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STATCOM optimal placement method applied to a Swiss urban distribution network considering future photovoltaic integration scenarios

Guillaume Courteau
IESE
HES-SO // HEIG-VD
Yverdon-les-Bains, Switzerland
guillaume.courteau@heig-vd.ch

Enea Auberson
ENERGY
HES-SO // HEIA-FR
Fribourg, Switzerland
Enea.Auberson@hefr.ch

Patrick Favre-Perrod
ENERGY
HES-SO // HEIA-FR
Fribourg, Switzerland
patrick.favre-perrod@hefr.ch

Olivier de Marignac
Services Industriels de Lausanne
Lausanne, Switzerland
olivier.demarignac@lausanne.ch

Mokhtar Bozorg
IESE
HES-SO // HEIG-VD
Yverdon-les-Bains, Switzerland
mokhtar.bozorg@heig-vd.ch

Mauro Carpita
IESE
HES-SO // HEIG-VD
Yverdon-les-Bains, Switzerland
Mauro.Carpita@heig-vd.ch

Abstract—**This paper proposes a pragmatic oriented exhaustive method to select a location that maximises the steady-state support of a static synchronous compensator (STATCOM) in a MV distribution network. This method is intended to be used during preliminary study, when STATCOM size and control strategy are not yet defined. To choose the most effective location, performance indices based on the network's required behaviour need to be defined. The presented method was designed in the frame of a research project named COSTAM, dealing with STATCOM behaviours in a real MV distribution network with massive photovoltaic (PV) production. The proposed method was applied to a real case MV network considering future PV integration scenarios. Network modelling, load/generation scenarios based on 2050 PV integration forecast, performance indices and STATCOM control strategies were defined for this case study, leading to the optimal STATCOM location selection. Method and results applied to this case study are detailed in this article to illustrate the general method. The main advantage of this method is its pragmatic approach. It is easily applicable by Distributed System Operators (DSO) in their network.**

Keywords—D-STATCOM, optimal placement, pragmatic method, steady-state, distribution network, photovoltaic integration, Distributed Generation, performance index, control strategy, load/generation scenarios forecast

I. INTRODUCTION

Distributed Generation (DG), mainly based on Renewable Energy Sources (RES), is rapidly increasing worldwide to face the foreseen lack of fossil energy as well as to counteract climate change and air pollution. In order to reduce its net greenhouse gas emissions to zero, the Swiss government has settled its energy strategy for 2050 [1].The aim is to meet the internationally agreed goal of limiting global climate warming to a maximum of 1.5° C versus the pre-industrial period. This strategy includes massive RES integration into distribution networks. Although DGs could take some advantages from RES production such as sustainability, less maintenance and low carbon emission, DGs power injections can cause power quality and reliability issues, such as voltage fluctuations, poor power factor and harmonics generation. Furthermore, it may increase the distribution system losses [2], [3]. Notwithstanding all these issues, distribution network has to address national grid-codes and of course reduce losses. Power electronics technologies, like Flexible Alternating Current Transmission Systems (FACTS) gain in attractiveness in distribution networks to address these grid-codes. They can provide a solution for reactive power compensation and unbalance loading in distribution system under both steady state and dynamic system conditions [4]. However, these devices must be placed in an effective way to maximise their support to the network.

This paper focuses on Distribution-STATCOM (D-STATCOM) topology of FACTS. It proposes a method to select a Point of Common Coupling (PCC) that maximises the steady-state STATCOM support to the MV network. This method utilises a network model, load/generation scenarios, different performance indices, STATCOM control strategies and nominal reactive powers to assess of the most suitable location. The general method is proposed in section II. This method was created specifically to allow the DSO to have a pragmatic tool in the frame of the COSTAM research project, which is still ongoing. This project deals mainly with the STATCOM behaviours in a real MV distribution network with the hypothesis of massive PV production. This method is verified on a real network case study including its PV production forecast until 2050. The case study is a portion of Lausanne (Switzerland) MV network. Information on the MV network is provided by Services Industriels de Lausanne (SIL) DSO, a partner of the COSTAM project. Section III describes the model of case study MV network used for the simulation. Load/generation scenarios based on PV production forecast until 2050 are explained in section IV. Specific performance indices and STATCOM control strategies designed for the case study are presented respectively in sections V and VI. Descriptions on how the general method was applied to the case study are given in section VII. The results of the applied method to this case study are proposed and discussed in section VIII. The conclusions of this paper are presented in section IX.

