ECONOMICAL DISTRIBUTED VOLTAGE CONTROL IN LOW-VOLTAGE GRIDS WITH HIGH PENETRATION OF PHOTOVOLTAIC

Obinna UNIGWE
University of Edinburgh – UK
o.unigwe@ed.ac.uk

Dahunsi OKEKUNLE
University of Edinburgh – UK
d.okekunle@ed.ac.uk

Aristides KIPRAKIS
University of Edinburgh – UK
Aristides.kiprakis@ed.ac.uk

ABSTRACT

This paper presents an economical distributed control scheme for operations in the low voltage (LV) network. The scheme aims to keep bus voltages within the desired statutory range of values while increasing the penetration of solar photovoltaic (PV) renewable energy within the network. Rather than curtailment, Battery Energy Storage System (BESS) is first brought to action by the controllers during periods of high output from PV. This is followed by reactive power action if overvoltage persists, and finally PV power curtailment as a last option. Simulations carried out on the test network show that in addition to successful overvoltage mitigation, the scheme is economical as it employs use of fewer BESS.

INTRODUCTION

In recent decades, considerable research and investment has gone into the development of cleaner Renewable Energy Sources (RES) such as PV. However, increased penetration of RES into the traditional grid has lead to problems of power quality, especially in distribution networks where a significant portion of these RES are connected. The power quality issues include voltage unbalance, overvoltage, line flickering and harmonics. Of these problems, overvoltage presents the major limiting factor to increased levels of penetration of RES into the grid. Overvoltage arises when the consumption on a feeder is below the production, causing voltages to increase beyond statutory levels [1].

Use of the reactive power capabilities of the PV inverters alongside active power curtailment is one method for solving the overvoltage problem. For this method, reactive power absorption is employed during overvoltage, followed by active power curtailment if the reactive power absorption is insufficient [2]. The problem with this approach is that curtailment of active power means that the gains from investment in PV are not maximised.

Using step voltage regulators (SVR) and on-load tap changers (OLTC) are traditional voltage control methods. However, these technologies, in the presence of high PV penetration are exposed to stress, leading to degradation and reduced lifetimes [3]. Incorporating BESS in networks with PV systems is a promising solution to the overvoltage problem as it provides flexible real power control within the network.

The inverters of PV systems are capable of providing reactive power services for the networks to which they are connected. This feature can be further explored in achieving voltage control together with the use of BESS.

This work presents a distributed control scheme for promoting greater penetration of PV on the distribution network while keeping voltages within the statutory range. In this scheme, during high PV generation that leads to overvoltage, the BESS is brought into action by the controllers. The reactive power resource of the PV inverters is then utilised if the BESS action fails to solve the overvoltage problem. Curtailment of PV active power (P_{PV}) is carried out as a last option if the previous two measures fail.

DISTRIBUTED CONTROL SCHEME

Distributed control is used for the management of the network to keep voltages within designated limits. The controllers are located on every node where PV is installed. Minimal communication is required in this distributed control scheme as inverters on the same feeder only need to send distress signals across the feeder using cheap and available Power Line Communication (PLC). An advantage of the distributed control is that there is no singular possible point of failure as is obtainable in centralised control schemes. Another advantage of the distributed scheme is that knowledge of the entire network state is not needed for the control. This scheme depends only on local measurement of voltages (V_{meas}) at the nodes for decisions and actions of the controllers. Figure 1 illustrates the different sections of the control scheme.

The different parts of operation of this distributed control scheme are described in the following subsections.

Normal Operations

In this state, the measured terminal voltage V_{meas} remains below the set voltage limit (V_{lim}) ($V_{meas} < V_{lim}$). No action is required by the controllers in this state since no set voltage limits are violated. This happens usually when P_{PV} is less than the total load demand P_{DEM}.

BESS Charging

A local controller switches to this state of operation when V_{meas} reaches the V_{lim} ($V_{meas} \geq V_{\lim}$). Usually, this happens in the day time when there are high values of P_{PV} that exceed load demand. When this occurs, an overvoltage signal is sent across the feeder by the controller located at the node of occurrence of overvoltage, to notify other controllers.

