Voltage Control with Local Decisions in Low Voltage Distribution Grids with DER Penetration

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Abstract: This paper presents two droop-based voltage control algorithms that try to achieve maximum generation by Distributed Energy Resources (DERs), while keeping the voltage levels within the operating limits. One of the algorithms is based on gradual adaptation using small power increments/decrements, while the other algorithm is based on a linear approximation of the function that relates the generated power with the voltage measured at the DER coupling point. These algorithms were comparatively evaluated against a state-of-the-art connect/disconnect scheme and an optimal centralized algorithm. Simulation results show that the performance of the proposed distributed algorithms approaches that of the centralized algorithm, with the incremental algorithm presenting faster convergence than the linear algorithm.

1 INTRODUCTION

The quest for additional energy sources in order to satisfy demand, as well as for loss reduction, is leading to deep changes of the power distribution grid, namely in Low Voltage (LV) distribution. This is translated into an increasing penetration of Distributed Energy Resources (DERs), encompassing Distributed Storage (DS) and Distributed Generation (DG). DG installations may belong to grid consumers, which become prosumers, i.e., both producers and consumers of energy. Photovoltaic (PV) DG in particular had a significant growth in recent years, with incentives given by EU countries like Portugal (see DL 153/2014), motivating its adoption and turning it into a business case.

Although the introduction of DERs has many advantages, it also brings significant challenges. High DER penetration may lead to local imbalance between energy production and consumption, with consequent instability of voltage levels, adding to the problem of load variability along the day. Violation of voltage operating limits leads to Quality of Power (QoP) degradation, with possible penalty to the DSO. It may also ultimately lead to conductor overheating and equipment failure (including user appliances) if no control procedures are in place. Currently, the usual control procedure is to let the DER generate the maximum contracted power while connected and automatically disconnect it from the grid once the voltage level measured at its grid coupling point becomes too high. Although this solution is simple and only relies on local measurements, it is usually inefficient, since it does not allow for a steady finer grain adaptation. Moreover, it may lead to voltage level instability, since several DERs may needlessly disconnect at the same time, causing a sudden drop in injected power, which can lead to the opposite situation: undervoltage.

This paper presents two droop-based algorithms for control of DG in LV distribution grids, together with a comparative evaluation. The objective of the proposed algorithms is to perform a fine grain adaption of power injected in the LV grid by DERs in order to maximize DG production up to the limit established by the contract between the DG client and the DSO, while keeping the voltage levels within operating limits. All decisions are made locally by the DERs based on local measurements at the coupling points. These algorithms can thus operate in LV distribution grids where a Smart Grid communication network is still not implemented or as a backup mechanism when the communication network is congested or broken.

The performance of the proposed algorithms was compared with the basic connect/disconnect

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mechanism described above, as well as with a future Smart Grid enabled centralized algorithm. Simulation results show that the performance of the proposed algorithms approaches that of the centralized algorithm, while being significantly better than the basic mechanism.

The rest of the paper is organized as follows: Section 2 presents the problem definition, including the abstract grid model; Section 3 presents the related work; Section 4 describes the proposed voltage regulation algorithms; Section 5 presents the comparative performance evaluation based on simulation results; Section 6 concludes the paper.

2 PROBLEM DEFINITION

The considered LV grid architecture is depicted in Figure 1.

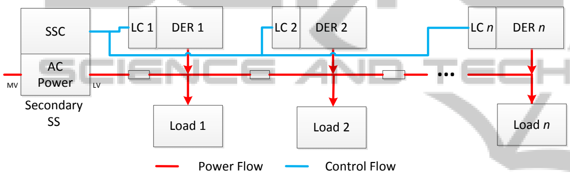

Figure 1: Considered LV grid architecture.

The Medium Voltage (MV) feeder terminates at the secondary substation (SS), where typically several LV feeders are connected to the LV side of the MV/LV transformer, which imposes the voltage level at the beginning of the LV feeders. This voltage level may be equal to the nominal voltage level (e.g., 230 V) or slightly higher in order to compensate technical losses, e.g., cable impedances, which are also represented in Figure 1. Notice that this is a simple abstract model, which can be tailored to specific scenarios by assigning impedance values to the loads and configuring the generation capacity of DERs. In this paper, only resistive loads will be included in the analysed scenarios.

