Integration of Distributed Generation in the Volt/VAR Management System for Active Distribution Networks

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***Abstract*—This paper investigates the use of voltage source converter interfaced distributed generators (DGs) for reactive power support in active distribution networks. Integration of DG management systems into decentralized parts of the Volt/VAR management system is proposed. The solution is designed to address issues connected to increased DG penetration, while at the same time avoiding the technical challenges and high costs related to state-of-the-art model-based Volt/VAR management. Coordination of DGs with conventional voltage regulation equipment is based on predefined control hierarchies. However, to reduce requirements for data handling capability, the distribution grid is divided into zones with individual voltage regulation and reactive support schemes. To add flexibility and scalability, these zones can be combined into larger zones with a common Volt/VAR management scheme. This is referred to as adaptive zoning. The results indicate that the control schemes successfully restore voltage to within limits after disturbance of grid conditions. Adaptive zoning effectively reduces system complexity and requirements for data handling capability, while still ensuring a grid-wide solution.**

***Index Terms*—Active distribution network, distributed generation (DG), reactive power support, Volt/VAR management system, voltage source converter (VSC).**

NOMENCLATURE

I_d	d component of current.
I_q	q component of current.
$I_{d\mathrm{ref}}$	d component of current reference.
$I_{q\mathrm{ref}}$	q component of current reference.
L_{DG}	Reactance of distributed generator.
P	Active power.
P_{out}	Output active power.
P_{ref}	Active power reference.
Q	Reactive power.
Q_{out}	Output reactive power.
Q_{ref}	Reactive power reference.
V_d	d component of voltage.
V_q	q component of voltage.
$V_{d\mathrm{ref}}$	d component of voltage reference.
$V_{q\mathrm{ref}}$	q component of voltage reference.
V_{ref}	Voltage reference.
V_{pcc}	Voltage at point of common coupling.
$V_{d\mathrm{new}}$	New d component of voltage.
$V_{q\mathrm{new}}$	New q component of voltage.
ω	Angular frequency.

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I. INTRODUCTION

IN RECENT years, the penetration of distributed generation in medium and low voltage (MV and LV) networks has increased significantly. Awareness of the environmental impacts of fossil-fueled generation leading to more ambitious energy policies, and deregulation of electricity markets all over the world have been a major drivers for renewable energy technology development [1]–[4]. At present, most distributed generators (DGs) are connected passively to the grid [4]–[6]. This considerably limits DG penetration, because of the possible negative impacts on voltage profiles and existing voltage regulation from unpredictable power flows [2], [7], [8].

Voltage regulation in traditional distribution grids is relatively simple and typically involves on-load tap changers (OLTCs) and switched shunt capacitor banks acting on local control commands [7], [9]. However, by actively controlling DG output, DGs can contribute to voltage regulation at the point of common coupling (PCC) and help mitigate the negative effects caused by its own penetration. Dynamic reactive power support from DGs in active distribution networks has been researched extensively. Rogers *et al.* [10] recognized the increase of power electronics interfaced energy resources on residential voltage levels and the possibility to use these for reactive power support to mitigate voltage collapses. A centralized management of the resources was proposed, but this management was also identified as the main challenge as the complexity increases with the number of devices. Also in [11], a centralized control system was proposed for DGs, but in the MV network. The suggested control scheme adjusted reactive power injections from DGs by controlling power factor and coordinated several DGs by means of sensitivity analysis. However, the method did not include fast and dynamic voltage response. In [12], an inverter control strategy was proposed to allow DGs to provide voltage support during voltage sags. Delfino *et al.* [13] developed a model to evaluate the limitations of real and reactive power injections from photovoltaic units providing reactive power support.

A fair amount of research has shown that also actively controlled DGs can interfere with existing voltage regulation if devices act on local control criteria [2], [8], [9]. Coordination of DGs (not specifically controlled for voltage regulation purposes) with OLTCs and capacitor banks respectively is investigated in [14] and [15]. Coordination of DGs providing reactive power support with OLTCs is investigated in [2] and [8]. In [9], coordination of OLTCs, substation and feeder capacitors, and DGs was investigated, with the findings that the number of OLTC operations can be significantly reduced and voltage fluctuations decreased. In that study, however, the DG control mode is fixed to either constant power factor, or constant reactive power output, or constant voltage at the PCC. In [16], reactive power support from DGs at MV level is coordinated with active power output from DG sources at LV level and with regulation from capacitor banks and OLTCs, by means of evolutionary particle swarm optimization.