BESS charging starts in a bid to consume the excess PV power, thereby preventing overvoltage. P_{BATT} refers to the total power consumed by the batteries at any time.

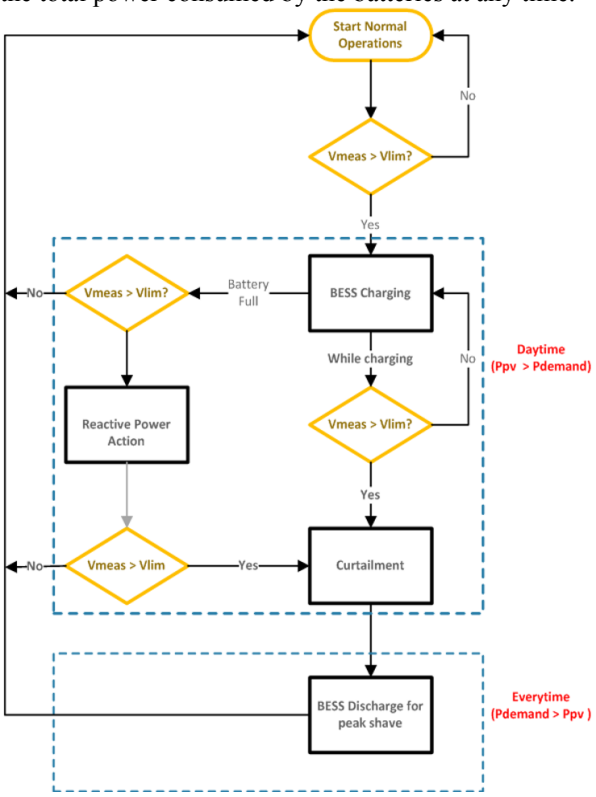

Figure 1: Distributed Control Scheme operation

PV Power Curtailment

The controllers switch to this state as a result of one of two conditions. The first condition is when BESS charging occurs simultaneously with overvoltage. P_{PV} being higher than the sum of P_{BATT} and P_{DEM} ($P_{PV} > P_{BATT} + P_{DEM}$) is a common cause of this situation. The second condition is when batteries are full, reactive power action has been taken (described in the next section), yet an overvoltage signal persists.

For any of these two conditions, a curtailment algorithm is run by the controllers to determine the minimum amount of active power to curtail in order to mitigate the overvoltage.

Reactive Power Absorption

This state is reached by the controllers when the batteries are fully charged and an overvoltage signal is still being received. Power quality - in this case appropriate voltage levels – on the distribution network can be improved by the use of PV inverters. The use of PV inverters for this purpose, however, comes under regulations by different countries. The specific country grid code defines whether this feature is allowed or not, as well as the permitted capability curve to be used. Figure 2 shows the capability curve of for a typical PV inverter.

PV inverters do not infinitely sink or source reactive power [4]. The maximum reactive power q_{max} that can be provided by the inverter is limited by the inverter's rated apparent power s_{PV} and the current active power generation $P_{(k)}$.

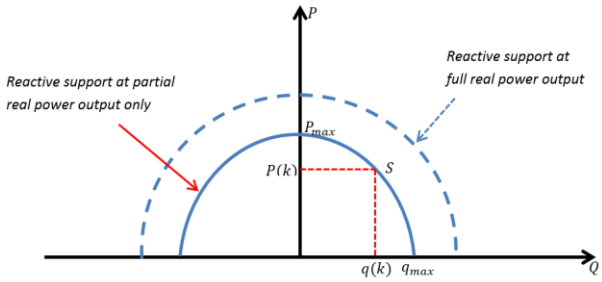

Figure 2: Inverter capability curve

The relationship between these quantities is given as

$$q_{(k)} \leq \sqrt{\left(s_{PV}^2 - p_{(k)}^2\right)} \equiv q_{max} \quad (1)$$

where $q_{(k)}$ is the reactive power available during real power output $p_{(K)}$. An oversized inverter, indicated by the dashed semi-circle in figure 2, is capable of reactive power support even when active power production is at maximum.