It is considered that the DSO has established a contract with the DG client, according to which the DSO will buy all the power injected by the DG client, up to a certain limit. The algorithms described in this paper aim to perform a fine grain control of power injected in the LV grid by DERs in order to maximize DG production up to the limit established by the contract. It should be noted that maximizing the DG production entails a voltage increase in case the load is too low. Consequently, the solutions generated by the algorithms must result in voltage values within the operating limits.

The proposed algorithms operate in a single phase of an LV feeder and should be replicated if there are more phases/feeders. Each DER is coupled to the LV feeder and its injected power may be limited by setpoints issued by a Local Controller (LC). The LC establishes these setpoints based on a local algorithm or based on setpoint commands centrally issued by the Secondary Substation Controller (SSC).

Only active power adaptation is taken into account, since reactive power adaptation is less cost-effective and efficient, requiring the DER or coupler hardware to integrate large capacitor banks in order to have a significant impact on the voltage level – an asset that is not available in every equipment.

3 RELATED WORK

During the last decades, DSOs have employed voltage regulation equipment such as transformer tap-changers, line regulators and shunt capacitors placed at the substations and distribution feeders in order to keep the voltages within the operating limits (U.S. Department of Energy, 2012). This equipment operates correctly in distribution grids without DERs, since they are designed to only compensate the voltage drop along the branch lines. Consequently, it is usually deployed in long branch lines, typical of suburban or rural environments. When DERs are present, the voltage along the grid becomes more unpredictable due to the more complex power flow. It may present values that are higher than the voltage imposed at the head end by the power transformer, and this may happen at any location. Planning for the installation of voltage regulation equipment becomes more difficult.

In Silva et al (2012), the authors analyse the impact of DG installation in the voltage profile of the LV distribution grid. They state that when there is significant DG penetration, the voltage is prone to rise. If the upper operating voltage limit is reached at some DG unit interfaces, the respective individual protections fire, removing those DG units from the grid, i.e., their injected power is reduced to zero. On the other hand, if there is a sudden power reduction due to DG intermittence, the voltage decreases very quickly, which also constitutes a problem. The paper proposes a solution based on the transmission of setpoints to the DG controllers whose output voltage exceeds the operating limits. Transmission of setpoints requires an integrated communication infrastructure of the kind to be found in the future Smart Grid.

Several proposals can be found in the literature on how to calculate the setpoints. In general, the methods are based on measurements of voltage, current and power factor at grid connection points. Based on these measurements, an algorithm calculates the power flow and issues the setpoints until the optimal power values are attained. A very popular method for power flow calculation is Backward/Forward Sweep (BFS). Krushna and Kumar (2012) propose a variant of this method that is suitable for radial topologies, which are typical of LV distribution grids.

Sajadi et al (2012) propose a distributed algorithm whereby the transformer tap-changer controller agent mitigates voltage limit violations by issuing permission to willing DG controllers to adapt their active and/or reactive power, or alternatively by adapting the tap-changer. This system also assumes that a Smart Grid communication infrastructure is in place, allowing sensing and control messages to be exchanged between the distributed agents.

Voltage control droop-based techniques were previously proposed in the literature, such as those proposed by Tonkovsky et al (2011) and by Samadi et al (2014). The former proposes two techniques for active power control, one using a fixed slope factor, another using location-based slope factors obtained from the voltage sensitivity matrix in order to achieve fairness among DG sites. Samadi et al (2014) proposes a multi-objective droop-based optimization scheme, which is also able to control the reactive power and minimize the line losses. Although the proposed techniques are able to effectively control line voltage, they assume that the voltage sensitivity matrix is known, unlike the techniques proposed in this paper. Besides, as far as the authors know, the problem of simultaneous conflictual decisions between DG controllers was not previously addressed.

4 ALGORITHM DESCRIPTON

Two droop-based algorithms (incremental and linear) were developed, which are based exclusively on local decisions based on voltage and current measurements taken at the DER interface with the grid, being suitable for implementation at LC level. These algorithms periodically sense the voltage level at the DER's interface and adapt the injected power accordingly. They differ in the way they perform this adaptation.