II. OPTIMAL STATCOM PLACEMENT IN DISTRIBUTION NETWORK: GENERAL METHOD

Many different papers as [5] and [6] use different indices in base case scenario to preliminary select possible optimal locations to integrate a STATCOM. Then the effects of the STATCOM is evaluated only at these specific locations. The method presented in this section aims to select an optimal STATCOM location inside a MV network via an exhaustive approach.

A. Key features of the method

The key features of the method are:

- A lumped parameter model of the lines, cables, transformers and other components of the network to study in a specific power system simulation software

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This paper is based on the results of the COSTAM project funded by Swiss Federal Office of Energy (SFOE). We would like to thank them for the financial support.

- Several load/generation scenarios over one year of each MV/LV substation of the network
- A set of performance indices that allows to assess of the STATCOM benefits in a particular location
- Different control strategies the DSO is able to apply to its network

B. Optimal STATCOM placement method

After the network lumped parameter model is implemented in the power system simulation software, several load/generation scenarios over one year of each MV/LV substation of the network and inside the MV network need to be created. These forecast scenarios will give a more accurate result for STATCOM placement considering future DG integration.

Then based on these scenarios, the main issues the network will face (i.e. steady state, dynamic, protection problems and others) must be identified. It will allow to define the most suitable performance indices to assess of the network state. In the same time, it will be possible to decide how to control the STATCOM.

Once all these elements are defined, the idea is to simulate over a sufficient period of time and with a sufficient time resolution, the multiple load/generation scenarios above mentioned without STATCOM for a first time. Thanks to the performance indices previously defined, a reference case score is found. This reference score is used to assess the STATCOM support to the MV network.

Then the idea is to simulate again the multiple load/generation scenarios above mentioned with the different STATCOM control strategies, placing the STATCOM successively at all the MV/LV substations in the network. Given that this method applies to preliminary study, the STATCOM rated power is not defined yet. It means multiple STATCOM nominal reactive power has to be tested too. At least three "sets of simulations" must be carried out.

The first "set of simulations" is done with unlimited reactive power availability for the STATCOM. The control strategy is free to determine the amount of reactive power to inject in the network. This "set of simulations" allows to determine the maximum reactive power required by the STATCOM at each position. In the same time, a score based on the performance indices has to be calculated for each possible STATCOM location.

The second and third "sets of simulations" are based on a limitation of the nominal reactive power, lower than the maximum value of the first trial. Reducing the nominal reactive power allows to optimise the system from the losses point of view. This reduction is also beneficial from the cost point of view. A reasonable value of nominal power has of course to be chosen, based on the first "set of simulations" results. As done for the first "set of simulations", a score based on the performance indices has to be calculated for each possible STATCOM location.

Based on these three "sets of results", an adequate range of power should have been reached to choose the best STATCOM location. Finally, the optimal location to install the STATCOM is the one with the best average ranking over the three "sets of simulations".

Other sets of simulations could be realised between minimum and maximum values chosen to obtain more accurate results. However, the drawback is important calculation time for large networks, which is the case here.

This general method of optimal STATCOM placement in distribution network was applied to a Lausanne MV network portion in the context of COSTAM project. The following sections present it.

III. LAUSANNE MV NETWORK SIMULATION MODEL

In this work, a portion of the Lausanne MV network is studied. A topological representation of the network is shown in Fig. 1. This portion is fed by one HV/MV transformer. This transformer corresponds to the square node number 1 (orange). The other round nodes (green) represent MV/LV substations. Each MV/LV substation is named by a number. In this network, the possible STATCOM locations are all chosen to be at the various MV/LV substations. This is a reasonable choice to explore the whole network without having too many locations to investigate.