Active components in the distribution network calls for enhanced operation planning and enhanced use of SCADA, as well as an enhanced communication infrastructure with possibility of real-time information exchange [7]. With this in place, new tools for network operation can be developed. Lately, advanced Volt/VAR management applications have received much attention in distribution grid operation.

The aim of this paper is to present a solution in which actively controlled DGs are integrated with the Volt/VAR management system to contribute to voltage regulation in the distribution network. To achieve a flexible and scalable solution while minimizing complexity and requirements for data-handling capability, DG management systems are integrated with decentralized parts of the Volt/VAR management system in smaller geographical zones. A similar concept was presented in [17] and decentralized voltage control and power-flow management in distribution grids with DGs has been proposed in a number of recent studies [18]–[20]. The main differences from [17] are as follows.

1) In [17], only DGs are considered in the proposed control scheme and reactive power support from DGs is always prioritized over OLTC action.
2) In [17], control zones are only formed where DGs are connected and are changing in real-time according to network conditions.

The main contributions from this paper are as follows.

1) The DG management integration to decentralized Volt/VAR control with multilayer control approach based on available controllable devices, also including OLTCs/voltage regulators (VRs), shunt capacitor banks and distribution static synchronous compensators (DSTATCOMs). Several approaches have been suggested where DG management has been coordinated with one or two types of voltage regulation devices, such as in [2], [8], [9], [14]–[16], and [19]. Just as in previously presented approaches, this concept reduces the need for installing new Volt/VAR control equipment by using existing DGs. In contrast to previously presented solutions, this concept can feasibly be applied in grid topologies with traditional voltage regulation as well as in grids with state-of-the-art equipment (DSTATCOMs) expected to be more common in the future.
2) A generalized theory for the division and combination of zones, which is formed based on shunt and series regulating device characteristics, priority and individual device limits.
3) The generalized zoning concept allows the solution to be applied to any grid topology and reduces complexity compared to centralized approaches such as [10] and [11]. It is feasible for gradual scaling-up or down by adding or removing control zones and allows for minor changes in grid topology, such as the addition/removal of DG units, to be taken care of on a local level.
4) Unlike in [17], control zone boundaries are fixed to reduce complexity of the control system, but zones can be combined if certain network condition criteria are fulfilled. The ability to combine zones provides flexibility in voltage regulation and reactive power control, while reduced complexity reduces ICT costs and increases speed of control. It is assumed that a tariff system is in place, which to some extent benefits production of reactive power from DGs. The solution is validated by simulations in a modified version of the IEEE 34-node test feeder.

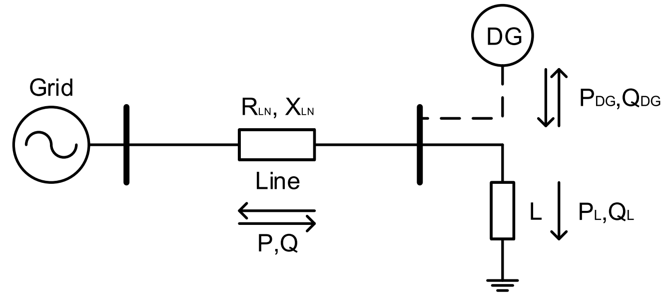

Fig. 1. Possible power flows on distribution grid feeder with DG.

II. Voltage Regulation in Distribution Networks With DGs

A. Impact of DGs on Distribution Network Operation

Traditional distribution system operation is based on unidirectional power flows from high voltage (HV) transmission networks to end-users connected to MV and LV feeders. Changes in power demand are compensated at transmission level and the distribution network distributes power while maintaining voltages and currents within allowed limits. Voltage regulation in distribution networks is therefore relatively simple and involves mainly OLTCs, line VRs, and switched or fixed capacitor banks.

With the introduction of DGs in MV and LV networks, the possibility of bidirectional power flow occurs (Fig. 1). This might cause overvoltages and might interfere with traditional voltage regulation.

