Increasing the Limits of Allowed Distributed Generations by Volt-VAR Control

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Abstract

Renewable energy resources are being introduced to the grid, both at transmission and distribution systems level. A particular challenge in integration of renewable energies at distribution systems is the issue of voltage rise on the feeders. Due to this technical issue, the penetration level of distributed generation has been limited in some areas to maintain the voltages within the acceptable ranges. In this paper, a volt-VAR control strategy is proposed to increase the capability of feeders to accommodate more renewable generations without jeopardizing system operation limits. This strategy is targeted for near-real-time operation and is expected to improve the overall system efficiency. A 69-node test system is used to demonstrate the effectiveness of the proposed algorithm.

Keywords: distributed generation, voltage rise, voltage-VAR control

Résumé

Les ressources énergétiques renouvelables sont intégrées à la fois aux réseaux électriques de transport et de distribution. Un défi particulier lors de l'intégration d'énergies renouvelables à des réseaux de distribution est la possibilité de surtensions aux départs de ligne. En raison de ce problème technique, le niveau de pénétration de la production décentralisée a été limité dans certaines zones pour maintenir les tensions à l'intérieur des limites acceptables. Dans cet article, une stratégie de contrôle volts-VAR est proposée afin d'augmenter la capacité d'intégration de sources d'énergie renouvelables des artères de distribution sans compromettre les limites de fonctionnement du système. Cette stratégie est destinée à fonctionner en temps quasi réel et devrait améliorer l'efficacité globale du système. Un système de test de 69 noeuds est utilisé afin de démontrer l'efficacité de l'algorithme proposé.

Mots clés : production décentralisée, surtension, tension de commande-VAR

1. Introduction

Due to the unsustainable and polluting nature of fossil fuels, renewable energy resources (RER) have been sought greatly in the past decades. The efforts in finding new sources of energy have led to numerous alternative generation methods, such as wind, solar, tidal, geothermal, biomass, fuel cell, etc. Among those, wind and solar power generations have taken the lead thank to the emerging technologies in energy conversions. As was mentioned in a report from the US Department of Energy in 2010, twenty four states are expected to supply 10%-40% of their load using renewable energies by 2015-2030 [1].

Despite the great benefits of replacing fuel-based generation units by renewable alternatives, the RERs cause many technical issues in power systems operation and control [2]. In the transmission systems, the problems stem from the three major characteristics of RERs, as follows: 1) non-dispatchable; 2) intermittent and uncertain; 3) incompatible with the conventional system. Whenever power is available from a RER, it should be all absorbed by the grid. In other words, there is no control on the amount of available power from a RER. This makes it very challenging for the system operator to coordinate other generation units in order to supply the variable load and maintain the load-generation balance at all times. Their intermittent and probabilistic nature of the RERs make it complicated to plan ahead of time and maintain a high reliability for the system operation. A large amount of system reserve is required to account for the unpredictable changes in the power generation from RERs [3]. The energy conversion technology that many of the RERs adopt is substantially different from the conventional synchronous machines used in thermal, hydro, CHP (combined heat and power), and nuclear power plants. For example, synchronous machines have a large mechanical inertia and it makes the system resilient to many disturbances. Many RERs, on the other hand, are connected to the network through a power electronic converter which does not provide any mechanical inertia. In that sense, higher penetration level of RERs is translated into a more vulnerable system with smaller inertia [4].

In distribution systems, smaller scale of RERs, called distributed generation (DG), are present. The type of problems these DGs may cause are, in part, different from those at the transmission systems. Distribution systems were built to operate in radial topology with the power flowing from the substation to the loads. All the control and protection schemes were designed based on this assumption. When DGs with considerable size are connected to a feeder, they create a reverse power flow back to the substation and increase the short-circuit levels at different parts of a feeder [5]. Besides interfering with the protection relays, high penetration of DGs can cause a voltage rise problem. Each utility has standards for the minimum and maximum range of voltages at the customer sides to ensure high quality power delivery to the customers. According to the Canadian Standard Association, the standard voltage ranges for distribution systems (below 50 kV) are defined for normal and extreme conditions in [6]. These values are reproduced here in Table 1 for reference. Due to this voltage rise problem, the penetration level of DGs at some feeders is limited [7], [8]. In this paper, a control strategy is proposed to maintain the voltages within the standard range and minimize power losses. Other methods have been developed in the literature and are briefly reviewed in the following.

