

# STATCOM Application for Voltage Profiling of a Distribution Grid with High Penetration of Distributed Energy Resources

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## Abstract

Distributed energy resources influence the power grid due to the low visibility of network operators towards distribution system. These resources cause reactive power imbalance, and thus puts a question mark on voltage loading of the grid. The paper discusses these effects of distributed energy resources on the node voltages of an Italian distribution grid. The paper analyses these effects on node voltages, and explains the common procedure and issues of reactive power provision by conventional synchronous generators, mostly through conventional coal and combined cycle power plants. To avoid these issues, the paper then investigates among different compensation techniques for the provision of reactive power. The comparison justifies the use of STATCOMs at the medium-voltage distribution nodes, and then discusses how the STATCOMs can add flexibility to the grid in terms of reactive power provision. The paper compares the effects on node voltages before and after the utilization of STATCOM device, with graphical representation of the analysis performed.

## 1 Introduction

There is a large diffusion of distributed energy resources these days, and it cause problems for both the distribution and transmission network operators, especially with respect to the hosting capacity, as discussed in [1]. The issues are discussed in [2-4], where the focus is to improve voltage stability, quality, billing, and efficiency of the grid. These distributed resources require changes in the grid for proper operation of the system. Details with respect to photovoltaic are available in [5].

One of the adverse effects of these distributed resources is the imbalance of the reactive power at the distribution side of the power system. These mismatches cause the violations of the voltage limits at the distribution nodes, which affects all sectors of the power system in terms of line loading and voltage at different nodes of the system, as discussed in [6]. However, the other important reason for reactive power imbalance is the transmission lines for which the details and solutions are addressed in [7] [8] [9]. Transmission lines are not considered in the context of this paper.

The paper illustrates the effects of these distributed energy resources on the node voltages of a medium-voltage distribution grid. The distribution grid is discussed in section 2. The grid is modelled in DIgSILENT; the static load flow analysis and the quasi-dynamic analysis for the network are performed to analyse the voltage loading of the grid (before the inclusion of distributed energy resources).

Section 3 is dedicated for the modelling of distributed generation sources, and the impacts on voltage loading with respect to them. The generation profiles for the four types of distributed resources, i.e. hydro, combined cycle, wind and solar are modelled and defined in DIgSILENT.

Section 4 discusses different techniques for the reactive power, and analyses how STATCOMs can generate flexibility for reactive power provision. The STATCOMs are added at the distributed generators described in section 3, and then the node voltages are investigated. Section 5 compares the node voltages, with and without the addition of STATCOMs. Section 6 concludes the paper.

## 2. Description of the Analysed Distribution Network

The distribution network used is a published urban network in Italy, which is the part of the dissemination of the project called ATLANTIDE as in [10] [11] [12] [13]. The network has 103 nodes, and 7 feeders that serve the MV loads. The feeders are further connected to the LV loads via load transformers.

There are 190 loads in total. The distribution transformer serves the MV end with 20KV, which is stepped down from 150KV at HV transmission end. This transmission system is under the control of TSO, which has the visibility to both generators and primary substations. This is as per the Italian power system structure as in [14]. The nominal rating of

apparent power by generator, and the active and reactive power ratings are parts of the grid data.

The project ATLANTIDE as in [10] [11] [12] [13] discusses the overall details of the network, which include the topology, voltage levels, profiles of distributed energy resources etc. The effects of the high penetration of distributed energy resources on the Italian grid are well discussed in the project, and all these details are skipped in this paper.

However, the idea presented in the paper is to model the distribution system and then select a representative feeder, and some nodes to carry out the analysis for voltage loading, the effects of wind and solar penetration, and the cascaded impacts. After that, the cascaded impact is compared with the addition of STATCOM. SIL of real grid, grid data, and generation profiles are skipped to avoid copyright issues.