In order to perform this study, it was necessary to establish a model in a suitable network simulation package. In our case, PowerFactory was chosen. The basis for the creation of network model were the following:

- The network topology was extracted from DSO database. This included the topology of lines, cables, nodes, switchgear and transformers in HV, MV and LV. Information regarding boundaries to other systems is included. Some manual adjustments were made based on plausibility checks in order to obtain a valid topology.
- The characteristics of network elements (such as impedances, etc.) have been selected based on typical component data and where possible, based on available information from the DSO database.
- Controller information of the HV/MV transformer were mainly based on a discussion with the DSO.

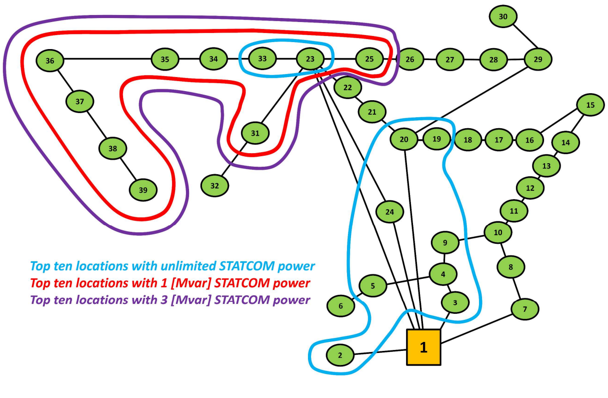

Fig. 1. Topological representation of MV network studied with best location areas to install STATCOM surrounded

IV. LOAD/GENERATION FORECAST SCENARIOS BASED ON PHOTOVOLTAIC PRODUCTION

As mentioned in the introduction, Swiss government has settled its energy strategy for 2050 including important increase of PV production all over the country. One of the COSTAM project goals was then to assess the effectiveness of using a STATCOM in a MV network considering high increase of PV production. It was necessary to create different load/generation scenarios. The scenarios were calculated over one year with 1-hour resolution for effective steady-state simulation accuracy as well as considering PV generation during each day.

The first scenario is based on 2019 measurements. HV/MV transformer load profile was based on current measurements by assuming nominal voltage. The one-year HV/MV transformer load profile with 1-hour resolution is shown in Fig. 2. The annual energy consumption of each MV/LV substation as well as the nominal powers of the transformers were used to approximate MV/LV transformers load profile without generation. Given that an urban network is considered, RES production is only based on PV. The annual solar irradiance profile has been obtained from a measurement station close to Lausanne. These data, combined with the nominal power of PV systems extracted from the DSO database, were used to create the generation profile of each secondary substation. The total PV generation in each LV grid is aggregated into a single generation unit connected to the LV side of the distribution transformer. PV generators directly connected to the MV grid are modelled individually.

Then 2030, 2040 and 2050 load/generation scenarios are also calculated to assess of the STATCOM benefits with high PV production inside the MV network. Load profiles are kept the same as from 2019 scenario, supposing no consumption evolution until 2050. PV production scenarios were realised based on the overall PV power forecast in Switzerland. Swiss PV production statistics from 2010 to 2019, taken from [7], were compared to Lausanne network PV production evolution (data provided by SIL). Results show the same trend. Based on this evaluation, on Swiss Federal Office of Energy (SFOE) forecasts for all Switzerland until 2050 [1] and on the 2019 installed power in the studied network (1.55 MW), it was possible to estimate the PV production forecast for 2050 in the studied network. Based on this MV network 2050 PV production forecast, the 2050 distribution between all MV/LV substations was based on the ratio between the total PV production in 2050 and the rating power of each MV/LV substation. Then, the distributions for 2030 and 2040 were realised to maximise the unexploited PV potential until 2050. It finally led to forecasts summarized in Table I.