BESS Peak-Shave Discharging

The controllers switch to this state when the power demand on the network exceeds a set power threshold P_{TH}. This usually occurs during times when P_{DEM} is much higher than P_{PV}. The BESS are made to start discharging during this peak loading period. Peak-shaving is important as it avoids the installation of additional capacity in the network to for the purpose of meeting peak demands.

IMPLEMENTATION OF CONTROL SCHEME

This section describes the tools, data and test network used to illustrate the distributed control scheme.

Implementation Tools

The algorithm for the distributed control scheme was developed in MATLAB and the distribution network models and resources were developed using OpenDSS. OpenDSS is an open source distribution network systems tool developed by Electric Power Research Institute (EPRI). It has the Component Object Model (COM) which enables it to interact with MATLAB and other similar programming tools. MATLAB was further utilised for all the analysis carried out in this work.

Test Network

The operation of the control scheme is illustrated using a single feeder distribution network, which is a section of the network presented in [5]. It has been modified for the purpose of this implementation. The diagram of this single feeder is shown in figure 3.

The single feeder consists of 10 nodes with PV units and loads installed on each of the nodes. The PV units are each rated 32.5 kWp and the equivalent load on a single node is rated at maximum 15 kVA apparent power. Different numbers of BESS are added on different nodes of the network to create different scenarios as discussed in the next sections. Each BESS is rated at 120kWh with state of charge (SOC) of 30% and an external dispatch mode. $V_{lim} = 1.07pu$ is used as the voltage limit for this study.

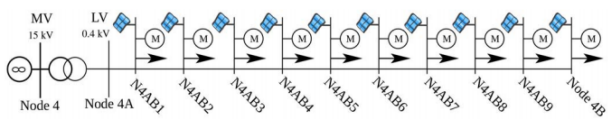

Figure 3: Single distribution network feeder

Load Demand and PV Profile Inputs

The load demand and PV power profiles used for the simulations are shown in figure 4.

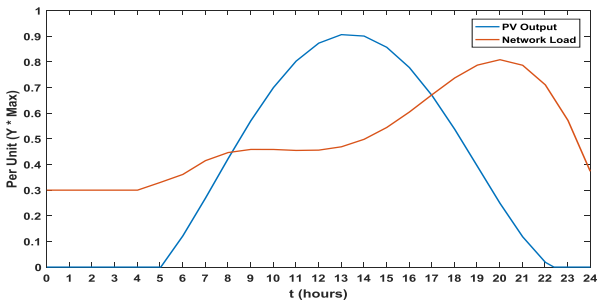

Figure 4: Load demand and PV profiles

The maximum PV value is 32.5 kWp while the maximum load value is 15 kVA. Both profiles are generic, representing typical characteristics of daily PV power output and daily residential demand. The profiles have not considered the fast variability and intermittent nature of load demand and PV output power respectively. This notwithstanding, the profiles provide a fair representation.

SIMULATION RESULTS

Daily simulations of 1-minute resolution (1440 minutes) are used throughout the study. P_{PV} and demand data are therefore also in 1-minute resolutions. The simulation cases highlight effects on the network characteristics (especially voltage) for different combinations of control. Knowledge of the amount of active power curtailed for each case is also important as this highlights the benefits of having this control.

Case 1

In this case, the network behaviour is observed with the penetration of PV, without application of the distributed control scheme. A plot of the voltage profile is shown in figure 5.

Overvoltage occurs on most of the nodes when no control actions are taken. Figure 6 shows the voltage profile when the excess P_{PV} is curtailed in order to avoid overvoltage. This is achieved by employing the algorithm for curtailment only. Figure 7 shows the amount of active power curtailed.