The idea is to use DGS (DIgSILENT Interface for GIS and SCADA), and to create the excel file with the representation of the network. The excel file is then imported into DIgSILENT using the DGS import facility. The procedure to create the excel file is discussed in [15] [16] [17]. Other relevant details are in [18] [19]. The general and the object tables are created, and the parametric values of the network are converted into the format supported by DGS.

One of the major object tables is ElmLne, which is used to define the data for lines and cables. Per length values of the positive, negative, and zero sequence resistances, capacitances, and inductances are described in TypLne, along with the rated current and voltage of each type of line. Some of the line sections are also created using the ElmLnesec object table [15] [16] [17] [18] [19].

The loads are defined in the object table called ElmLod. Next step is to define the buses and nodes using ElmTerm, where the nominal line-to-line voltage of the nodes are mentioned. With the iUsage field in the object, the nodes of this distribution system are indicated as either bus bar, junction, or internal node [15] [16] [17] [18] [19].

The external grid feeding from 150KV end and the distributed generators are explicitly mentioned in object table called ElmXnet, with the potential to indicate operating real power, reactive power, voltage, and torque angle. Other object files include the StaCubic, StaSwitch, and ElmShnt, which define the shunts, breakers, and switch details [15] [16] [17] [18] [19].

The remaining component is the distribution transformer, which is defined using ElmTr2 and TypTr2 object tables. In this way, the excel file can indicate DIgSILENT of how each of the components are connected to each of the terminals. The graphical coordinates of the terminals are mentioned in the object file called IntGrf [15] [16] [17] [18] [19].

After exporting the excel file into DIgSILENT, a .PFD file is generated which allows to edit the data for the network using the Network Model Manager. The manager gives access to all the components, types of components, and the terminals, where all the parameters of basic data, load flow, and other operations can be edited. This is the place where the transformers at the loads are also defined.

The step now is to define the area, feeders, and zones so that the grid is represented in a standard way. Within an area, seven feeders are defined for a particular defined zone. The feeders are marked with different colours in order to make the simulations in a friendlier version. The feeders and grid are well represented in DIgSILENT.

The network is now ready with all the required parameters, and thus the next step is to perform the load flow analysis. It requires defining the PQ, PV, and slack buses. All the loads are defined as PQ buses (with the ratings already mentioned in the network manager), and the external grid is considered as slack bus (ignoring the distributed generators). The load-scaling factor is set to 100% now for all the loads. The load flow is run, and the Newton-Raphson algorithm is converged with three iterations. The software generates a load-flow calculation report.

To analyse the behaviour of grid, it is not sufficient to perform load analysis for a static time instant. It is therefore necessary to perform the load flow for a period, and to see the behaviour of voltage at nodes, and loading of lines throughout that period. This is in fact the motivation towards the quasi-dynamic analysis, so that the grid behaviour can be analysed through graphs. The step towards this is to define a particular parameter of loads for the window period.

The scaling factor of loads is a parameter that is chosen for the purpose, and the data is defined for a particular day, with increments of 1 hour. Guidelines for the load scaling are taken from [20] [21]. The loads are categorized as aggregators, residential-LV, industrial-MV 1, industrial-MV 2, and industrial-MV 3. These loads are representatives of the loads connected to the distribution network.

The vectors are created for this parameter characteristic of scaling factor by creating ChaVec object table in the excel file. The loads are characterized according to their types by creating ChaRef object table, where each of the load is mapped to one of the types as in ChaVec.

The idea is to create a mixed aggregation and demand response scenario, and the loads are connected in a complex fashion in order to create a better picture for simulations. A 24-hour time scale is created with a window size of 1 hour, using an object table called TriTime. The excel file is now ready with all the parameters for quasi-dynamic simulations, and it is imported to .PFD file of the DIgSILENT. The scaling values for the types of loads are generated in a table for 24-hour scale, and the values for each hour are fed. The software can generate a curve for this discrete values, so that a dynamic picture of simulation is developed. A well-

approximated load-curve is generated for aggregator, and the hermite approximation is used for the creation of curve.