The impacts of high penetration of photovoltaic (PV) DGs on distribution feeders were analyzed in [9]. The voltage rise and reverse power flows were shown in [9] to be among the important limiting factors for high penetration of PVs. A power curtailment algorithm was proposed in [10] to reduce the voltage rise effect during the peak power production of PVs. A coordinated power curtailment strategy was also proposed in [11] which considers a droop for each PV unit to control the amount of curtailment per each unit. However, by curtailing the power generation, the chance of producing clean energy is lost. The authors in [12] proposed adding a battery storage system to each PV unit to make the injected power to the network manageable. However, adding batteries causes additional costs and environmental concerns. To avoid batteries, a simple compensator was added to the PV converters in [13] to exchange arbitrary amount of reactive power with the network. This method is a good solution. However, it requires coordination with other voltage-VAR control equipment, such as line voltage regulators, capacitor banks, distribution static compensators (D-STATCOM), etc. The issue is partially addressed in [14] in which a coordination strategy is proposed to control voltage regulators and battery storage systems when loads and PV generation varies substantially during the day. In [15], DGs are taken advantage of in providing reactive power support to the grid. However, at the peak generation interval, the full capacity of

Table 1 Standard voltage ranges for distribution systems according to CSA

	V_{min} (p.u.)	V_{max} (p.u.)
Normal operating range	0.92	1.04
Extreme operating range	0.88	1.06

DGs is usually used for active power production and there is no room for reactive power exchange with the grid. For instance, the maximum output power of PVs usually occurs when the load is not at peak and, therefore, PVs cannot be relied on to provide VAR compensation at this time, when it is most needed. The application of D-STATCOM for voltage regulation in distribution systems with high penetration of PVs was studied in [16]. It was shown that by adopting the D-STATCOM there is no need for active power curtailment. However, the coordination of D-STATCOM with other compensation equipment was not considered in [16].

In this paper, an optimization problem is formulated for centralized coordination of D-STATCOM and line voltage regulator in a distribution feeder with high penetration of RERs. Without loss of generality, the RERs are considered to be PVs. The proposed optimization routine reduces the network losses while ensuring the voltage limits and feeder's ampacity. This method is based on the linear power flow (LPF) formulation developed by the authors in [17]. Using a linear formulation instead of the conventional nonlinear and non-convex equations leads to a better performance in the solution of an optimization problem.

The rest of the paper is organized as follows. In Section 2, the proposed optimization strategy is described. Simulation results and test cases are given in Section 3. The main findings of this study are summarized in Section 4.

2. Centralized Coordination Algorithm

The objective of voltage-VAR control (VVC) in this paper is to allow for higher penetration level of DGs. The constraints are the nodal voltage limits, feeder's ampacity, limits of compensation devices, and limits on tap positions of under-load tap-changing transformers (ULTC). In order to perform VVC in near-real-time, load data and line impedances are needed. In a centralized control mechanism, it is assumed that the communication infrastructure is available between all the control equipment and the control centre. Also, the amount of active power generation from each significant DG is communicated to the control centre. In the following, a brief description of network modelling is provided.

2.1 Linear power flow

Loads are essentially voltage-dependent and the constant-power load model may not be valid for distribution systems analysis. In this paper, loads' voltage dependence is modeled using the following equations:

$$P = C_Z V^2 + C_I V \tag{1}$$

$$Q = C'_Z V^2 + C'_I V \tag{2}$$

in which C_Z, C_I, C'_Z, C'_I are parameters determining the voltage dependence of each particular load; P and Q are the active and reactive power of load in per-unit, respectively; V is the terminal voltage in per-unit. DGs are modelled as constant-power loads with negative values. For constant-power load model, the following parameters are used: $C_Z = -1, C_I = 2$. Using the proposed load model, and assuming small voltage angles in distribution systems, a linear power flow (LPF) formulation was derived in [17]. The LPF equations are as follows:

$$\sum_{k=1}^{n}\left(G_{m,k}V_k^{\mathrm{re}} - B_{m,k}V_k^{\mathrm{im}}\right) = I_{p,m} \tag{3}$$

$$\sum_{k=1}^{n}\left(G_{m,k}V_k^{\mathrm{im}} + B_{m,k}V_k^{\mathrm{re}}\right) = I_{q,m} \tag{4}$$

where *G* and *B* are the real and imaginary parts of the modified admittance matrix; *n* is the number of nodes; V^{re} and V^{im} are the real and imaginary parts of the nodal voltages, respectively. In the modified admittance matrix, the impedance parts of the loads are added to its corresponding diagonal elements; the current injection parts of loads appear in the right-hand side of (3) and (4) as I_p and I_q.

