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Comparison of Voltage Support Services by Means of STATCOM and Smart Transformer in Medium Voltage Grid

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Abstract—Due to the increasing demand of electrical energy, especially in urban areas, the traditional distribution power grid reaches its limitations of operation (e.g. large current flow or voltage deviation). The distribution grid needs to be upgraded to ensure stability margin of operation. Since the cost of space is expensive and there is also resistance against installation of extra equipment from local resident, to install new equipment in distribution grid becomes difficult. The choice of new device to support the grid must consider not only the services but also the cost of equipment and space. The devices based on power electronics (STATCOM, smart transformer (ST)) are able to provide ancillary services such as voltage support to medium voltage (MV) distribution grid. In this paper, the ST is analyzed and compared with the STATCOM in terms of cost and performance. By means of literature review and simulation, the performance of ST has been analyzed. The result shows that the ST provides more services to assist the control in distribution grid than STATCOM. In order to achieve the same performance of voltage support, the investment of ST is less.

Index Terms—Smart Transformer, voltage support in distribution grid, reactive power control, MV grid control, STATCOM.

I. INTRODUCTION

The demand of electrical energy has been increased by 10% in last 20 years and will continue to increase [1]. The increasing demand causes higher current flow, larger voltage drops and higher losses through the power grid, leading to the electric power grid operating more often close to its safety limitation, in particular, the violations of voltage limits are more frequently in distribution grid. The normal operation of grid is threatened by above challenges, pushing the grid to be upgraded.

Besides the tap-changer transformer, the distribution grid voltage control can be further improved by reactive compensation like using capacitor banks. Thanks to the development of power semiconductors and cost reductions, it is more common to install the power electronics-based devices in grid. The functionalities of this kind of devices such as STATCOM and SVC, to support power grid operation by reactive power injection/absorption, have been analysed widely [2]–[6]. With these functionalities, the grid operation can satisfy the safety limits within an acceptable margin.

To install the equipment such as STATCOM, a practical issue must be considered is the cost of space. In urban areas, especially in large metropolis, it is very crowded with high density of business offices and residents. This makes the cost of free space very expensive [7]. The space for installation becomes one essential obstacle to upgrade of grid.

The smart transformer (ST), which is a power electronics based transformer, aims not only to adapt the voltage levels from the MV to the LV (low voltage) grids, but also to provide ancillary services [8]. Compared to installation of extra STATCOM, the grid upgrade by replacing the existing transformer with the ST, has more advantages. First, it does not need extra space for installation. Moreover, the ST decouples the AC load flow between the MV and LV grids, by means of a DC link stage. Besides the transfer of active power, the grids in both sides are operated individually, disturbances originated in one side of grid can be damped by means of proper control action to the other side. One possible topology of ST is shown in Fig. 1. In MV grid, the ST can perform grid current congestion, power factor correction, harmonics mitigation [9], [10]. By providing reactive power in MV grid, the ST can also support MV grid voltage performance, similarly to the STATCOM [11], [12].

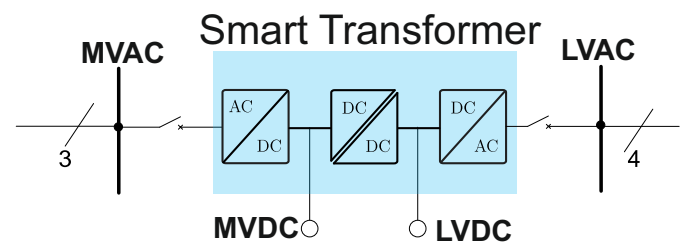


Fig. 1. ST of 3-stage topology in the grid

This paper compares the performances and cost between the STATCOM and ST as a guide for design of ancillary services. This paper is structured as follows: Section II explains briefly the concept and control of STATCOM and ST; Section III analyzes the advantages and disadvantages of STATCOM and ST; Section IV presents the testing grid and explains the criterion to compare the technical performance of STATCOM

and ST; The cost comparison of ST and STATCOM based on case study is carried out in Section V; eventually, the conclusions derived from analysis and simulation are given in Section VI.

II. CONCEPT AND CONTROL OF STATCOM AND SMART TRANSFORMER

A. STATCOM

The STATCOM is a shunt FACTS device with the capability to provide either leading or lagging reactive power of a specified amount to the grid. STATCOM consists of a voltage source converter and a capacitor bank. The STATCOM supplies reactive power by shifting the voltage and current waveforms and keeps capacitor being charged to the required voltage level. The capacitor bank has the task to support and stabilize the voltage of the DC link. The traditional way to connect STATCOM to MV grid uses a low frequency transformer (LFT) to step up voltage. There are also modular multilevel converter (MMC) based STATCOM, which connects directly to MV grid, as shown in Fig. 2. The MMC based STATCOM will be analyzed in this paper.