The quasi-dynamic simulations are performed now, and the software requires the time duration and step size for the simulations. In the context of this paper, the time interval is a full day of 7/4/2017, with a 1-minute step size. For better precision, 1-second step-size can be used too; however, it takes a lot of time for the simulations to proceed. The software is capable of producing report based on loading ranges (maximum and minimum in percentage) of components, and the voltage ranges (maximum and minimum in per unit) of nodes. The graphs for behavior of these components and nodes can also be visualized through the software.

Line 2-34 is the one with maximum loading of 97.98%, and it complies that none of the lines is overloaded. The next step is to check for the voltage loading of the distribution grid, such that none of the nodes undergoes under-voltage and over-voltage violations. The voltage is assumed acceptable within the limits of 0.95 per-unit to 1.05 per-unit. The usual medium voltage range of 90%-110% is little under-estimated as the DERs are not simulated in a widespread manner. Lower range is used for more pessimistic bounds. Nodes 2 and 56 experience the maximum voltage of 1.022 per-unit, and node 37 experiences the minimum voltage of 0.97 per-unit. The voltage profiles for the two selected nodes, i.e. 2 and 37, are shown in Fig. 1 and 2 respectively. Thus, there are no issues of line over-loading and voltage instability for the selected grid.

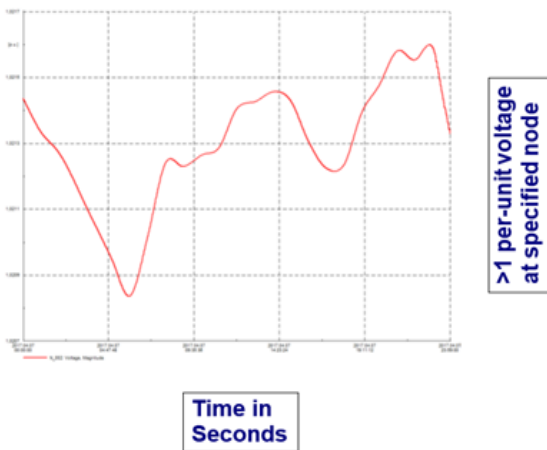


Figure 1 Node 2 voltage in per-unit

### 3. Modelling of Distribution Network

The next step is the addition of distributed resources at some of the selected nodes. It helps to analyse the impacts on the overall stability of the grid. The selected nodes are 9, 36, 44, and 63 with the inclusion of hydro distributed generation, combined cycle distributed generation, wind distributed resource, and solar distributed resource respectively. The inclusion of wind and solar above demonstrate the combined

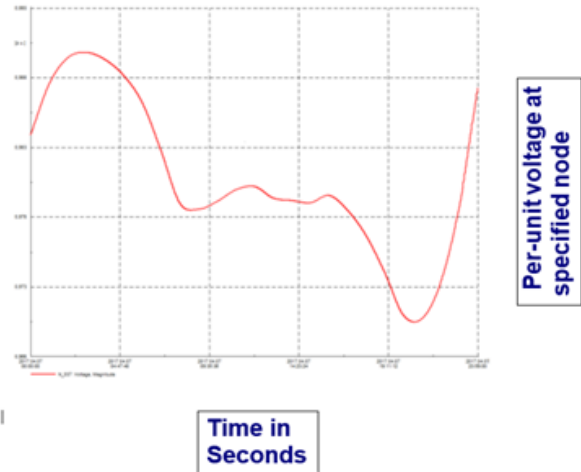


Figure 2 Node 37 voltage in per-unit

effects of wind plants and solar plants on the low voltage nodes for the MV nodes 44 and 63 respectively.

For the quasi-dynamic analysis, the factor of scaling is taken to be the reactive power, which is defined in the same way as the scaling factor for loads in the previous case. This scaling is the representation of the overall impact on the reactive power for the particular node. The four types of the generations are described in the object table ElmXnet, and the vectors for the scaling are created in the ChaVec object table. All the other parameters and representations remain the same.