2.2 Under-load tap-changing transformer

ULTCs are equipped with tap changers. Tap changer can dynamically adjust the transformer ratio, normally with discrete steps, and regulates the voltage on its secondary side with respect to a reference set point. Tap position, denoted by a, can be used to model the ULTC using variable passive elements, as in [18]. Figure 1 shows the equivalent circuit for the voltage regulator. Increasing the tap above 1 creates an inductive shunt at the primary and a capacitive shunt at the secondary. This increases the voltage on the secondary side, while potentially reducing the voltage on the primary side.
The tap position a is essentially an integer quantity. However, it can be modelled as a continuous variable and then rounded to the closest integer value. By doing this, it is not possible to guarantee the global optimality of the solution. Another approach is to model this as an integer variable and adopt mixed-integer programming techniques to solve the optimization problem. It is well known that mixed-integer programming problems are computationally intense problems to solve and are not suitable for online applications. Therefore, a continuous relaxation of the problem is considered here, which provides a fast, while suboptimal, solution using nonlinear programming (NLP) algorithms. The tap position is bounded to its maximum and minimum values:

$$a^{\min} \le a \le a^{\max} \tag{5}$$

where $a^{\min}$ and $a^{\max}$ are the minimum and maximum tap positions.

2.3 Distribution static compensator

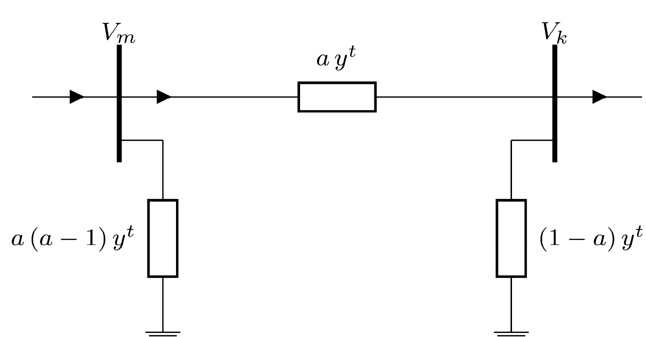

Figure 1. Equivalent circuit of ULTC (y^t : transformer short-circuit impedance; a : tap position).

A D-STATCOM is a member of the flexible alternative current transmission systems (FACTS). It consists of a power electronic interface, inductors (coupling transformer) and capacitors. By controlling the inverter, it is possible to exchange reactive power with the grid. It has a significant advantage over static VAR compensator (SVC). The terminal voltage does not affect the amount of VAR that can be injected to the network by D-STATCOM, while it changes quadratically with the terminal voltage in SVCs. In this paper, it is assumed that the amount of reactive power exchange can be remotely controlled in D-STATCOM [19]. The internal active power losses in D-STATCOM is assumed to be negligible. The amount of VAR exchange is constrained using the following equation:

$$Q_s^{\min} \leq Q_s \leq Q_s^{\max} \tag{6}$$

in which $Q_s^{\min}$ and $Q_s^{\max}$ are the minimum and maximum limits on the VAR exchange of D-STATCOM, respectively.

2.3 Volt-VAR control algorithm

The coordinated voltage and VAR control has four major parts, as shown in Fig. 2. All the data is collected at the control centre and a decision is made based on the received measurements. In a more realistic case, a state estimation algorithm is used to estimate the data for the unmonitored nodes and remove outlier measurements. Distributed generations are assumed to be non-dispatchable, meaning that the full amount of available power will be injected to the network.

A closed-loop near-real-time algorithm for VVC is proposed here, as shown in Fig. 3. In this algorithm, an optimization routine is called anytime a considerable change happens in the network. A considerable change is defined as large deviation in network voltages from their last recorded values when the previous settings were sent out. It can be quantified by setting the following threshold limit:

$$| V_{\text{now}} - V_{\text{old}} | \leq V_{\text{th}} \tag{7}$$

where V_{now} is the most recent voltage measurement; V_{old} is the voltage measurement record from the last time any settings were sent out; V_{th} is a threshold set for triggering the algorithm to modify the controllers. The value of this threshold should be chosen in a way to always maintain the voltages within acceptable ranges while not triggering the algorithm too often and mechanically stress the equipment by frequently altering their settings.