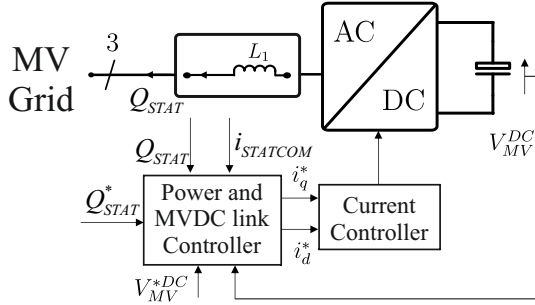


Fig. 2. Structure of STATCOM

The STATCOM provides services such as voltage support and power factor correction in grid. It is employed to sustain the voltage in case of the voltage flicker, sag/swell, dynamic oscillation. The controller of STATCOM can be a droop controller using local state variables like voltage. If the grid is equipped with communication system, the centralized control is implemented and the STATCOM can execute the order from control center. In order to fully exploit the capability of STATCOM, the centralized control is used in this paper. The STATCOM aims to support the voltage of the entire MV feeder, to which the STATCOM is connected. The voltage of feeder should be maintained within the pre-defined limit. Once there is voltage violation, the central control will order STATCOM to restore the voltage by provision of reactive power. The amount of reactive power Q^* is computed by means of the optimization function in the central controller. The local controller of STATCOM adjusts its output of reactive power to match Q^* . If the power losses is negligible, the STATCOM does not operate any active power, then the capability of reactive power control is restricted by the size of STATCOM $Q_{STAT,max}$.

$$Q_{STAT} \leq Q_{STAT,max} \quad (1)$$

B. Smart transformer

Although several topology solutions (3-stage, back-to-back) have been proposed [13], the basic control strategy is substantially the same for each ST solutions. Fig.3 shows the basic control structure for a 3-stage ST. The LV side converter controls the voltage waveform in the LV grid [8]. It provides a symmetrical voltage waveform with nominal amplitude and frequency independently from the load power request in LV grid. The current waveform is instead decided solely by the load.

The DC/DC converter has two main tasks: adapting the voltage from MV to LV and controlling the DC link of LV side. The DC/DC converter is regulated by means of a power flow controller and it regulates the power flow between the two DC stages to keep the LV DC link voltage at its nominal value. The power constraints are set between P_{max} , determined by the ST sizing, and P_{min} , that can be set or equal to $-P_{max}$ (if there is high penetration of DG), or in order to avoid the reverse power flow, equal to zero.

The MV converter controls the DC link voltage in the MV side, meanwhile regulating the active and reactive current output in the MV grid. The active power is determined by the demand in LV grid. The reactive power is a degree of freedom for the MV converter of ST: the ST can work unity power factor, or support the voltage providing reactive power. The required amount of reactive power output is determined by the controller and is used to generate the current reference i_q^* . In this paper, the same centralized controller as STATCOM is used for ST. The maximal amount of reactive power output must respect always the active power demand of the LV grid and the size of MV converter of ST. The reactive power availability can be evaluated as (2).

$$Q_{ST,max} = \pm \sqrt{S_{ST}^2 - P_{Load}^2} \quad (2)$$

The ST decouples the MV and LV grids, the MV converter of ST is released from supply the reactive power to the LV grid, which gives the MV side converter more freedom to support the MV voltage. The size of different stage of ST can also be different to optimize the cost and services.

III. ANALYSIS OF STATCOM AND ST

A. The cost of STATCOM and ST

The cost of installation of STATCOM and ST is analyzed. There are 2 parts considered in the analysis: 1). the cost of device; 2). the cost of space for installation.

1) *Cost of STATCOM*: The MMC based STATCOM has one MV voltage source converter. Based on data from [15], [16], the STATCOM of the size between hundreds of $kVar$ to a few $MVar$ can cost at least 40 Euro/ $kVar$. The STATCOM in most cases requires the extra space for installation. It is estimated that to install a STATCOM of 400 kVA to 1000 kVA , an extra space of minimal $5m^2$ is necessary [13]. According to the data from Ministry of Land and Resources of China, in cities on the eastern coast of China, where most big cities and important industries locate, the price of residential