The quasi-dynamic analysis is performed for the same day, and the results for voltage at nodes, and the line-loading are analyzed. None of the lines violate the loading conditions, which is in accordance with the previous conditions too. However, there are three nodes that violate the over-voltage conditions, and there are eight nodes which are very close to the high-voltage threshold. The results are shown in Table 1, with indications of the maximum encountered voltage by the specified nodes. There are no under-voltage violations.

Table 1 Example Over-voltage violations

Node Numbers	Maximum Voltages in per-unit	Number.
10, 19, and 9(overvoltage)	1.056, 1.056, and 1.052.	1
32, 33, 20, 8, 4, 29, 25, and 18(close to overvoltage)	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, and 1.040.	2

### 4. Modelling STATCOM

Literature suggests many techniques for the compensation of reactive power. The comparison of the techniques are discussed in [22]. The conventional one is the synchronous

generator, with restrictions of real power loss, and the limitations of some system parameters. In fact the conventional method is to provide the excessive reactive power through the synchronous generators; with the capability of real power being compromised for the purpose. The other techniques for reactive power compensation are the use of static capacitors, inductors, and synchronous condensers.

Synchronous Voltage Condenser and STATCOMs are discussed too in [22], and the possibility of using wind farm AC-DC-AC power converters, and solar panels employed inverters are discussed in [23] [24]. The paper [22] suggests the use of STATCOM as a better option in terms of other options, and it concludes that the provision of STATCOM can give flexibility to TSO in terms of reactive power.

There is a possibility of aggregation of different existing reactive power compensation techniques, as illustrated in Fig. 3. The horizontal axis shows the requirement of investments in terms of capital and operating costs, and the loss of real power due to the provision of reactive power. The vertical axis shows the quantity of reactive power capability. Synchronous generators with auxiliary loads and storage are the best options; however, the option of STATCOM is considered in the context of the paper because it has a higher capability with readiness, but at the expense of high costs.

Addition of STATCOM at the generating end (high voltage end) can give relaxation to conventional combined cycle and coal-fired power plants. This section demonstrates the flexibility a STATCOM at high-voltage end can provide. A test case is established in DigSILENT, which includes the electric output end of a coal-fired power plant, and a high voltage cable that connects the electrical output end of the power plant to the point of interconnection. Details of the power plant are out of the scope of the paper, however [25] is followed for the calculation of losses during the proceeding simulations. The variations in voltage (i.e. the reactive power) are incorporated by TSO, and thus the TSO-controller at the point of interconnection provides the reactive power mismatches.

The STATCOM model is taken from [26], which has the capability of 20 MVAR. The reactive power provision is provided through a controller that is in accordance with the power-electronics based components. The STATCOM is connected to the low-voltage end of the transformer to assure the voltage compatibility, and the high voltage end is supplied to the point of interconnection for reactive power provision. Table 2 shows the results of scenarios created with respect to the variations set by the TSO controller.

For the voltage violated distribution grid, the TSO controller manages the reactive power accordingly to counter for the imbalances. The controller sits at the high voltage end of the transmission grid, which senses the mismatches at the transmission lines, and at the distribution grid. For the sake of better understanding of the functionality of the controller, the reactive power losses at the transmission lines are ignored.

Thus, the TSO controller senses the reactive power mismatches, and gets compensation from the conventional power plants.

Table 2 Flexibility for Reactive Power

VAR variations by TSO	Reactive Power Provision by Power Plant	Reactive Power Provision by STATCOM
Increase of 20 MVAR	Supply of 1.36 MVAR	Supply of 18.64 MVAR
Increase of 25 MVAR	Supply of 10.78 MVAR	Supply of 14.21 MVAR
Increase of 35 MVAR	Supply of 16.38 MVAR	Supply of 18.61 MVAR
Decrease of 20 MVAR	Consumption of 1.90 MVAR	Consumption of 21.90 MVAR
Decrease of 25 MVAR	Consumption of 3.11 MVAR	Consumption of 21.88 MVAR
Decrease of 35 MVAR	Consumption of 13.14 MVAR	Consumption of 21.85 MVAR

The flexibility STATCOM can generate to the conventional synchronous generators can be viewed in a different perspective. From the conventional point of view, distributed resources cause reactive power mismatches(hence voltage instability) at the MV node. TSO asks for conventional coal and CCGT plants for the compensation, where STATCOM can generate flexibility in terms of reactive power provision. From another perspective of transmission operator, these STATCOMs can be installed at the distributed generation nodes, where stability can be achieved directly with less remuneration from the power plants.