TABLE I. 2030, 2040 AND 2050 PV NOMINAL POWER FORCASTS FOR LAUSANNE NETWORK PORTION STUDIED

Year	***2030***	***2040***	***2050***
PV nominal power forecast [MW]	2.1	4.7	7.9

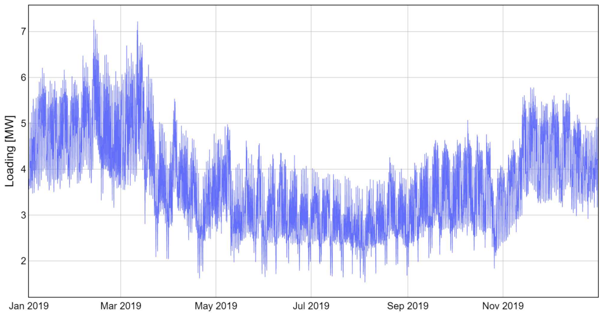

Fig. 2. Load profile of HV/MV transformer over one year, used in all scenarios

V. PERFORMANCE INDICES AND RANKING DEFINITION

As already mentioned, this paper focuses on STATCOM steady state operation, so voltage variation and power losses are the major issues to be solved in MV network [8].

A. *Primary performance indices definition*

To assess these issues on the considered network, multiple indices already exist. For example, optimal placement of D-STATCOM was already realised using "power loss index" in [9]. Another example concerning voltage stability, used a "reactive power index" for D-STATCOM optimal placement in [10]. In our paper, four primary indices are taken from a former project dealing with a Soft-Open Point demonstrator [11]. They can be defined as follows:

- Voltage index: it considers maximum voltage magnitude variation for each bus connected to a load in the network. The maximum voltage variation margin is set to 3%.
- Current index: it introduces a penalty for lines that are loaded more than 50%. It gives an insight of the overall lines/cables loading in the network.
- Transformer loading index: it indicates the peak load of the HV/MV transformer reached during simulations, in per-unit.
- Network losses index: it allows to assess of overall network losses. It computes the mean value of total losses during simulation, in per-unit. In this paper, total losses include lines/cables, transformers and converter losses (if STATCOM is connected).

One primary index for each one of the four categories above mentioned is calculated during "one simulation for each possible STATCOM location". In this paper, "one simulation for each possible STATCOM location" means one-year QDS simulation with 1-hour resolution considering all load/generation scenarios while one STATCOM location is fixed, one STATCOM power is fixed and one control strategy is used.

B. *"Intermediate index" definition*

When the "one simulation for each possible STATCOM location" is realised for every possible STATCOM locations, we can say that one "control set of simulations" is completed. It means that each possible STATCOM location contains a vector with its four primary indices considering one fixed STATCOM power and one control strategy.

To avoid huge gaps between primary indices of the same category in each "control set of simulations", they are normalised by category. This means that each normalised primary index value of the same category for each possible STATCOM location in each "control set of simulations" can vary between 0 and 1.

To assess each STATCOM location effectiveness in each "control set of simulations", the four normalised primary indices of each possible STATCOM location are summed together with the same weighting (no normalised primary index is dominating). The result is called "intermediate index". At this stage, each STATCOM possible location holds an "intermediate index" assessing of its effectiveness compared to other locations, considering a fixed STATCOM power and one particular control strategy.

C. *"Power index" definition*

In order to compare different STATCOM powers, another index called "power index" is introduced. This index is the multiplication of "intermediate index" with maximum STATCOM reactive power reached during "one simulation for each possible STATCOM location" (in Mvar for this paper). At this stage, each STATCOM possible location holds a "power index" assessing of its effectiveness, considering a fixed STATCOM power and one particular control strategy.

D. *"Score" definition*

In order to consider all control strategies in the STATCOM possible locations ranking process for one nominal STATCOM power, a last grade called "score" is calculated by adding "power index" of each control strategy. This "score" is used to rank the STATCOM possible locations between each other considering one nominal STATCOM power.

E. *Ranking definition*

All primary indices indicate the level of issues in the network. It means, the lower they are, the better the network state is and, consequently, the lower are the normalised indices, the better the network state is. "Intermediate indices" come from the sum of normalised indices, so the lower they are, the better the network state is. Lower STATCOM maximum reactive power reached during simulation implies lower technical and financial effort to achieve this performance. It means, the lower the "power indices" are, the better the network state is. The "scores" being the sum of "power indices", the lower they are, the better the network state is.

Based on the above paragraph and considering a fixed STATCOM power, the STATCOM location with the lowest "score" is the optimal location according to this scoring process. Then a ranking is made.