The optimization routine can be set to one of the following cases.

2.3.1 Minimizing losses

The total power losses in the network can be defined as:

$$P_{\text{loss}} = \sum_{m<k} G_{m,k}\left[(V_m^{\text{re}} - V_k^{\text{re}})^2 + (V_m^{\text{im}} - V_k^{\text{im}})^2\right] \tag{8}$$

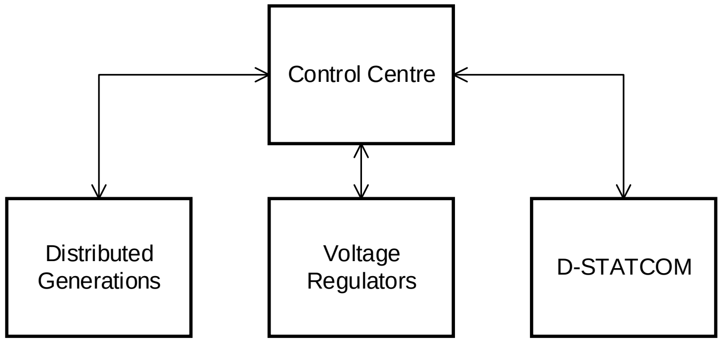

Figure 2. Communication between control centre and the control equipment.

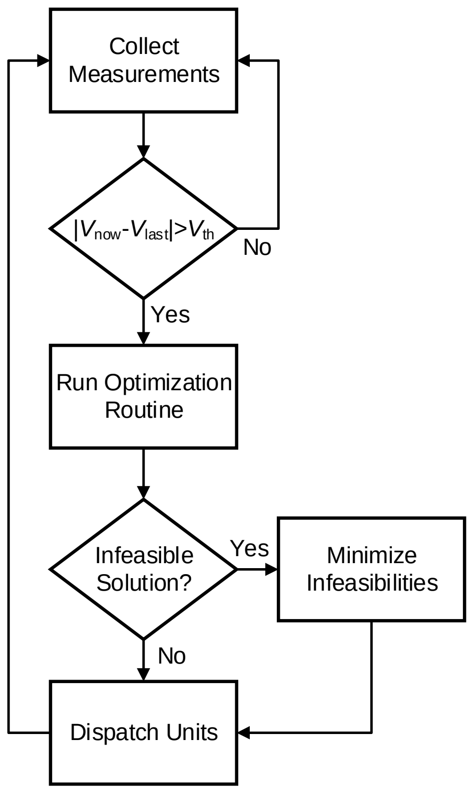

Figure 3. Closed-loop Volt-VAR control algorithm for near-real-time.

The optimization problem consists of minimizing (8) subject to the power flow equations of (3) and (4), tap position limits in (5), limits of D-STATCOM output in (6), and the following constraints:

$$V^{\min} \leq V_i \leq V^{\max} \tag{9}$$

$$|I_i| \leq I_i^{\max} \tag{10}$$

where V_i is the voltage magnitude at node *i* and I_i is the current magnitude in branch *i*.

2.3.2 Flattening voltage profile

In order to flatten the voltage profile, it is desirable to have all the voltages close to a certain value, e.g., 1 per-unit. In order to express this statement in a mathematical formula, the following voltage index is defined:

$$\alpha = \sum_{j=1}^{n} |V_j - V_{\text{tar}}|^2 \tag{11}$$

in which V_{tar} is the target value for the voltage profile. Usually, it is desirable to have all the voltages close to 1 per-unit. By minimizing α subject to the same constraints as in Subsection 2.3.1, voltage profile of the network can be brought close to the targeted value.

2.3.3 Minimizing infeasibilities

In some of the real situations, it is not always possible to satisfy all the constraints of the optimization problem. In such cases, the problem is infeasible. The best practice in those cases is to minimize the infeasibilities. Let us assume that some of the inequality constraints are infeasible:

$$f_i(x) \le 0,\ i \in IF \tag{12}$$

where *IF* is the set of infeasible constraints. In such cases, the objective of the VVC would be to minimize the violations. New variables, z_i, are introduced to the problem and the constraints in (12) change to the following constraints:

$$f_i(x) \le z_i,\ i \in IF \tag{13}$$

The objective function in this case is to minimize β, where β is defined as

$$\beta = \sum_i z_i, \quad z_i \ge 0 \tag{14}$$

The rest of the constraints, i.e. voltage limits, feeders' ampacity, load flow, etc., should also be added to the problem.