B. Reactive Power Support From Actively Controlled DGs

Because of the possible negative impacts, a fairly low penetration of passively integrated DGs can be allowed in

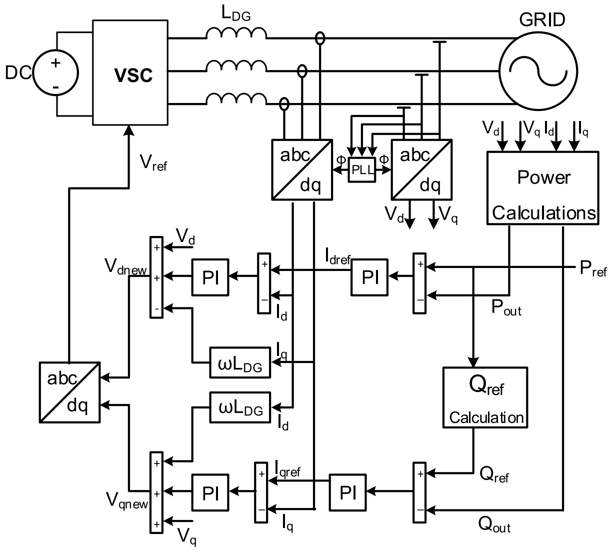

Fig. 2. Control scheme of a DG in power reference (P_{ref}) mode.

traditional distribution systems. However, if DGs are actively controlled, the benefits of distributed generation can be ensured and the penetration can be allowed to increase. With the proper market models and regulation in place, DGs could be used for reactive power (Q) support in addition to active power (P) production [21].

The voltage source converter (VSC) interface is often preferred for integration of actively controlled DGs, since it offers the highest controllability compared to other interfacing technologies [3], [22]. Today, the IEEE standard 1547 [23] does not allow DGs to actively regulate voltage, but it is currently being updated to address these questions and in some countries DGs are already required to provide active voltage regulation. Consequently, this paper deals with VSC-interfaced DGs in grid-supporting mode.

Converter control for DGs can be implemented in many ways. A simple control scheme with reference signals for P and Q (P_{ref} and Q_{ref}) is presented in Fig. 2. Equations (1) and (2) are control equations for the generation of $I_{d\text{ref}}$ and $I_{q\text{ref}}$. This control mode is referred to as power reference or P_{ref} mode. The reference signal for Q is generated as in (3) from P_{ref} and is based on the available current limit headroom after injection of active power. In normal operation, P_{ref} is the rated power output of the generator. P_{ref} could also be used to curtail power output or to regulate frequency, though it is not discussed in this paper. For a fixed power factor operating mode the current control changes the reactive power with the available active power within the current limit. The other alternative is to modulate the reactive power based on local voltage with a limited relaxation in active power.

P and Q can also be controlled with the aim to maintain a certain voltage at the PCC. In this case, a reference for Q is generated from the error between the voltage reference signal (V_{ref}) and the actual voltage (V_{pcc}) (Figs. 3 and 4). In both control modes, a new reference signal for the VSC output voltage is generated via (5) and (6)

$$I_{d\text{ref}} = \left(K_p + \frac{K_{ip}}{s}\right)(P_{\text{ref}} - P_{\text{out}}) \tag{1}$$

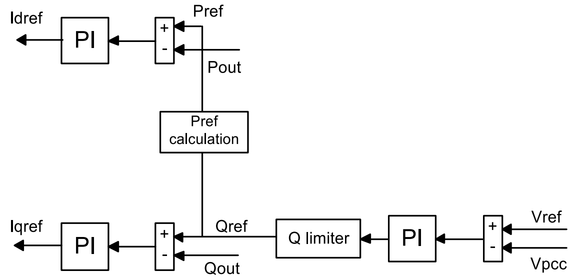

Fig. 3. DG control in voltage reference (V_{ref}) mode.

$$I_{q\text{ref}} = \left(K_q + \frac{K_{iq}}{s}\right)(Q_{\text{ref}} - Q_{\text{out}}) \tag{2}$$

$$Q_{\text{ref}} \leq \sqrt{S_{\text{rated}}^2 - P_{\text{ref}}^2} \tag{3}$$

$$Q_{\text{ref}} = \left(K_v + \frac{K_{iv}}{s}\right)\left(V_{\text{ref}} - V_{\text{pcc}}\right) \tag{4}$$

$$V_{d\text{new}} = V_d + \left(K_{vd} + \frac{K_{ivd}}{s}\right)(I_{d\text{ref}} - I_d) - I_q\omega L_{\text{DG}} \tag{5}$$

$$V_{q\text{new}} = V_q + \left(K_{vq} + \frac{K_{ivq}}{s}\right)\left(I_{q\text{ref}} - I_q\right) + I_d\omega L_{\text{DG}} \tag{6}$$

where the *K:s* are controller gains.

C. Other Voltage Regulation Equipment

It is important to note that reactive power support from DGs might interfere with existing voltage regulation equipment. Therefore, the management of actively controlled DGs should be coordinated with the operation of other voltage regulation devices. The voltage regulation devices considered in this paper are as follows: 1) OLTCs/VRs and capacitor banks (as key equipment in distribution system voltage regulation); and 2) DSTATCOMs (as they are increasingly considered for use in distribution grids).