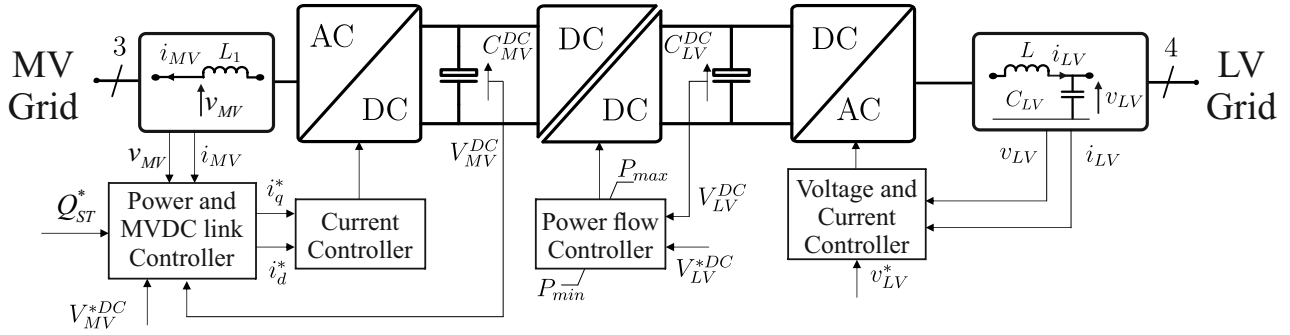


Fig. 3. The proposed structure and control scheme of ST [14]

and business area is between 940 to 2700 Euro / m^2 [17]. This means in order to install one STATCOM, an extra cost between 4700 to 13500 Euro must be added. The median value of 9100 Euro is chosen for further analysis.

The STATCOM does not operate the load of its connected bus. A LFT is required to deliver the power to load and adapt the voltage. [13] shows that a LFT up to a few MVA costs at least 21 Euro/ kVA .

2) *Cost of ST*: Currently, the ST is still in the phase of research and development. The cost of ST depends on the types of module (e.g. IGBT module of different current and voltage rating), switching frequency, the DC voltage level, the topologies (dual active bridge, quad active bridge). There is currently no data of cost from industry. Based on available analysis, reference [9] estimated that the ST can cost 120 Euro/ kVA . The ST is used to replace one existing LFT in the distribution grid and the volume of ST is smaller than LFT of the same power rating [13]. Therefore, there is no additional cost for LFT and extra space.

It is noted that ST must operate both active power and reactive power. In Section V, the cost of STATCOM is compared to the cost of additional size of ST. The additional size of ST is the increased size in order to provide reactive power. The cost comparison of STATCOM and ST is summarized in Table I.

TABLE I
COST OF INSTALLATION OF STATCOM AND ST

	STATCOM	ST
Cost of device (Euro/ kVA)	40	120
Cost of LFT (Euro/ kVA)	21	0
Cost of installation space (Euro)	9100	0

B. The provision of services by STATCOM and ST

The provision of ancillary services to grid is an important feature of power electronics devices. The devices condition the grid by adjusting the reactive power, active power and frequency.

The main functionality of STATCOM is to provide voltage support in grid. When there is a disturbance such as voltage

flicker, voltage swell/sag, the STATCOM can reduce the influence from those disturbances by adopting its output of reactive power. The STATCOM can also contribute to improve grid dynamic stability, e.g. participation of damping the oscillation in the grid [18]–[20].

In MV grid, the ST can provide the similar services as STATCOM. Since the ST connects to MV grid directly without a LFT, the issue of extra magnetic saturation is avoided distorting voltage waveform. Additionally, the ST can also support MV grid by controlling active power flow in some extent.

ST can provide DC links of both MV and LV voltage level. The LVDC link provides the connection for charging station of electric vehicle, for PV unit, or for storage system. The MVDC link provides the connection for high power DC application such as fast charging station. If there is disturbance in grid, the ST is able to use one DC link to damp the oscillations and maintain the stability of the other DC link, where the critical loads are connected.

In the LV grid, the ST gains the fully controllability of the LV grid due to the structure of decoupling the MV grid and LV grid. The ST controls flexibly the voltage waveform, amplitude and frequency according to the requirements of the users. The issues like frequency and voltage fluctuation in MV grid cannot affect the LV grid and vice versa. ST regulates the load softly to avoid overload, reverse power flow. This is done by exploiting the load sensitivity to voltage and frequency [14], [21]. The load control can participate into voltage support in MV grid by adaption of the active power. In a distribution grid where the R/X ratio of the distribution lines is higher, control of active power is more effective than control of only reactive power. The services of STATCOM and ST are summarized in Table II.

The deployment of ST will be benefited due to the fact that ST has the capability to provide more ancillary services to grid and gains more controllability.