Notice that, if the feeder has more than one LC, each LC independently runs the algorithm. This brings the issue of convergence when different LCs are making interfering decisions. In order to tackle this problem, a time division scheme is proposed. According to this scheme, time is divided into timeslot windows. A timeslot window corresponds to an iteration, i.e., to a decision cycle. The LCs are synchronized to a common clock (e.g., GPS synchronization) and each tries to separate its decision in time by randomly selecting a time slot within the timeslot window in each iteration. The duration of the timeslot is assumed fixed and related with the response time of the DER, which is a specific characteristic of the equipment in use.

The following subsections describe how the proposed distributed algorithms running at each LC make their decisions within the respective timeslots, in each iteration. Since these algorithms will be compared with a basic connect/disconnect scheme and a centralized algorithm, a summary of the latter is also presented. From this point onward, when we refer simply to the injected power, this will mean the active power only, as already stated in Section 2.

4.1 Incremental Algorithm

In the incremental algorithm, in each iteration t, the LC performs the following steps within its assigned timeslot:

1. Measures the root mean square (RMS) voltage and current at the DER's coupling point, respectively V_{rms}^t, $I_{rms}^t(t)$ and power factor (PF). Then, it calculates an estimate of the power currently being injected:

$$P_G^t = V_{rms}^t \cdot I_{rms}^t \cdot PF \quad (1)$$

2. Adapts the respective maximum allowed injected power (P_{max}) as follows:

$$P_{max}^{t+1} = \begin{cases} P_{MAX}, \propto_1 \cdot P_G(t), & V(t) > V_{max} \\ P_G(t), & V(t) = V_{max} \\ min[P_{MAX}, \propto_2 \cdot P_G(t)], & V(t) < V_{max} \end{cases} \quad (2)$$

Where $\propto_1$ and $\propto_2$ are constants ($0 < \propto_1 < 1$ and $\propto_2 > 1$), V_{max} is the high RMS voltage limit and P_{MAX} is the maximum power that the DER is able to inject at that moment into the network (it may correspond to either technical or a contract limit).

4.2 Linear Algorithm

In the linear algorithm, in each iteration t, the LC performs the following steps within its assigned timeslot:

1. Measures V_{rms}^{t}, $I_{rms}^{t}(t)$ and PF, and then calculates the P_G^t estimate as in Equation (1).
2. Performs a test, setting the injected power to $P_{test} = \beta \cdot P_G^t$, with $0 < \beta < 1$. It then measures the resultant RMS voltage V_{rms}^{test} and RMS current I_{rms}^{test}.
3. It adapts P_{max} assuming that the relationship between RMS voltage and RMS current is approximately linear (Ohm's Law), as follows:

$$P_{max}^{t+1} = min\left[P_{MAX}, V_{nom} \cdot \left[I_{rms}^{t} + (V_{max} - V_{rms}^{t}) \cdot (I_{test} - I_{rms}^{t})\right]\right] \quad (3)$$

It should be noted that, due to the fact that a power change and measurement test is performed in each timeslot, the timeslots in the linear algorithm should be considered twice as long as those in the incremental algorithm.

4.3 Basic Connect/Disconnect Scheme

In the basic connect/disconnect mechanism, which is common in commercial photovoltaic inverters, the DERs try to inject the maximum power while connected, but will disconnect if the voltage at the coupling point rises beyond V_{max}. In the implementation considered in this paper, in each iteration t, the LC performs the following decision within its assigned timeslot:

$$P_{max}^{t+1} = \begin{cases} 0, & V(t) \geq V_{max} \\ P_{MAX}, & V(t) < V_{max} \end{cases} \quad (4)$$

4.4 Centralized Algorithm

The centralized algorithm was submitted as patent (Nunes, 2014) and will be the subject of another publication. As such, only a short summary of its operation is provided. The algorithm is meant to run at the SSC. It takes measurements of voltage, current and power factor variation at each one of DER coupling points for different power values injected by the different DERs, from which an impedance matrix is defined that allows the calculation of the currents and voltages at the different DERs for different production values. Based on the referred impedance matrix, a solution for the production of each DER is obtained that optimizes an objective function, subject to a set of restrictions on currents and voltages at the output of each DG. Different objective functions can be defined. In this study, the objective function seeks to optimize the total power injected by the DERs.