3. Simulation Results

In this section, without loss of generality, the loss minimization case is considered. The objective function can be changed to voltage profile flattening.

2.3 Test case

In order to demonstrate the application of the proposed algorithm, a test system is used here. The data for this system is available in [20]. The system configuration is reproduced here for reference in Fig. 4. Three DGs are present in this system connected to Nodes 12, 20, and 54. Maximum capacity of each unit is assumed to be 3.4 MVA, with unity power factor (zero reactive power). Reactive power supports are available from two locations by D-STATCOMs at Nodes 25 and 60. The limits of reactive power exchange capabilities of these two units are assumed to be ±2 MVAR. The voltage regulator connected between Nodes 6 and 7 has 20 tap positions, allowing the transformation ratio to vary between 0.9 and 1.1. A daily load curve is assumed for the feeder and all the nodal loads are scaled according to this load curve shown in Fig. 5. DGs are assumed to be photovoltaic type, with the generation pattern shown in Fig. 6. All loads are assumed to have the same voltage dependence characteristics with $C_z = 0.6,\ C'_z = 2.3$.

Two cases are studied here and their results are compared. The first case assumes no reactive power support from the D-STATCOMs and no voltage regulator. The second case assumes both D-STATCOMs and the voltage regulator. The minimum and maximum nodal voltages are shown in Fig. 7. The maximum voltages are above the limit (1.04 p.u.) in almost half of the time during the day in the case without any control. By introducing the VVC algorithm, the voltages are bounded within the standard range. In case of losses, as shown in Fig. 8, about 27% reduction was achieved between 1pm and 3pm when the VVC routine is applied. The losses are slightly higher in hours that the generation is not significant when VVC is applied. It is the result of brining the voltages down within the standard limit. Higher voltages can lead to lower losses in the network in some cases. The reactive power drawn from the substation, shown in Fig. 9, has substantially reduced due to the VAR support provided by the D-STATCOMs. The total active power injection by the substation, given in Fig. 10, did not change significantly as was expected since there were no changes in the loads or generation. The only changes are the results of changes in losses and voltage-dependent loads. Figure 11 shows the optimum tap positions when VVC is applied. Figure 12 shows the reactive power exchange of the D-STATCOMs. As can be seen, during the peak generation time, reactive power is absorbed by the second D-STATCOM to help lowering the voltages. Also, the voltage regulator was set at low tap positions to reduce the voltage rise effect.

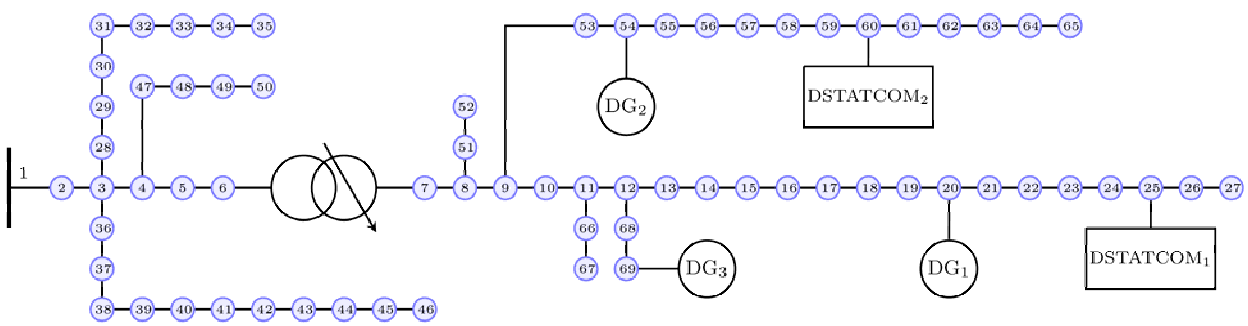

Figure 4. The 69-node test system with DGs and DSTATCOMs locations.