## 5. Results

The STATCOMs with provision of 2 MVAR are installed at the nodes 9, 36, 44, and 63 where the distributed generators are present. All the other conditions remain the same and the quasi-dynamic analysis are performed. The results are shown in Table 3. It is obvious that the addition of STATCOMs reduce the over-voltage from 1.056 per-unit to 1.052 per-unit at node 10. At other nodes also, the effect is visible, and there are only two nodes (i.e. 10 and 19) now with over-voltages. There is no overloading of lines, and no under-voltage violations.

As per the VQ curve in, and the study in [28] [29], the appropriate ratings of STATCOMs are used, and the curve provides the maximum stability at a value of 1.5 MVAR. The results are shown in the Table 4. There is no overloading of lines, and no under-voltage violations. Table 4 indicates that the grid now with no voltage violations.

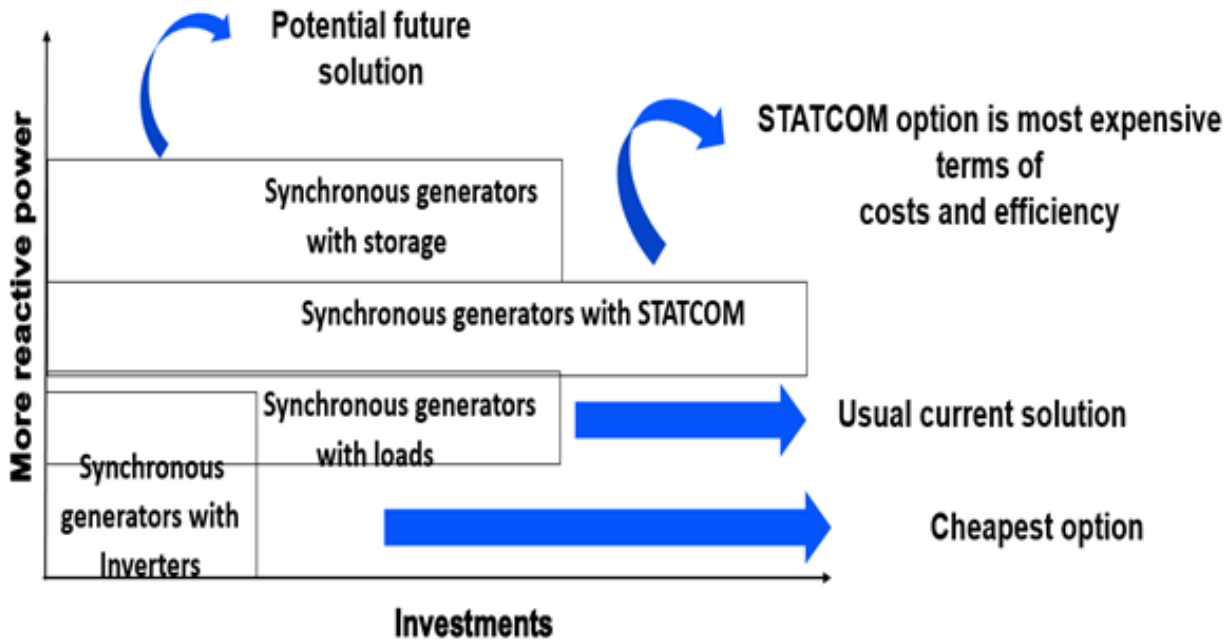


Figure 3 Aggregation Solution

Table 3 Stability after 2 MVAR STACOMs

Node Numbers	Maximum Voltages in per-unit(Before 2 MVAR STATCOM)	Maximum Voltages in per-unit(After 2 MVAR STATCOM)
10, 19, and 9(over-voltage)	1.056, 1.056, and 1.052	1.052, 1.052, and 1.048.
32, 33, 20, 8, 4, 29, 25, and 18(close to over-voltage)	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, and 1.040	1.046, 1.045, 1.040, 1.039, 1.040, 1.038, and 1.037.