5 SIMULATION RESULTS

The simulated grid configuration is an instantiation of the topology described in Section 2, with four equal resistive loads and four co-located DERs. It is considered that the DERs are able to inject up to $P_{MAX} = 6$ kW into the grid, which may correspond to either the contracted limit or to a technical limit. The voltage imposed by the SS at the beginning of the LV feeder corresponds to the nominal value $V_{nom} = 230\,V$. The voltage limits are $V_{max} = 1.1 \times V_{nom} = 230\,V$ and $V_{min} = 0.9 \times V_{nom} = 207\,V$. It is considered that the power consumption contract establishes a maximum of 6 kW of consumed power for each load. This means that the lowest acceptable load resistance value is approximately $\frac{(V_{min})^2}{6000} = 7.1\,\Omega$. Two values were chosen for the line resistances: 0.1 Ω and 0.2 Ω, which correspond to two different scenarios: shorter and longer feeder, respectively. Although the longer feeder scenario entails a higher risk of undervoltage in case of heavy load (especially at the most distant client sites), it is valid under the assumption that the coincidence factor estimated by the DSO is low. In the beginning, all DERs are configured to inject 6 kW into the grid.

The distributed algorithm parameters are listed in Table 1.

Table 1: Parameters of the distributed algorithms.

α_1	0.95
α_2	1.02
β	0.95

Three performance metrics were selected:

- Convergence latency: this is related to the time that it will take to converge to a good enough solution. The convergence criteria require that the achieved voltage values at DER coupling points fall within the operating limits and that the difference between successive values is less than 3 V. The latency is normalized to the

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length of the timeslot of the incremental algorithm. Latency will not be considered for the centralized algorithm, since in this case it would depend on the performance of the supporting communication technologies, which is out-of-scope in this paper.

- Total DER production: This is the sum of the values of power injected by the DERs.
- Production fairness: since the DSO will buy all the power injected by the DER clients, the latter is interested on maximizing this value. However, compliance with voltage limits may lead to some DERs being forced to reduce their production, which may lead to unfairness, especially if the power setpoints are generated locally. In order to evaluate the fairness of the proposed algorithms, the Jain's fairness index is used.

In the charts that follow, each point corresponds to the average of 10 simulations.

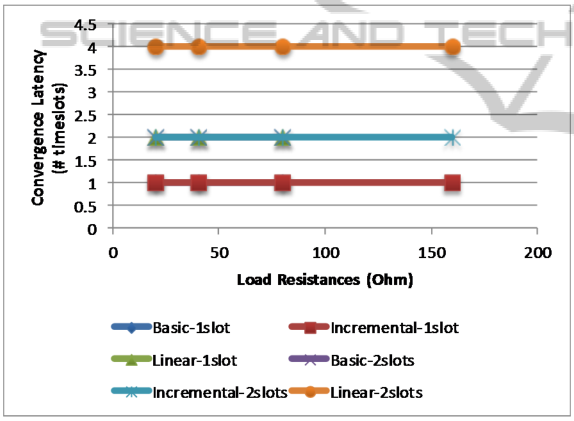

Figure 2: Convergence latency with line resistances of 0.1 Ω.

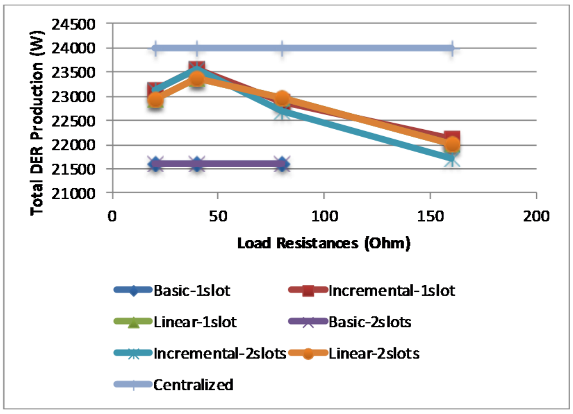

Figure 3: Total DER production with line resistances of 0.1 Ω.