IV. DESCRIPTION OF THE TESTING GRID AND CRITERION FOR COMPARISON

A. Grid under test

In order to analyze the ST voltage support service, the model of CIGRE MV grid is developed and tested (as shown

TABLE II
ANCILLARY SERVICES OF STATCOM AND ST

Services	STATCOM	ST
AC voltage support in MV grid	✓	✓
Active damping resonance	✓	✓
DC link of LV	✓	✓
DC link of MV		✓
Grid operation with fault		✓
LV grid fault current limit		✓
LV grid load identification		✓
Active power flow control		✓
Phase load balancing		✓

in Fig.4). The 110kV grid is working as slack bus and the voltage is kept as 1pu. The data of distribution lines is referred to [22]. The data of peak load case, which is listed in Table III, indicates the worst case of voltage deviation. The load tap-changer, the capacitor banks and the distribution generation are not considered in the simulation. All switches, S_1 , S_2 and S_3 are switched on.

TABLE III
LOAD PARAMETERS

Bus	P(MW)	Q(MVar)	Bus	P(MW)	Q(MVar)
3	0.6	0.12	4	0.5	0.1
5	0.8	0.16	6	0.6	0.12
8	0.75	0.15	10	0.5	0.1
11	0.7	0.14			

3 different buses, Bus 3, Bus 6 and Bus 10 are selected to install the STATCOM/ST and to implement the performance comparison. The voltage along the feeder should be maintained within limit. If the voltage limit is violated, in Case 1, the connected STATCOM/ST is activated to restore the voltage back within the limit by provision of only reactive power; in Case 2, the ST is activated to implement both active power regulation by load variation (maximal $\pm 10\%$) and the provision of reactive power to support the voltage.

B. Criterion for comparison

The simulation executes the optimization tasks to compute minimal amount of reactive power provision of both devices, so that to calculate the minimal size of devices. The objective functions of optimization tasks for both cases are formulated as (3) and (4).

$$F_{obj,Case1} = \min. |Q_{STAT/ST}| \quad (3)$$

$Q_{STAT/ST}$ is the output of reactive power from STATCOM/ST.

$$F_{obj,Case2} = \min. \sqrt{P_{ST}^2 + Q_{ST}^2} \quad (4)$$

P_{ST} is the real power consumed in LV grid.

In order to get the optimization results, both equality constraints and inequality constraints are subjected. The equality

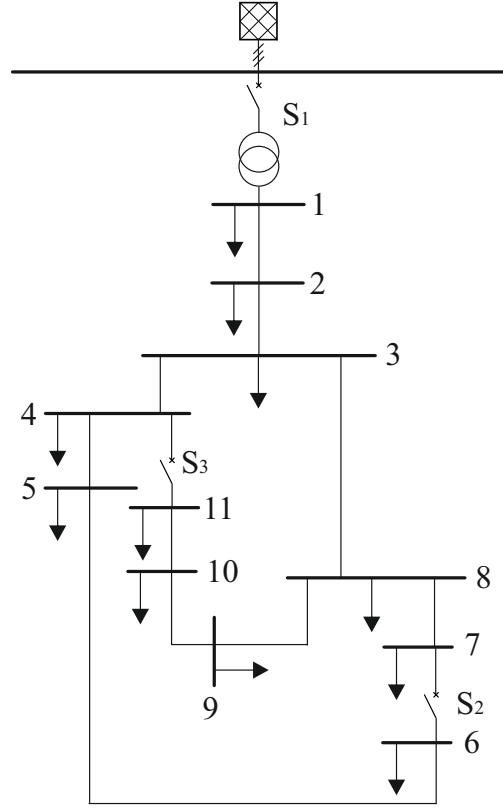


Fig. 4. Testing feeder

constraints to be respected are the power flow equations defined as:

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{N_L} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)] \quad (5)$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{N_L} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)] \quad (6)$$

for $i, j = 1 \dots N_L$, where N_L is the number of buses; P_{Gi} and Q_{Gi} are active and reactive power generation at bus i respectively; P_{Di} and Q_{Di} are active and reactive power load at bus i ; and G_{ij} and B_{ij} are transfer conductance and susceptance between bus i and bus j , which derived from admittance matrix.

The inequality constraints to be respected are defined as follows:

1). the voltage of the grid should be kept within the limits:

$$0.95 \leq V_i \leq 1.05 \quad (7)$$

where V_i represents the voltage of the bus i .

2). the variation of active power in Case 2 should be kept within the limits:

$$0.9 \cdot P_{i,LV} \leq P_{i,LV} \leq 1.1 \cdot P_{i,LV} \quad (8)$$

where P_i represents the active power consumed by ST connected LV grid.