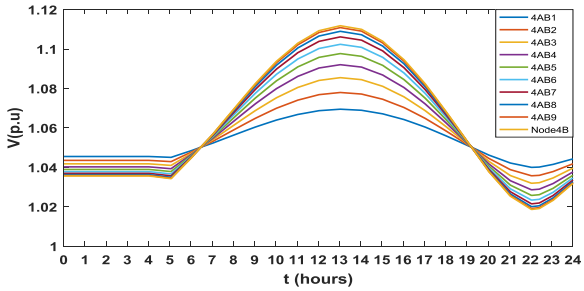

Figure 5: Feeder voltage profile without controls

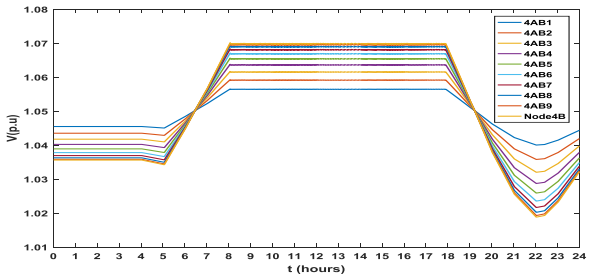

Figure 6: Feeder voltage profile with curtailment-only

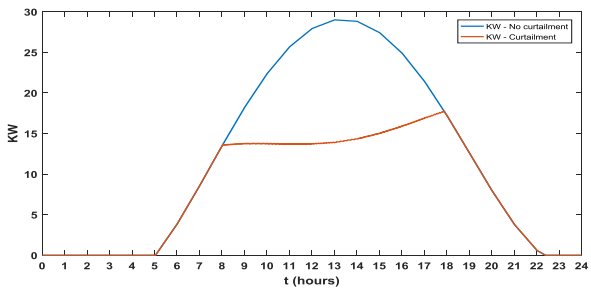

Figure 7: PV active power curtailment

V_{meas} for Node4B reaches $V_{\lim}$. at $t = 485\,mins$ (just after the 8th hour). The total energy curtailed is $94.5kWh$.

Case 2

In this case, the distributed control algorithm is deployed with BESS installed on all the nodes on the feeder. The reactive power action has been disabled for this case, to represent a possible real life scenario where the PV systems do not have this capability. Figure 8 shows the voltage profile for this case while figure 9 shows the curtailment.

Again, V_{meas} for Node4B reaches $V_{\lim}$. at $t = 485\,mins$ (after the 8th hour) and the controllers switch to the BESS charging state. The batteries are fully charged at time $t = 1024\,mins$ (just after the 17th hour) and a small curtailment is observed in this case (figure 9). The curtailment is small because at this time of the day, P_{PV} is decreasing and tending towards zero.

Peak shaving to ease loading on the network starts at time $t = 1025\,mins$ (after the 17th hour), when the P_{TH} is reached as a result of high load demands around this time (See figure 3).

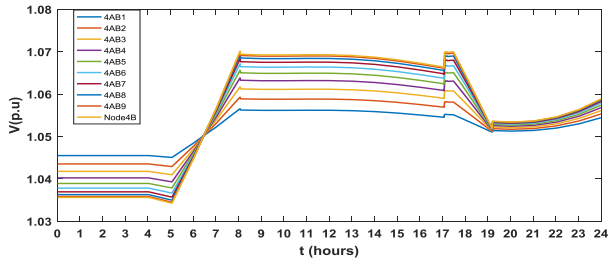

Figure 8: Feeder voltage profile for case 2

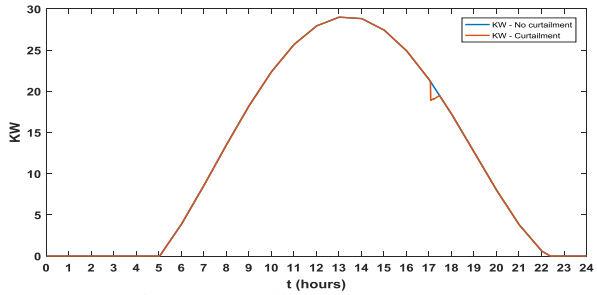

Figure 9: PV active power curtailment for case 2

Case 3

In this case, the distributed control scheme is again deployed on the test feeder as in Case 2, but this time, with the reactive power action enabled. Another difference this case has from Case 2 is that fewer BESS have been installed on the nodes of the test feeder. BESS installations for this case are only on nodes 4AB2, 4AB4, 4AB6, 4AB8 and Node4B. This is to represent a possible real life scenario where an attempt is made to cut the cost of installation of BESS units. The voltage profile is shown in figure 10.