Table 4 Stability after 1.5 MVAR STACOMs

Node Numbers	Maximum Voltages in per-unit(Before 2 MVAR STATCOM)	Maximum Voltages in per-unit(After 2 MVAR STATCOM)
10, 19, and 9(over-voltage)	1.056, 1.056, and 1.052	1.047, 1.047, and 1.044.
32, 33, 20, 8, 4, 29, 25, and 18(close to over-voltage)	1.047, 1.046, 1.043, 1.042, 1.041, 1.041, and 1.040	1.043, 1.042, 1.038, 1.037, 1.036, 1.038, 1.036, and 1.035.

The results are shown in Fig. 4, where the blue line indicates the voltages at the selected nodes before the addition of

STATCOM, and the orange line indicates the voltages at the selected nodes after the addition of 1.5 MVAR STATCOM. From the plot, it is clear that the addition of STATCOMs reduce the over-voltages at the nodes, and none of the nodes exceed above the threshold of 1.05 per-unit.

## 6. Conclusion

Distributed energy resources affect the grid in both positive and negative ways. The paper discusses the negative impact on the voltage of a chosen distributed grid, due to the influence of these distributed resources. The selected grid is defined and modelled in a software tool called DIgSILENT. The static and the quasi-dynamic analysis are performed, and the results indicate no voltage violations without taking into account the distributed resources.

The distributed resources are modelled using DIgSILENT, and are added to the nodes of the distribution grid. The quasi-dynamic analysis indicates the issues of voltage violations at some of the nodes after the influence of these distributed resources in the grid. The paper then suggests the management of voltage limits by the provision of reactive power, using reactive power compensation devices.

Reactive power compensation devices are compared, and then the use of STATCOM is finalized at the nodes of distributed generators. The STATCOM is modelled within DIgSILENT, and the flexibility for the provision of reactive power is discussed. The STATCOMs are then added to the nodes where generators are connected, and then the quasi-dynamic analysis is repeated. The results suggest that the addition of STATCOMs improve the grid in terms of voltage violations.

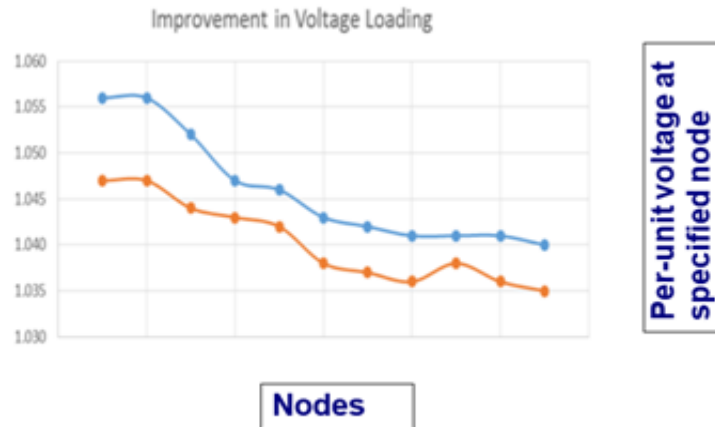


Figure 4 Comparison of Node Voltages

In the paper, the sources of reactive power mismatch (and hence the mismatch of the voltages at nodes) is the distribution grid (in terms of demand and addition of distributed resources). Another major source of imbalance, which is the transmission line, should be the point of emphasis in the future work. Another point of addition is the inclusion of market scenario, where a detailed market model of TSO is employed to give a real-time picture of deployment of reactive power in power system. STATCOM is just one option for reactive power compensation, and there are other options, which are more economical, as discussed in [22].

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