In this paper, as mentioned in section II, three different "sets of simulations" with different maximum STATCOM powers are realised. Each "set of simulations" holds its own ranking of STATCOM locations. To get the optimal STATCOM location over all the "sets of simulations", the average ranking over the three "sets of simulations" is calculated. STATCOM location with the lowest average ranking is the optimal location.

VI. CONTROL STRATEGIES DEFINITION

The effect of the STATCOM on the network performance indices will largely depend on the specific control being applied. As already mentioned, this paper focuses on a real case scenario. It means that different DSOs should be able to set up these control strategies in their own network. A number of three different control strategies were performed in order to have enough control to be representative without having too many controls and keep a reasonable simulation process time. These control strategies are described in the following subsections.

A. *Control the busbar at which the STATCOM is installed to 1 pu*

In the MV network of this paper, the HV/MV transformer is not continuously regulated using On-Load Tap Changers (OLTC). Instead, the HV is controlled. The result is that all MV buses voltages will vary slightly more in this case. This will be worsened in our case because of the increasing of PV production. This is why the MV busbar voltage at which the STATCOM is installed is proposed to be regulated to 1 pu.

B. *Control the highest voltage difference between MV busbar and secondary busbar of HV/MV transformer to zero*

The variation of voltage during the day increases due to load and generations. Some buses can have important voltage variations with respect to secondary busbar of HV/MV transformer. This STATCOM control aims to decrease this extreme voltage difference.

C. *Control the reactive power exchange with the HV network to zero*

This control aims to reduce the adverse influence of the loaded MV network lines/cables on the HV network.

VII. DETAILED LAUSANNE CASE STUDY APPLIED METHOD

This section applies the general method described in section II to the specific case study of Lausanne MV network.

As described in section III, the network model was realised in PowerFactory. The load/generation scenarios predicting the future PV production until 2050 are presented in section IV. As already mentioned in previous sections, this study focuses on steady state issues of the MV network leading to the specific performance indices as well as ranking process defined in section V. The control strategies used in this case study are explained in section VI and recalled in Table II.

For reader's better understanding, it is recommended to read this section while watching the flux diagram of the process to calculate the "score" for each possible STATCOM location, in the 1 Mvar "set of simulations" shown in Fig. 3.

As announced in general method of section II, a previous "set of simulations" is realised without STATCOM. It means that the modelled network without STATCOM is simulated in four PowerFactory simulations, one for each PV production scenario. One Quasi Dynamic Simulation (QDS) by PV production scenario is realised over 1 year, with 1-hour resolution. These settings for reference case "set of simulations" are summarized in Table II. Results are presented in section VIII.

TABLE II. SETS OF SIMULATIONS SETTINGS FOR EACH POSSIBLE LOCATION

Set of simulations title	***Reference case***	***Unlimited power***	***1 Mvar***	***3 Mvar***
Maximum STATCOM power allowed	No STATCOM	Unlimited	1 Mvar	3 Mvar
Type of simulation	Quasi Dynamic Simulation (QDS)			
Duration time	One year			
Time resolution	1 hour			
Control strategies used	No control	• Control the busbar at which the STATCOM is installed to 1 pu • Control the MV busbar with the highest voltage variation with respect to secondary busbar of HV/MV transformer • Control the reactive power exchange with the HV network to zero		
Load/generation scenarios	• 2019 current scenario • 2030 forcast scenario • 2040 forcast scenario • 2050 forcast scenario			

For this study, three “sets of simulations” with STATCOM are realised. The settings for the three “sets of simulations” are also summarized in Table II. A first “set of simulations” is done with unlimited reactive power availability for the STATCOM. The second “set of simulations” limits STATCOM nominal power to 1 Mvar. This limitation is chosen because during the first “set of simulations” (considering all possible STATCOM locations and control strategies), it was seen that the STATCOM power was essentially in the range of 1 to 4 Mvar. The maximum power measured was a bit more than 5 Mvar. The STATCOM power limitation for the last “set of simulations” was chosen equal to the average between the 5 Mvar maximum power reached and 1 Mvar. This led to 3 Mvar limitation.