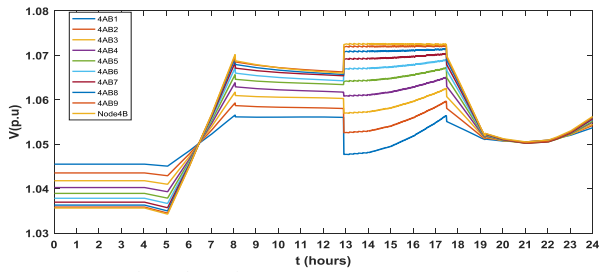

Figure 10: Feeder voltage for case 3

The batteries start charging and are fully charged at times $t = 485\,mins$ (after the 8th hour) and $t = 774\,mins$ (before the 13th hour) respectively. The reactive power action takes up the control immediately the batteries get full. The maximum amount of reactive power that can be absorbed by the inverters at this time is given by (1). The voltage dip that can be observed at the point of reactive power action, especially for the nodes closer to the substation, is as a result of the controller operating uniformly and absorbing the same amount of reactive power. This therefore has different impacts on the terminal voltage of different nodes on the feeder. If the reactive power action was not activated for this case, a large amount of energy would be curtailed as shown in figure 11.

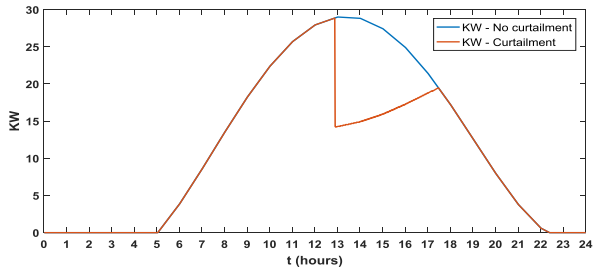

Figure 11: Curtailment for case 3 without reactive power action.

DISCUSSION

This scheme has demonstrated the use of BESS and reactive power to mitigate overvoltage on the distribution network. The tests however, were carried out without consideration of the variability of load and intermittency of PV power. The illustration was made simplistic to obtain preliminary results and information for further development.

Using this scheme, it is possible to have no curtailment of active power. This maximises the benefits of investment in PV systems and reduction in greenhouse gas emissions, but it comes at the cost of having to install BESS, which are expensive. Holistic cost-benefit assessments are important in order to ascertain the exact economic benefits of using BESS versus curtailing active power.

Optimum BESS sizing and location are also important factors to consider if this scheme is to be deployed in a larger network. This is to avoid situations where BESS may be oversized, as this would lead to greater cost.

Losses on the power lines due to use of reactive power for voltage control is a factor that should also be considered.

CONCLUSION

This paper presented a distributed control scheme for mitigation of overvoltage on low voltage distribution networks with high penetration of PV. The scheme was tested on a single feeder distribution network. BESS was employed to accommodate excess PV production, especially during the day when there is light loading and high PV power production. Simulations show that this scheme successfully keeps voltages within statutory limits. Fewer numbers of BESS were installed on critical nodes and this achieves almost the same results as when BESS are installed on all the nodes. The control scheme therefore is economical in this sense.

REFERENCES

[1] B. EN, "50160:'Voltage characteristics of electricity supplied by public distribution systems'," *British Standards Institution,* 2000.

[2] F. Olivier, P. Aristidou, D. Ernst, and T. Van Cutsem, "Active management of low-voltage networks for mitigating overvoltages due to photovoltaic units," *IEEE Transactions on Smart Grid,* vol. 7, pp. 926-936, 2016.

[3] Y. Yang, H. Li, A. Aichhorn, J. Zheng, and M. Greenleaf, "Sizing strategy of distributed battery storage system with high penetration of photovoltaic for voltage regulation and peak load shaving," *IEEE Transactions on Smart Grid,* vol. 5, pp. 982-991, 2014.

[4] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Options for control of reactive power by distributed photovoltaic generators," *Proceedings of the IEEE,* vol. 99, pp. 1063-1073, 2011.

[5] B. Otomega and T. Van Cutsem, "Distributed load interruption and shedding against voltage delayed recovery or instability," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*, 2013, pp. 1-6.