For Case 1, the optimization results of reactive power provided from STATCOM and ST are compared. Furthermore, let $S_P = P_{ST}$ represent that maximal amount of active power which ST needs to deliver to LV grid. Q_{ST} is the minimal reactive power which the MV converter of ST needs to provide to MV grid. The size of ST MV converter must be increased to:

$$S_{Case1} = S_P + jQ_{ST} \quad (9)$$

The increased size is ΔS_{Case1} :

$$\Delta S_{Case1} = S_{Case1} - S_P \quad (10)$$

ΔS_{Case1} and the corresponding cost are computed. As discussed aforementioned, besides reactive power support, the ST needs to transfer power to feed LV grid connected loads. Thus, in order to make a fair comparison, the cost increment caused by the reactive power compensation in the ST is considered to compare with the cost of STATCOM.

For Case 2, the minimal size S_{Case2} of ST is computed and compared with the size S_{Case1} . The increased size ΔS_{Case2} and the corresponding cost are computed.

V. CASE STUDY

The 2 different cases with above 3 scenarios respectively are executed.

A. Case 1

The voltage variations of the feeder are the same after the implementation of voltage support from STATCOM and ST.

The results of Q_{STAT} , Q_{ST} , and ΔS_{Case1} are listed in Table IV. From 3 scenarios, it is observed that, in order to have the same performance, the minimal reactive power provision of STATCOM is always more than ST. The STATCOM needs to inject at least 13% more of reactive power than ST (scenario 3). There reason for the addition reactive power from STATCOM is due to that in a grid with ST, the reactive power in LV grid does not affect the MV grid (in scenario 3, $100kVar$ of reactive power is decoupled by ST).

TABLE IV
PROVISION OF REACTIVE POWER AND INCREASE SIZE OF ST

Scenario	Q_{STAT}^1	Q_{ST}^1	$S_{Case1}^{2,3}$	ΔS_{Case1}^2	Q_{STAT}/Q_{ST}
1	911	791	993	393	1.15
2	838	718	935	335	1.17
3	877	777	924	424	1.13

¹ in $kVar$

² in kVA

³ P_{ST} is $600kW$ of S1,2 and $500kW$ of S3

The rated power of ST MV converter needs to be increased to provide the reactive power. Due to the different sensitivity of voltage/reactive power, at Bus 6, the ratio of increased rated power is 56%, at Bus 10, the ratio reaches 85%.

The cost of STATCOM and the additional size ΔS of scenario 2 (lowest cost) is listed in Table VI.

In order to provide reactive power to grid, the cost of STATCOM and additional cost of ST are at the same level. The lowest cost derived from Scenario 2 shows that the solution of ST is even cheaper than the solution of STATCOM.

B. Case 2

The voltage variations of the feeder in Case 2 are the same as that with ST in Case 1.

The size of ST for both cases are listed in Table V. It is concluded that, by applying the function of load reduction along with provision of reactive power, the size of ST can be reduced. This reduction depends on the sensitivity of voltage/active power. At Bus 6, the maximal reduction of 7.2% is derived and the minimal reduction is derived at Bus 10, which is 5.7%

TABLE V
PROVISION OF REACTIVE POWER AND INCREASED SIZE OF ST

Scenario	S_{Case1} (kVA)	S_2^* (kVA)	Size reduction (%)
1	993	927	6.6
2	935	868	7.2
3	924	871	5.7

The cost of STATCOM and the additional size ΔS_{Case2} of Scenario 2 (lowest cost) is listed in Table VI. With the operation of active power, the additional cost of ST is smaller than the cost of STATCOM.

TABLE VI
COST OF STATCOM AND ADDITIONAL SIZE OF ST

Item	STATCOM	ST	
		Case 1	Case 2
Component (Euro)	33520	40200	32160
Space (Euro)	9100	0	0
Total (Euro)	42620	40200	32160

VI. CONCLUSION

The distribution grids need to be upgraded to satisfy increasing energy demand, maintaining safety operation. The capability to assist the grid operation of STATCOM and ST has been studied in this paper. The cost and services of both devices have been analyzed by literature review. To study the performance of both devices, the simulation is implemented with CIGRE MV grid. Scenarios of different location in the grid are considered. The results show that ST has more freedom of controllability and provides more ancillary services to grid. To support the voltage in MV grid by providing reactive power, ST achieves the same performance as STATCOM but with less investment. The flexible active power flow control can further reduce the cost of ST with the same voltage support performances.

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