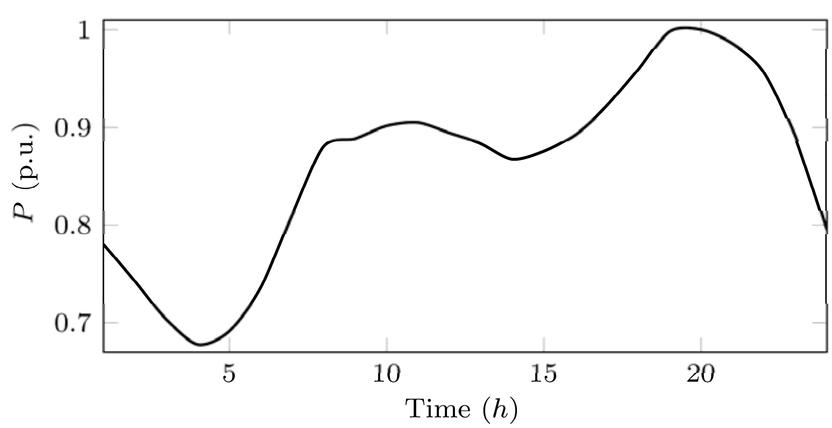

Figure 5. Daily load curve for the test system.

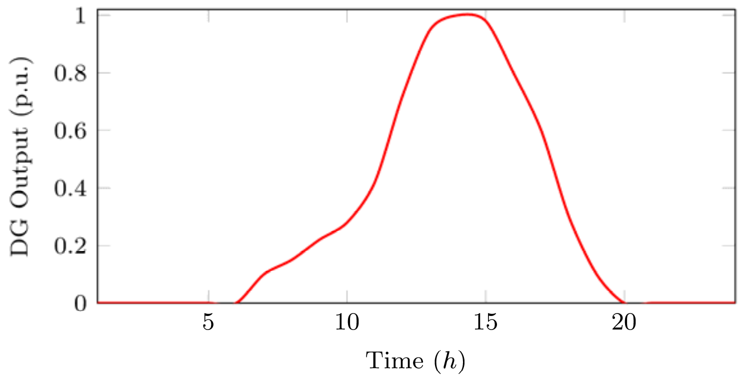

Figure 6. Daily generation curve for DGs (photovoltaic system).

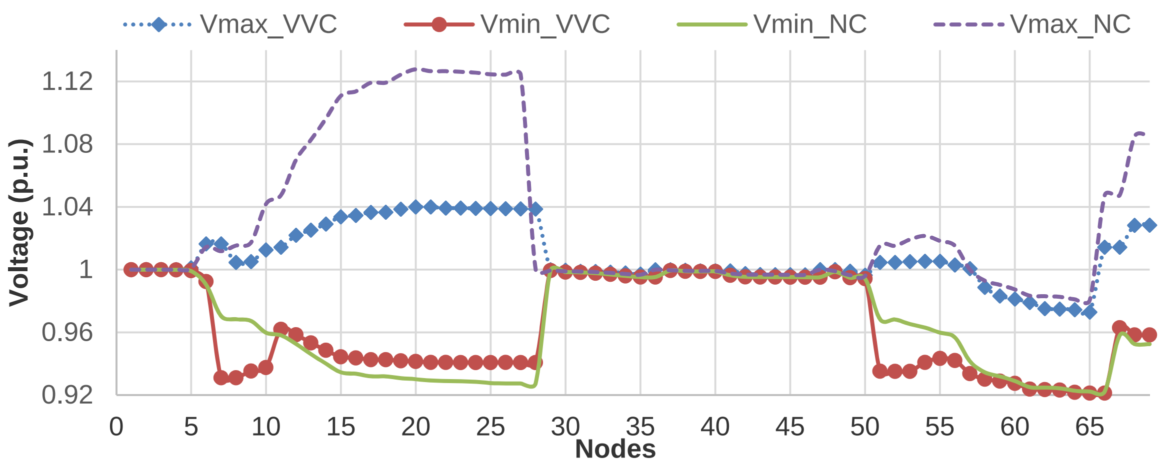

Figure 7. Minimum and maximum nodal voltages for “No Control” and “VVC” cases.