Capacitor banks and DSTATCOMs are connected in shunt with power lines and regulate voltage by providing reactive power support, while OLTCs/VRs are connected in series and regulate voltage directly. The different types of devices are therefore referred to as shunt and series devices in this paper.

III. Challenges in Volt/VAR Management at High DG Penetration

Volt/VAR management is the process of optimizing power flows while maintaining acceptable voltages at all buses in the system. Presently, the two main challenges for Volt/VAR management are: 1) the impact on existing Volt/VAR management from increased DG penetration and 2) how to integrate power electronics interfaced DGs into Volt/VAR management [24].

Generally, there are three control strategies for Volt/VAR management [25]–[27], which are as follows:

1) independent and local control of compensation devices;
2) centralized control based on a predefined set of rules, including some extent of coordination between devices of the same kind, for example a number of capacitor banks along a feeder;

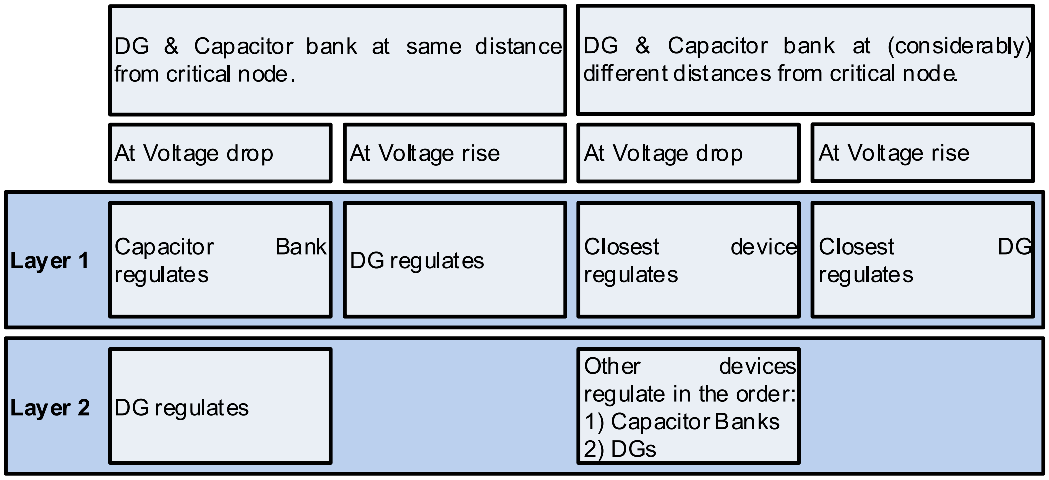

Fig. 4. Control hierarchy for DGs and capacitor banks.

TABLE I
EXISTING VOLT/VAR MANAGEMENT METHODS

Volt/VAR management method	Advantages	Limitations
Local control	• Low cost • Low needs for communication • Scalable	• Possibility of negative interaction between devices • Requires higher safety margins • May not be able to handle integration of DGs
Centralized control	• More efficient than local control during most conditions • Smaller safety margins needed with access to remote measurements	• Requires more communication • Does not adapt to changing feeder configuration • Does not adapt to changing operation needs • No coordination between regulation devices of different kinds • Does not handle integration of DGs well
Model-based control	• Fully coordinated, optimal solution • Can handle changing operation and system configuration, due to real-time update of system state • Handles integration of DGs well	• Not very scalable – control system for whole distribution network • Technical challenges of system efficiency and robustness leading to high costs of implementation and operation.

3) distribution system model-based Volt/VAR management, utilizing real-time data, state estimation, and online power-flow calculations.

The advantages and limitations of the three methods are listed in Table I [25]. None of the two first alternatives considers issues related to integration of distributed generation, since they were developed previous to large-scale penetration of DGs. The third and most modern alternative allows integration of DGs as providers of reactive power support in Volt/VAR management. However, solutions that can avoid/reduce the technical challenges and high costs of model-based Volt/VAR management should be of high interest for distribution system operators (DSOs).

IV. Proposed Coordinated Control and Adaptive Zoning

The solution presented in this paper proposes integration of DG management systems into decentralized parts of a Volt/VAR management system. It is designed to address issues connected to increased DG penetration, while at the same time avoiding the challenges related to state-of-the-art model-based Volt/VAR management.

Actively controlled DGs are coordinated with conventional voltage regulation devices to provide reactive power support without interfering with the function of existing equipment. Similar to centralized Volt/VAR management, the coordination follows control schemes based on predefined rules. The control schemes are referred to as control hierarchies. To create modularity, the distribution grid is divided into zones. Each zone has its individual and decentralized Volt/VAR control scheme.

