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

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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 limits [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.

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. \( P_{\text{BATT}} \) refers to the total power consumed by the batteries at any time.

\[ q_{(k)} \leq \sqrt{(s_{PV}^2 - p_{(k)H})} \equiv q_{\text{max}} \]  

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. $V_{\text{lim}} = 1.07 \, \text{pu}$ is used as the voltage limit for this study.

**Load Demand and PV Profile Inputs**

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

![Load demand and PV profiles](image)

**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.

![Feeder voltage profile without controls](image)

**Figure 5: Feeder voltage profile without controls**

![Feeder voltage profile with curtailment-only](image)

**Figure 6: Feeder voltage profile with curtailment-only**

![PV active power curtailment](image)

**Figure 7: PV active power curtailment**

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

**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, $V_{\text{meas}}$ for Node4B reaches $V_{\text{lim}}$ at $t = 485 \, \text{mins}$ (after the 8th hour) and the controllers switch to the BESS charging state. The batteries are fully charged at time $t = 1024 \, \text{mins}$ (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 $t = 1025 \text{ mins}$ (after the 17th hour), when the $P_{TH}$ is reached as a result of high load demands around this time (See figure 3).

The batteries start charging and are fully charged at times $t = 485 \text{ mins}$ (after the 8th hour) and $t = 774 \text{ mins}$ (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.

**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