Each “set of simulations” of Table II is realised for every STATCOM possible locations. As mentioned in section V, a “score” for each STATCOM possible location in each “set of simulations” is calculated. These “scores” are presented in the next section as well as the process until the optimal STATCOM location selection for our case study.

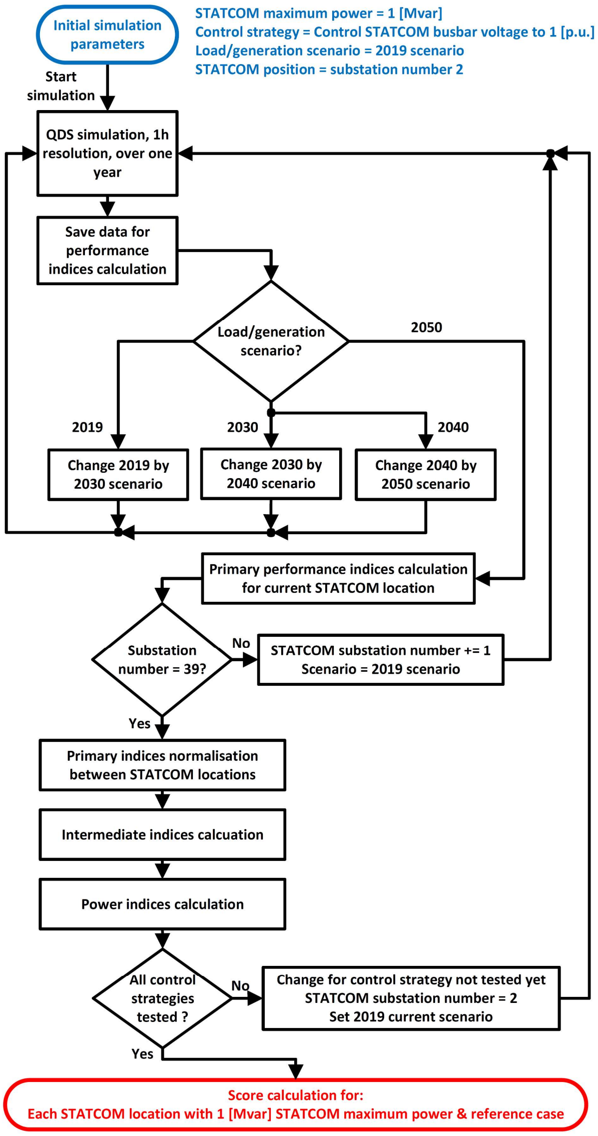

Fig. 3. Simulation process to calculate the “score” for each possible STATCOM location in 1 Mvar “set of simulations” (considering reference case “set of simulations” already done)

VIII. OPTIMAL STATCOM PLACEMENT RESULT FOR LAUSANNE CASE STUDY

All main results are proposed in Table III, table IV and table V, as well as in Fig 1. These tables expose the top ten best STATCOM locations respectively for unlimited power, 1 Mvar and 3 Mvar “set of simulations”. Furthermore, they provide reference case “intermediate score” (normalized with each “set of STATCOM simulations”). Each table provides the STATCOM substations number in reference to Fig. 1, the “power indices” for each control and the “score” of each STATCOM location. These top ten STATCOM locations are ranked from the best one to the worst one (from the lowest to the highest “score”) in each table.

Given that the ten best locations are the same for 1 Mvar and 3 Mvar while at the same time only substations number 23 and 33 are part of top ten in all “sets of simulations”, the only possible candidates to the optimal STATCOM location are substations number 23 et 33. Their average ranking over the three “sets of simulations” are respectively 4 and 4.3. It means that according to the method presented in this paper, substation number 23 is the optimal location to connect the STATCOM in the MV network studied. Interestingly, this optimal location is favourable for every STATCOM power considered. This is probably due to its well interconnected position in this network.