In some cases several zones might be affected by a disturbance or there might be similar disturbances in adjacent zones. To ensure efficient voltage regulation in these cases a concept has been introduced, which allows zones to be combined into larger zones with a common Volt/VAR control scheme. This concept is named adaptive zoning and shares some features with model-based Volt/VAR management in that it requires extensive control and communication technology to be in place. However, since the system design is modular, the distribution system-wide computations of model-based Volt/VAR management are avoided. Adaptive zoning only combines as many adjacent zones as is required to solve the occurred voltage deviations and therefore keeps control as local as possible. If voltage exceeds limits in three zones for example, voltages and regulation devices only within these zones need to be considered when finding the subsequent control action.

The benefits of the proposed solution compared to previous Volt/VAR management systems are as follows.

1) *Less Complex Computations:* Because control hierarchies and zones are predefined, the suggested solution will result in less complexity compared to a solution where control zones are continuously redefined and where control action is evaluated on a case-to-case basis instead of following a set of predetermined rules.
2) Lower amounts of data to handle since control action is carried out within the decentralized control zones, the contrast being a model-based Volt/VAR management system evaluating data from much larger areas with many more devices.
3) Based on the two points above, cost for the proposed system is thought to be lower than for a model-based Volt/VAR management system. Control, information, and communication technology cost depends largely on distance and solutions for shorter distances (smaller control systems with less communication technology) can achieve considerable cost reductions.
4) *Scalable and Flexible:* Since control is zone-based, the solution allows for gradual addition (or removal) of new control zones.

It must be noted that detailed techno-economic analysis is outside scope of project.

The following sections describe the coordination control hierarchies, as well as when and how zones are combined according to the adaptive zoning concept.

A. Control Hierarchies

Control hierarchies determine in what order the devices within a zone should contribute to voltage regulation in case of a disturbance such as a sudden load increase or a DG output change. For all regulation action, it is assumed that we want to maintain voltage within some limits. These limits could be the ±10% of the EN 50160 standard or they could be defined by the local utility standards. There is a different control hierarchy for each combination of shunt devices. If a series device is present in the zone, a separate logic is used to determine the control action.

All control hierarchies have similar structures (Fig. 4): there are two different control hierarchies depending on device distance from the critical node (devices are at the same distance or at different distances from the critical node). Control layer 1 represents the control action that should be carried out first, layer 2 the control action that should be carried out if the first action cannot fully compensate the voltage change, layer 3 is activated if the second control action is insufficient, and so on. The control hierarchies are created based on the principles listed below.

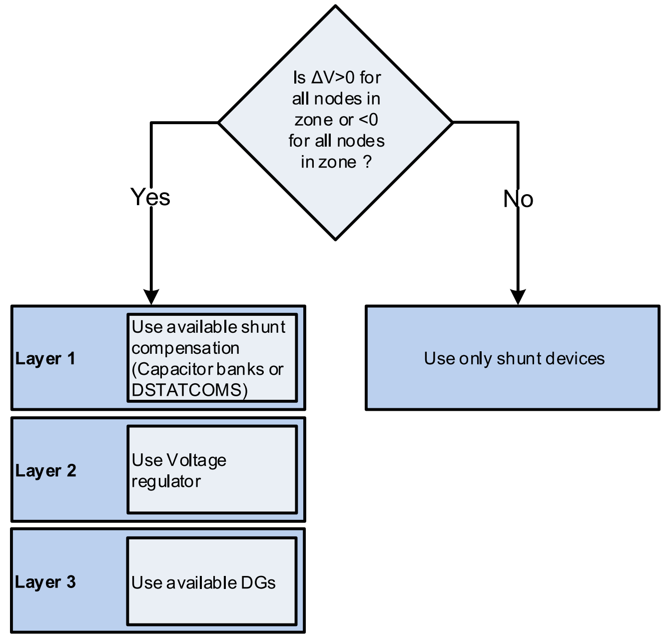

Fig. 5. Logic for coordination of shunt and series devices.

1) Of all shunt regulation devices in a zone located at the same distance from the critical node, the DGs should regulate last.
2) If shunt devices are located at different distances from the critical node, the closest device should regulate first.
3) Local shunt regulation should always be used before series regulation in a zone with both shunt and series devices, since this minimizes reactive power flows. The exception is DGs that should regulate after both conventional shunt regulation and series regulation devices have been used.