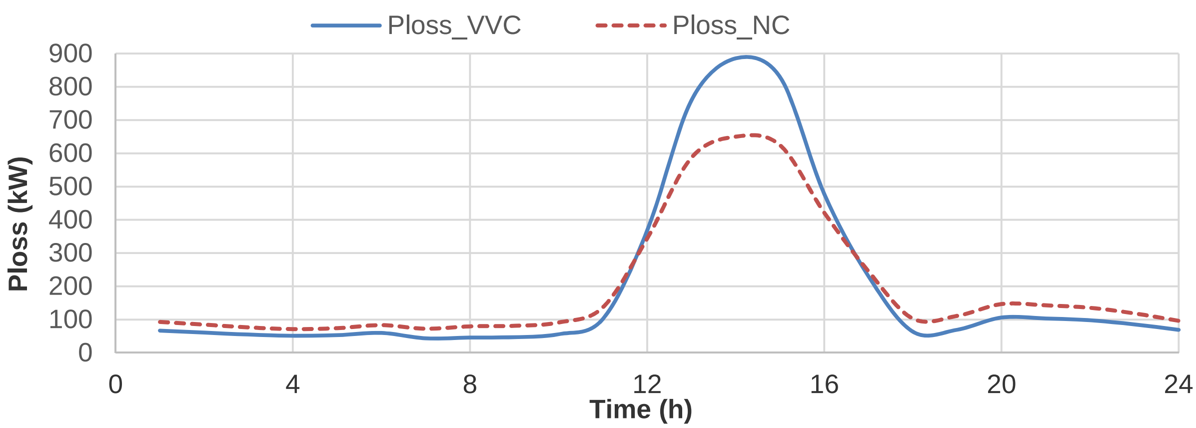

Figure 8. Total losses for “No Control” and “VVC” cases.

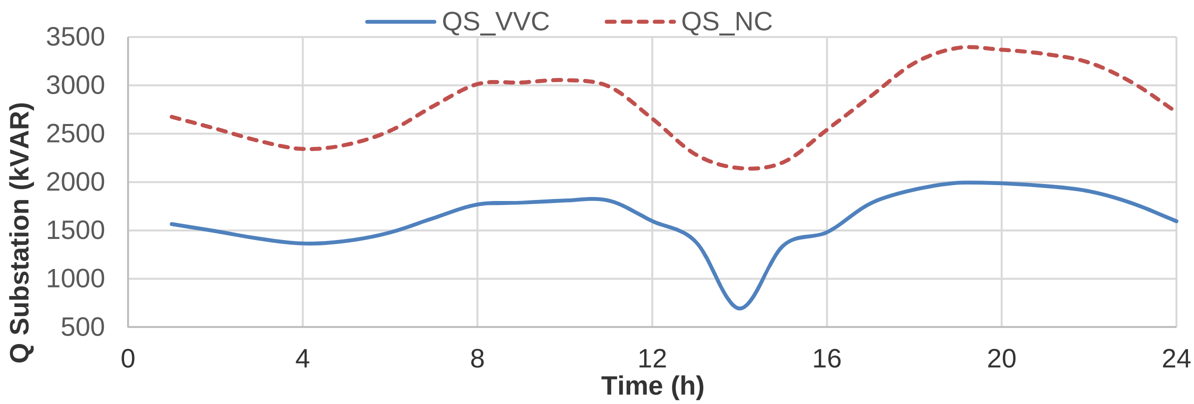

Figure 9. Total reactive power injection by the substation for "No Control" and "VVC" cases.

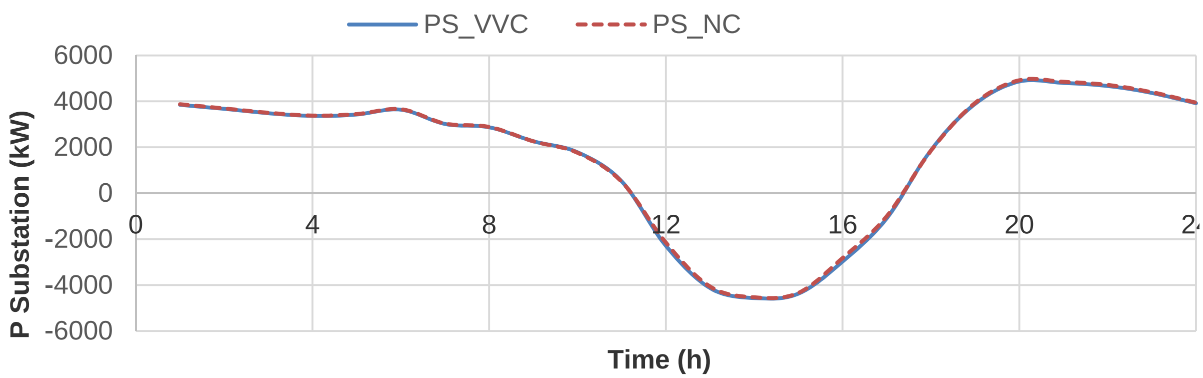

Figure 10. Total active power injection by the substation for "No Control" and "VVC" cases.

