TABLE IV.

TABLE IV. Effect of the dynamic reference adjustment strategies proposed for DVC on the voltage quality of the grid

Parameter	Value	
	DR1-DVC	DR2-DVC
Voltage range of network (V)	226.9 - 237.5	225.7 - 236.2
Max. current of the feeder(A)	168.9	169.9
Max. hosting of the feeder (%)	31.0	31.2

According to the results, in both of the dynamic reference adjustment strategies, the range of the voltage variation is less than the 13.2 V of the static reference DVC. Moreover, the minimum and maximum of the voltage values in the grid are much closer to the nominal voltage of the grid. Finally, due to a little increase of the voltage, it is clear that the maximum current of the grid has also decreased comparing the No-DVC and SR-DVC cases due to the nature of the loads. According to all of these descriptions, there has been a potential provided for a higher hosting capacity in the network in the presence of the DVC with the dynamic reference voltage adjustment strategies. The assessment of the hosting capacity for the different studied cases is provided in the following subsection.

B. Hosting capacity assessment

In order to assess the hosting capacity of the network in this subsection, the existing active and reactive power profile of the grid in whole buses is gradually increased with the step of 10% and the yearly assessments are repeated for each of them. When a violation is monitored in any voltage or current values among all busses and lines even for one sample during the whole year, the previous step is considered as the maximum hosting capacity of the grid.

1) Base grid (No-DVC)

The minimum and maximum of the voltage in the grid busses and the maximum flow in the lines for the different load multipliers in the No-DVC case are provided in Fig. 4. As it is clear, after a little increase of the loads/generation-units, the grid faces with the violation of the minimum voltage while the used capacity of the cable is far from the nominal one. In other words, the low voltage is a limiting factor for having more hosting capacity in the grid. A summary of the hosting capacity assessment result in this case is also provide in TABLE V.

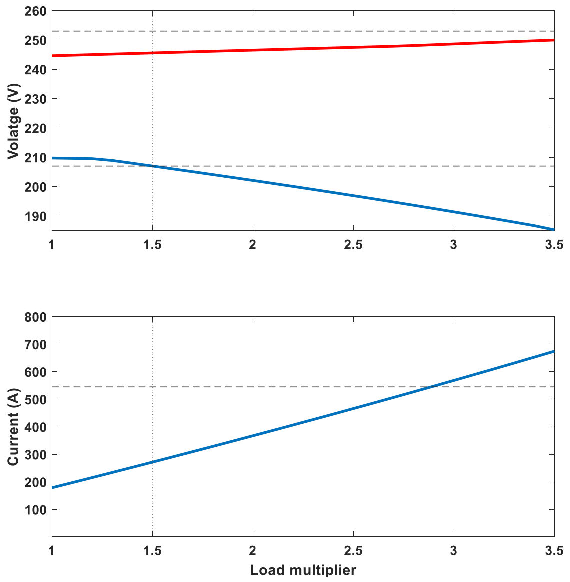

Fig. 4. Minimum/maximum voltage in the grid and the maximum feeder current in the No-DVC case

TABLE V. HOSTING CAPACITY ASSESSMENT IN NO-DVC CASE

Parameter	Value
Load multiplier	1.5
Voltage range of network (V)	207.0 - 245.6
Max. possible hosting of the feeder (%)	49.8

According to the results given in TABLE V, the maximum hosting capacity in the No-DVC case due to the violation of the minimum voltage limit is around 50%. Accordingly, voltage stabilization strategies are necessary to improve the grid capability for hosting new loads and generation units.

2) Static Reference DVC (SR-DVC)

In the next step, the static reference DVC is added to the grid and the hosting capacity assessments are repeated. The voltage and current flow assessment results in this case are provided in Fig. 5.

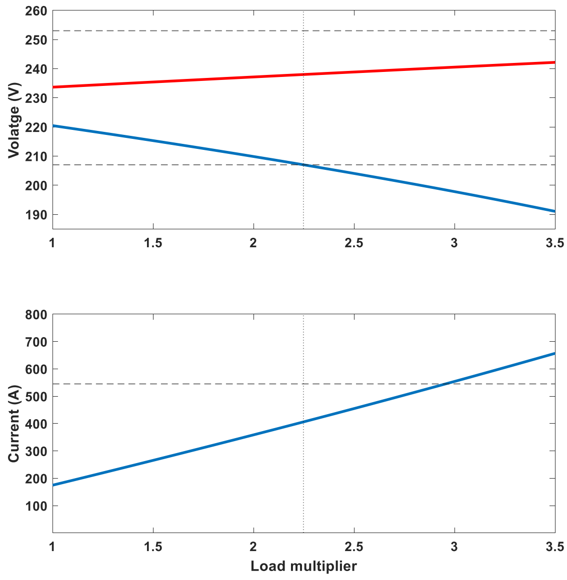

Fig. 5. Minimum/maximum voltage in the grid and the maximum feeder current in presence of the static-reference DVC

According to the results given in Fig. 5, the successful stabilization of the voltage has provided the possibility of hosting much more loads and generation units. However, as it is clear, even in this case, the minimum voltage of the grid is the limiting factor through the effective utilization of the cable capacity. The summary of the hosting capacity assessment in this case is also provided in TABLE VI. According to the results, in the presence of the SR-DVC, the hosting capacity is increased to around 73%.