In some cases, OLTC duty might be reduced if DGs would adjust reactive power output before OLTCs are used. However, the suggested method assumes that DGs are prioritized to supply active power, which is why other voltage regulation devices are activated first. An example of a control hierarchy for a zone with only shunt devices (in this example DGs and capacitor banks) is presented in Fig. 4. (The control hierarchy assumes that all capacitor banks are disconnected before disturbance and that all DGs are in P_{ref} mode.) The control logic for a zone containing both shunt and series devices is presented in Fig. 5.

B. Adaptive Zoning

This section describes the following. 1) definition and location of different types of zones; 2) what conditions zones should be combined; 3) voltage regulation strategy for combined zones; and 4) practical considerations of adaptive zoning.

Zones can be located in series or in parallel. An OLTC or a VR separates two zones located in series, whereas zones in parallel are connected to the same PCC. (Parallel parts of feeders with the same PCC do not always have to be in separate zones. This depends on the length and the impedance of the feeder parts and whether there is any regulation devices

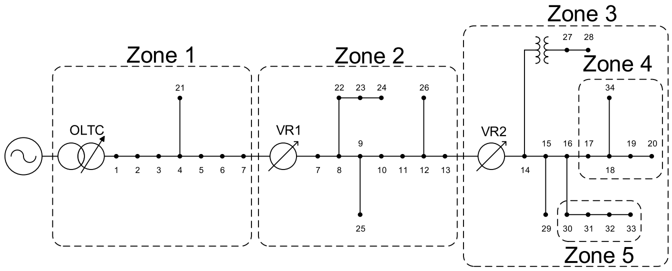

Fig. 6. IEEE 34-node test feeder divided into zones.

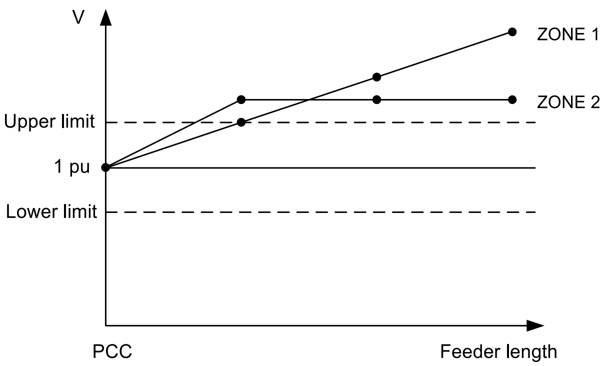

Fig. 7. Two parallel zones that should be combined according to adaptive zoning.

located along them.) Fig. 6 shows the modified IEEE 34-node test feeder, which is divided into three zones in series according to these principles (Zones 1–3). Zone 3 also contains two parallel zones (Zones 4 and 5).

Combining zones means that the decentralized Volt/VAR control schemes are coordinated. Zones are combined when certain requirements are fulfilled about voltage deviations at nodes within the zones. The requirements differ for zones located in parallel and in series.

Parallel zones are combined if $\Delta V > 0$ (i.e., a voltage rise) at all nodes in both zones or $\Delta V < 0$ (i.e., a voltage drop) at all nodes in both zones, and at least one node is outside voltage regulation limits in both zones. Voltage needs to be regulated in the same direction in both zones and it is therefore possible to use a regulation device at or very close to the PCC, in addition to the devices within the zones. Fig. 7 shows an example of two zones in parallel that should be combined: Zones 1 and 2 consist of two parallel feeders with three nodes each and voltage is outside limits in both zones.

The prerequisite for combining two zones in series is that voltage is outside regulation limits at one or more nodes in both zones. If voltage is outside limits in only one of the zones, regulation should be carried out within the individual zone with available shunt devices. Even in the case when zones in series are combined, conventional shunt devices should be used prior to OLTCs or VRs. As a last option, available DGs can be used for voltage regulation.

To be able to know when to combine zones, voltage has to be monitored at many nodes in the distribution system. However, it should not be necessary to monitor voltage at all nodes. Nodes where critical loads, DGs, or regulation devices are connected should always be equipped with monitor and communication possibilities. Depending on the network configuration, also other important nodes can be selected for monitoring.

When implementing adaptive zoning, a number of practical aspects will have to be considered.