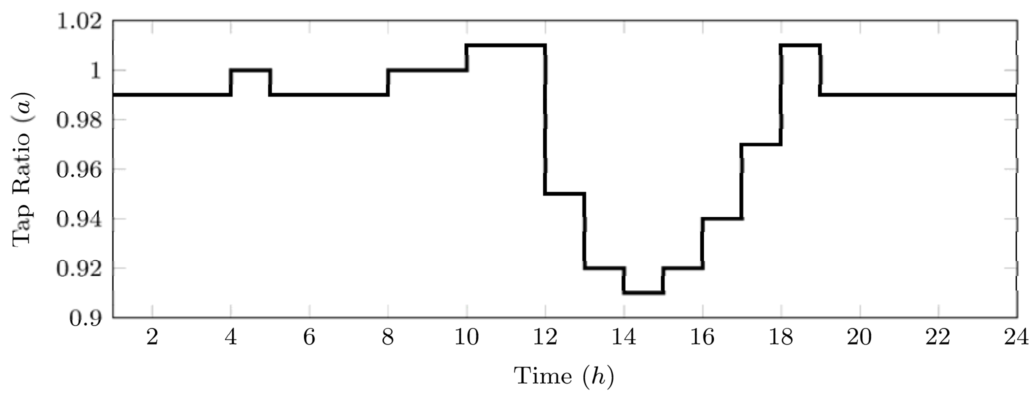

Figure 11. Tap ratio for the voltage regulator obtained using VVC algorithm.

7. Conclusion

A voltage-VAR control scheme is proposed in this paper that allows for increasing the penetration level of distributed generation without violating the system operational limits. In this study, D-STATCOM was considered as a source of reactive power support. However, it does not limit the application of the proposed algorithm to any other sources of VAR support, such as DGs,

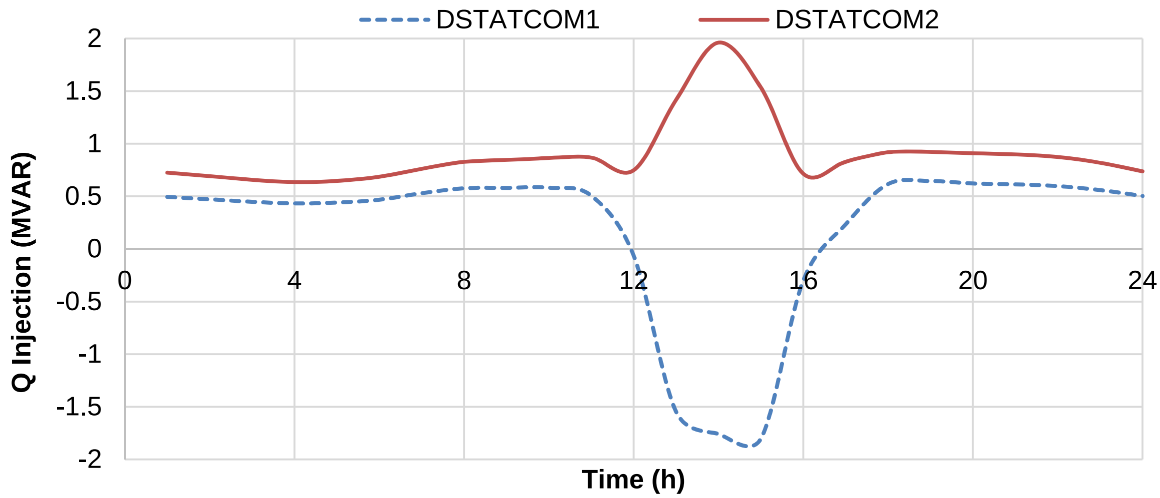

Figure 12. DSTATCOMs output obtained using VVC algorithm.

batteries, switchable capacitor banks, etc. This algorithm also reduces the losses in the network and relives the reactive power drawn from the upper level sub-transmission and transmission level. A cost-benefit analysis would be required to demonstrate the financial justification of installing D-STATCOM in a distribution feeder. This includes the capital and maintenance costs versus the revenues gained by reducing losses and increasing the penetration of clean energies.

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10. Biography

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