TABLE III. TOP TEN STATCOM SUBSTATIONS RANKING FOR UNLIMITED SET OF SIMULATIONS AND REFERENCE CASE

STATCOM substation number	***Power Indices***			***SCORE***
	Local busbar at 1 pu	***Busbar with max deviation with feeder transfo secondary***	***Q flow at feeder transfo fixed at 0 var***	
2	0.753	1.362	0.440	2.555
3	0.786	1.424	0.445	2.655
23	1.187	1.631	0.241	3.059
33	1.281	1.573	0.207	3.061
24	1.029	1.675	0.487	3.191
4	1.122	1.743	0.505	3.370
20	1.254	1.964	0.503	3.721
9	1.322	1.935	0.577	3.834
5	1.360	1.963	0.601	3.924
19	1.434	2.115	0.542	4.091
Reference case	0.506	0.504	0.513	

TABLE IV. TOP TEN STATCOM SUBSTATIONS RANKING FOR 1 MVAR SET OF SIMULATIONS AND REFERENCE CASE

STATCOM substation number	***Power Indices***			***SCORE***
	Local busbar at 1 pu	***Busbar with max deviation with feeder transfo secondary***	***Q flow at feeder transfo fixed at 0 var***	
39	0.070	0.045	0.048	0.163
38	0.071	0.048	0.050	0.169
37	0.076	0.053	0.055	0.184
36	0.083	0.059	0.060	0.202
35	0.099	0.072	0.072	0.244
34	0.122	0.091	0.085	0.298
33	0.158	0.124	0.097	0.379
23	0.216	0.168	0.144	0.528
25	0.220	0.180	0.156	0.556
31	0.222	0.180	0.155	0.557
Reference case	0.725	0.749	0.691	

TABLE V. TOP TEN STATCOM SUBSTATIONS RANKING FOR 3 MVAR SET OF SIMULATIONS AND REFERENCE CASE

STATCOM substation number	***Power Indices***			***SCORE***
	Local busbar at 1 pu	***Busbar with max deviation with feeder transfo secondary***	***Q flow at feeder transfo fixed at 0 var***	
23	0.698	0.322	0.285	1.305
33	0.716	0.453	0.213	1.382
34	0.791	0.582	0.247	1.620
31	0.827	0.488	0.351	1.666
35	0.806	0.659	0.234	1.699
36	0.816	0.733	0.215	1.764
25	0.866	0.542	0.380	1.788
37	0.824	0.770	0.216	1.810
38	0.834	0.813	0.219	1.866
39	0.838	0.853	0.227	1.918
Reference case	0.506	0.515	0.528	

Some other interesting remarks can also be raised. In Fig 1., the top ten STATCOM locations for each "set of simulations" are surrounded. It can be seen that the more STATCOM power is, the closer from HV/MV transformer the best locations are. Conversely, the less STATCOM power is, the more the distance between the best locations and HV/MV transformer is. Furthermore, radial nodes seem more attractive with less STATCOM power.

It is interesting to see that, even if the ranking is not the same, top ten locations contains the same substations for both 1 Mvar and 3 Mvar "set of simulations".

The reference case "intermediate indices" and "power indices" were added in the results to show the STATCOM controls effectiveness. In 1 Mvar "set of simulations", reference case "intermediate indices" can directly be compared with STATCOM "power indices". Indeed, in this case, "intermediate index" and "power index" are the same. From Table IV, it is possible to see that STATCOM is always beneficial because their indices are far lower than reference case ones whatever the substation and the control. Knowing that each maximum STATCOM power reached are around 5 Mvar in Table III and around 3 Mvar in Table V, leads to the same conclusion as for 1 Mvar "set of simulations". STATCOM is always beneficial for the network.

IX. CONCLUSION

In this paper, an optimal placement method of D-STATCOM in a preliminary study considering steady-state operation was proposed. The ranking principle, based on losses and voltage stability improvement, includes different easy to understand indices to calculate. Furthermore, although STATCOM controls are voluntarily basic, because DSO must be able to implement them in real, they are effective to improve the network. It should be noticed that an important effort on network modelling and load/generation scenario creation are necessary to get consistent results. One noteworthy drawback is that this method is unable to treat dynamic situations like post-fault recovery or flickers. In this paper, the method proposed was applied on a portion of the real Lausanne MV network. MV/LV substation number 23 is the optimal STATCOM location. In this network and based on this method, the optimal STATCOM location is the most interconnected MV/LV substation. To go further, it should be interesting to use another placement method and compare the results with the ones of this article.

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