1) *Zone Division:* Zones might not always be divided by a VR/OLTC or at a PCC of parallel feeders. Electrical distance needs to be considered when defining zone boundaries and a radial feeder might be divided into two zones without a VR/OLTC being located somewhere along it, at the point of maximum reach of reactive compensation devices.
2) *Control Zone Addition/Reprogramming:* To avoid having to reprogram the control hierarchies at the addition of each new DG unit, several DGs should be added at the same time. Until DGs are added to the control system they have to work in traditional curtailment mode and have to be treated as passive network components. If enough DGs and/or voltage regulation devices are added to a part of the grid that is not yet part of the adaptive zoning system, a new zone can be created and coordinated with adjacent zones.
3) *Control Center Location:* An important practical consideration is where to place the control centers for each zone and which control centers should be responsible for combining zones when feasible. The distribution control center will be implemented in the substations and depending on the substation location a higher one might lead the instructions. However, the control instructions go through the lower control center. The combination is only done in terms of control logic.
4) *Dynamic Network Topologies:* In meshed distribution grids that can switch network topology for protection purposes, these possible topology changes and how they affect zone boundaries need to be taken into account. Where this is the case, it adds some complexity to the concept. However, since the number of alternative grid topologies in distribution networks usually is very limited, so is the impact on complexity of the control schemes.
5) *Third Party Ownership:* Third party DG owners must be prepared to allow utility access to and control of their DG units. As mentioned, it is in this paper assumed that a tariff system in place that reimburses DG owners for reactive as well as active power, but the details of such a system are outside the scope of this paper.

C. Systems With Intermittent Energy Sources

Power output from intermittent DGs varies and therefore, the impact from the DGs on line power flow as well as line voltage. While the real-power deficiency is tackled with main grid, storage, and load shedding, reactive power shortage is primarily solved with other distribution equipment as described in Section IV-A. If the fluctuation is below the Volt/VAR management control bandwidth, storage is one of the key components used to compensate for that. A high penetration of DGs with variable power thus requires more storage for leveling and firming. One possible storage product for such scenarios is PowerStore, which injects real and reactive power based on continuous frequency and voltage fluctuation [28]. Furthermore, in the proposed control method DGs can actually compensate their own sudden power output changes by adjusting the relation between active and reactive power output. For slower variations of power flow and voltage (within bandwidth and beyond time delays), the capacitors and regulators participate in reactive support and voltage profiling. With advanced switched capacitors and power electronic tap changers it is possible to achieve a much improved device control for the proposed method in those scenarios.

Advanced capacitor banks are available with a power circuit breaker, protection and control panel (e.g., ABB Modular Capacitor Bank) and there are some capacitors for variable load application (e.g., ABB Dynacomp). These offer power factor compensation and reduction of voltage drops with transient-free switching and advanced communication features, among other things.

Power electronics tap changers are still in research and not yet commercially available. The main advantage is lower losses and four quadrant operation. These tap changers can work much faster, without significant jitters and can easily be integrated to Volt/VAR management system solutions via communications. Further information can be found in [29]–[31].

D. Selection of Controllers

It must be noted that the controller selection for regulators, OLTCs, capacitor bank has significant impact on the Volt/VAR control of the proposed method. The most important settings for the regulators are set voltage, bandwidth, time delay, and line compensations. A brief discussion of these settings for the proposed method is given below.

1) Set Voltage: The set voltage for each of the regulators is calculated based on the distribution transformer ratio, VR ratio, and the base voltage. The set voltage is controlled through the VR ratio and it must be ensured that the set voltage stays in the middle of the acceptable voltage range. In special scenarios for feeders with more overvoltage or LV problem, the set voltage can be set to achieve the total VR bandwidth.

2) Bandwidth: The bandwidth is the voltage range around set voltage, which the regulator can control. Usual 5/8% taps from minimum 2 to 32 taps are used to cover the bandwidth. The bandwidth setting in a multizone system decides which regulator would respond first for a voltage deviation. In the proposed method, if the regulators are in series the regulator bandwidth can be controlled in two ways. In the first method, the regulator higher up in the distribution system will have lower bandwidth than the downstream one, and will thus react first. This ensures the headroom in the down zone with the second regulator. The alternative would be to have decreasing bandwidth from substation down along the feeder, so that the regulator furthest out always reacts first. In some cases the disadvantage would be frequent limit-hitting of the downstream regulator. It must be noted that the actual setting of the bandwidths for the distribution system must be selected based on the DGs, loads, and capacitors connected. It must be noted that in either case, the proposed zone-based control can be adopted to solve the Volt/VAR management within a zone and depending on the current tap positions of the regulators, they can be coordinated to provide the reactive support.