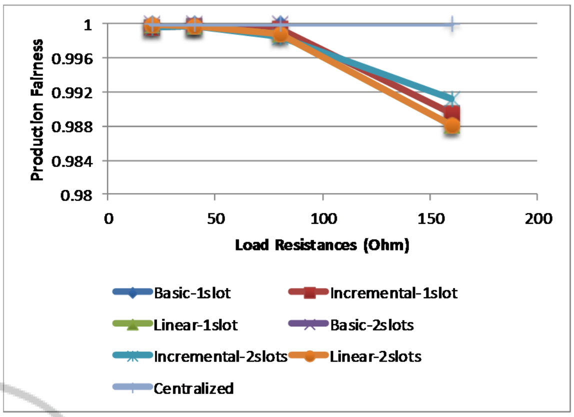

Figure 4: Production fairness with line resistances of 0.1 Ω.

The convergence latency, total DER production and fairness as functions of the value of load resistances, are depicted for the short feeder scenario in Figure 2, Figure 3 and Figure 4, respectively. Four values of load resistance were considered: 20 Ω, 40 Ω, 80 Ω and 160 Ω. Different algorithm configurations are labelled with the name of the algorithm, followed by the number of timeslots that an iteration comprises.

In this scenario, the load is able to sink most of the injected DER power in all configurations. Potential voltage limit violations will only arise for load resistance values of 160 Ω. This is the only place where the basic connect/disconnect scheme will not converge. All other algorithm configurations converge within a single iteration. The differences in latency are thus due to the different iteration lengths. As expected, the highest latency belongs to the linear-2slot configuration, with the linear-1slot latency being the same as that of the incremental-2slot configuration.

Regarding the total DER production, the performance is very similar in all converging settings. As expected, the maximum value is achieved by the centralized algorithm, followed by the incremental and linear algorithms. The lowest performance is presented by the basic connect/disconnect scheme. It should be noted that the incremental and linear algorithm configurations present a trend to gradually reduce the DER production as the value of load resistance increases.

The production fairness approaches the maximum of 1.0 in all configurations. Again, a slight reduction is observed for the incremental and linear algorithms, when the load resistance increases beyond 80 Ω.

For the longer feeder scenario, the metrics are depicted in Figure 5, Figure 6 and Figure 7. This

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scenario is more challenging, which is illustrated by the fact that the basic connect/disconnect scheme only converges for the lowest value of load resistance (20 Ω). As the load resistance increases, the convergence latency also increases. The linear-1slot configuration only converges for 20 Ω and 40 Ω, where it presents the highest values. This is due to conflictual decisions between different LCs when a single timeslot is used. The latency is lower for the linear-2slot configuration, which is lower than that of incremental-2slots. However, incremental-1slot presents the lowest latency. Total DER production and fairness present very similar curves in all converging configurations, which only slightly depart from the values achieved by the centralized algorithm. Again, production and fairness tend to get worse as the value of load resistance increases.

From these results, it can be concluded that the basic connect/disconnect scheme widely employed in commercial DER equipment will potentially lead to convergence problems in scenarios with higher line and load resistance, resulting in decreased DER production efficiency. The incremental algorithm achieves the best performance, approaching the ideal solution found by the centralized algorithm. It can and should be employed in a single slot configuration. Although at first sight the linear algorithm had the potential to converge faster, since it allows larger variations of injected power in each iteration, this may lead to more significant conflictual LC decisions when employed in a single timeslot configuration. With two timeslots, while resolving the conflicts, it will be slower than the incremental algorithm using a single timeslot. The latter is more robust to LC decision conflicts, since the LCs performs small state changes in each decision cycle.

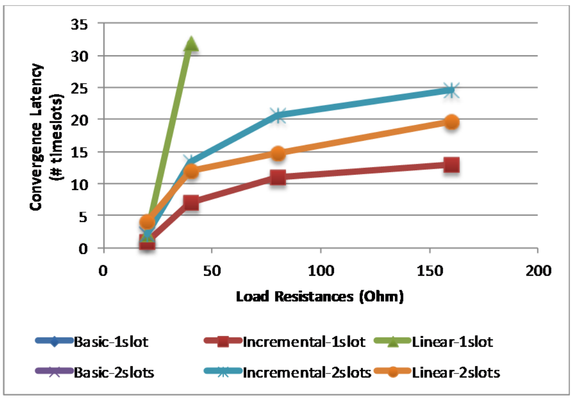

Figure 5: Convergence latency with line resistances of 0.2 Ω.