TABLE VI. EFFECT OF STATIC REFERENCE DVC ON THE HOSTING CAPACITY OF THE NETWORK

Parameter	Value
Load multiplier	2.2
Voltage range of network (V)	207.6 – 237.8
Max. possible hosting of the feeder (%)	72.7

3) Dynamic reference strategies for DVC

Finally, the assessments are implemented in the presence of the dynamically adjusted DVC and the results are provided in Fig. 6 and Fig. 7 for DR1-DVC and DR2-DVC cases respectively. Moreover, the summary of hosting capacity results for these two cases are given in TABLE VII.

Comparing Fig. 6 as the DR1-DVC case with results of SR-DVC, it is clear that higher levels of hosting capacity are provided through the effective stabilization of the voltage. Regarding the results of TABLE VII, in DR1-DVC case, the maximum of the voltage is limiting the hosting capacity of the grid. However, the hosting capacity reaches around 88% that is an acceptable value.

Finally, regarding Fig. 7, it is clear that in DR2-DVC case, the voltage is not the limiting factor for hosting more loads and generation units; In other words, in this case, 100% of the cable capacity can be used while the voltage values are inside the specified limits. However, due the steps applied in the simulation, the maximum level of loading/generation in this case given in TABLE VII reaches around 99% of cable capacity. In other words, the next step will have the violation of the current capacity while the voltages are still inside the limits.

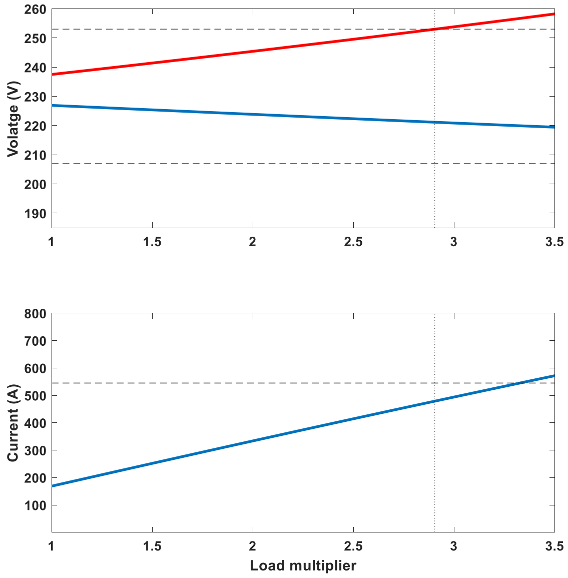

Fig. 6. Minimum/maximum voltage in the grid and the maximum feeder current for the DR1-DVC case

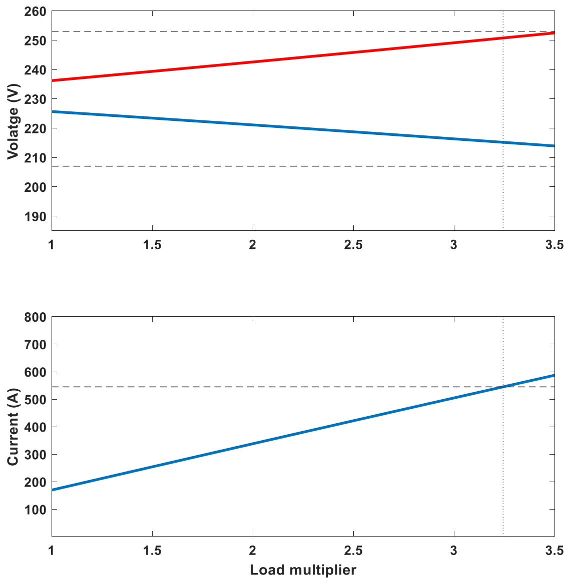

Fig. 7. Minimum/maximum voltage in the grid and the maximum feeder current for the DR2-DVC case

TABLE VII. Effect of the Dynamic Reference Adjustment Strategies Proposed for DVC on the Hosting Capacity of the Network

Parameter	Value	
	DR1-DVC	DR2-DVC
Load multiplier	2.9	3.2
Voltage range of network (V)	221.2 – 253.0	215.4 – 250.5
Max. hosting of the feeder (%)	87.7	98.7

V. Conclusion

In this paper, two different dynamic reference voltage adjustment strategies have been proposed for DVC to improve the quality of voltage and increase the hosting capacity of the grid regarding the different loading conditions. These methods are developed to apply only the current measurements in the substation and limited data of the grid to adjust the reference voltage of DVC. The proposed methods are then applied to a 4-bus LV network with real measured data and yearly assessment results are given and discussed. According to the results, both methods provided the capability of hosting more prosumers in the network. Among them, the "two-bus model based reference adjustment strategy" provided the 100% of hosting capacity through the effective stabilization of the voltage; however, the necessity of knowing the impedance data of the feeder may limit the application of the methods especially in more complex networks. On the other hand, applying the other reference adjustment method based on real component of the current in the substation could also reach around 88% of the hosting capacity while it only applies the nominal capacity of the cable. However, further assessments on more complicated grids are needed to examine the applicability of each method in different LV distribution network topologies.

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