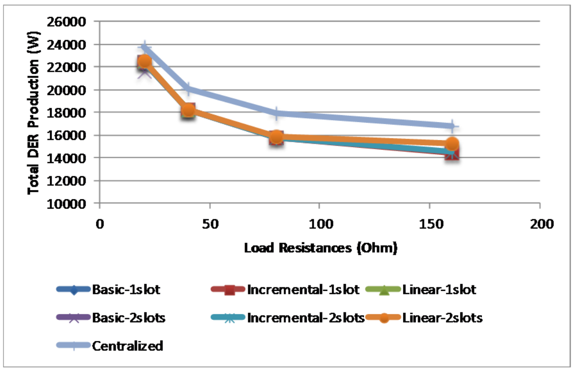

Figure 6: Total DER production with line resistances of 0.2 Ω.

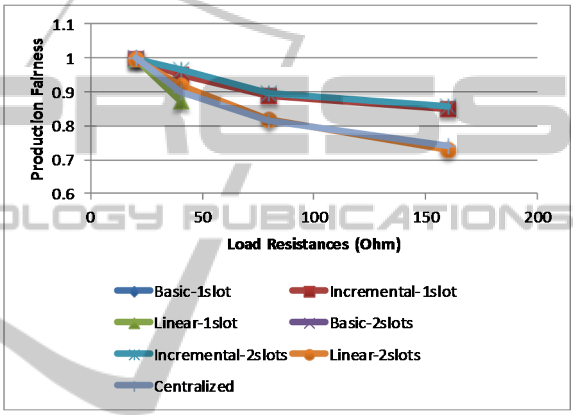

Figure 7: Production fairness with line resistances of 0.2 Ω.

6 CONCLUSIONS

This paper has presented two distributed algorithms that try to maximize DER production in LV distribution grids with DER penetration, while keeping the voltage levels within the operating limits. The incremental algorithm performs small changes of injected active power in each decision cycle, while the linear algorithms changes the injected power based in the assumption of a linear relationship between the injected power and the voltage level at the coupling point.

The proposed algorithms were evaluated and compared with a state-of-the-art connect/disconnect scheme and a centralized algorithm that makes decisions based on knowledge about voltage and current levels at all DER coupling points. Simulation results show that the proposed algorithms approach the optimal solutions obtained by the centralized algorithm, with the incremental algorithm presenting

faster convergence. The latter remained stable in all tested scenarios and configurations.
As future work, the authors plan to study the impact of communication network performance on the centralized voltage control schemes, as well as to define hybrid distributed/centralized algorithms.

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REFERENCES

DL 153/2014, 20th of October, by which the distributed electricity generation activity is regulated.

Krushna, K., Kumar, S.V., 2012. Three-Phase Unbalanced Radial Distribution Load Flow Method. International Refereed Journal of Engineering and Science (IRJES), ISSN (Online) 2319-183X, (Print) 2319-1821 Volume 1, Issue 1, pp.039-042.

Nunes, M., 2014. Dynamic control method of power injected into the power grid for micro and mini producers for voltage regulation, PT107831 INPI, Patent submitted in August 2014, Lisbon.

Sajadi, A., Sebtahmadi, S., Koniak, M., Biczel, P., Mekhilef, S., 2012. Distributed control scheme for voltage regulation in Smart Grids. International Journal of Smart Grid and Clean Energy (SGCE), ISSN (Online) 2373-3594, (Print) 2315-4462, Vol. 1, No. 1, pp. 53–59.

Samadi, A., Shayesteh, E., Eriksson, R., Rawn, B., Soeder, L., 2014. Multi-objective coordinated droop-based voltage regulation in distribution grids with PV systems. Renewable Energy, Elsevier, 71, 2014, pp. 315-323.

Silva, N., Delgado, N., Costa, N., Bernardo A., Carrapatoso, A., 2012. Control architectures to perform voltage regulation on low voltage networks using DG. In CIRED 2012 Workshop, Integration of Renewables into the Distribution Grid, ISBN: 978-1-84919-628-4, Lisbon, pp. 1-4.

Tonkosky, R., Lopes, L., El-Fouly, T., 2011. Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention. IEEE Transactions on Sustainable Energy, Vol. 2, No. 2, April 2011, pp. 139-147.

U.S. Department of Energy, 2012. Application of Automated Controls for Voltage a Reactive Power Management.

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