3) Time Delay: The time delay is the delay in seconds that the regulator control waits after the voltage deviation before tap change, to avoid the transient voltage fluctuation. In case of series operation of regulators, time delays can be set in two ways as bandwidth. Having the substation regulator responding first would help the feeder regulator to have the headroom after correction. On the other hand, a faster feeder regulator would first work locally. This may be effective in many situations with frequent local voltage variation (e.g., an intermittent DG with variable power output).

4) Line Compensation: Line compensation may be used if the regulators are intended to control voltage at some particular point down the feeder. But for local voltage control of the regulator no line compensation is used. Both types can be used for zone-based control. It must be noted that in this paper line compensation has not been used. If line compensation is used, it is important to adapt the compensation factor while combining the zones and regulating a voltage at a different point depending on the distance and line impedance.

5) Operating Modes: There are various operating modes possible with the VRs. With the proposed method and in presence of DGs, the VR operates in bidirectional or cogeneration mode depending on the DG owners. For a third-party power producer the VR is operated in cogeneration mode. As in this paper, all the DGs are assumed either to be owned by a utility or integrated to the DSO energy management system and only bidirectional mode is considered.

The capacitors in this paper are controlled based on the local voltage measurement for VAR support. They are automatically switched in in heavy load period and switched off at light load period. They can be also controlled with local or remote control, voltage or temperature override, adjustable over and under voltage settings and different operations counters. In the proposed method, the capacitors are switched in before DGs to improve local voltage, as the main aim for the DGs is to provide active power.

The actual parameter selection will largely depend on the system structure. The key steps in the controller setting are as follows.

1) Forming the set voltages in the different zones based on load, DGs, and connected grid.
2) The set voltages can vary within the acceptable voltage in the network and desires reactive power flow.
3) Setting the bandwidths so the feeder controller reacts first during disturbances at feeder end.
4) Capacitors, DGs, and other regulation devices are also set with control bandwidth to act based on hierarchy to inject the reactive power at the connected node.
5) Time delays are set accordingly to control the activation time of each controller.
6) The controller settings are adapted while combining two or more zones into one.

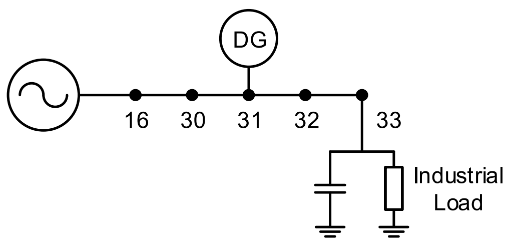

Fig. 8. Added devices for control hierarchy simulation.

Example controller settings for individual and combined zones are shown in Appendix II.

V. Simulations

Time domain simulations to validate the proposed solution have been carried out in the SimPowerSystems toolbox in the MATLAB Simulink platform. This paper presents results from three simulations of regulation according to control hierarchies within one zone and one simulation of adaptive zoning where two zones are combined. In all cases, an industrial load increase is simulated to cause a voltage deviation outside regulation limits. More simulation results are presented in [32].

A. Coordination of DG and Shunt Voltage Regulation Device in One Zone

This case aims to show the coordination of a DG and a second shunt device (a capacitor bank or a DSTATCOM) located at different distances from the critical node. To do this, a DG, a capacitor bank/DSTATCOM, and an industrial load are added to Zone 5 in the test system (Fig. 6) according to the line diagram shown in Fig. 8. (Fig. 8 shows the case with a capacitor bank.) At t = 0.2 s, the industrial load is increased by 100% and critical node voltage (node 33) drops below the lower regulation limit (0.96 pu). The device closest to the critical node, in this case the capacitor bank/DSTATCOM, is connected after a time deadband of 150 ms. In neither the case with a capacitor bank NOR with a DSTATCOM is this regulation action sufficient and the DG is therefore switched to voltage regulation mode (V_{ref} mode), which brings voltage back within limits. The outputs of the devices and the subsequent impact on voltage at node 33 are shown in Fig. 9 (with capacitor bank) and Fig. 10 (with DSTATCOM). The large oscillation in DG power output is largely due to the mode change from power to voltage control mode. Optimal tuning of controllers can also reduce oscillations. The impact of regulation actions on the voltage profile in Zone 5 is shown in Fig. 11 (with capacitor bank) and Fig. 12 (with DSTATCOM). For increased clarity, the voltages at node 33 during the regulation sequence are listed in Tables II and III.

In Appendix I, a simulation of Zone 5 with four DGs connected to nodes 30–33 shows system behavior at higher DG penetration.

B. Combining Two Zones According to Adaptive Zoning

In this case, combination of two zones in series is demonstrated. It also shows an example of coordination of shunt and series devices. Two DGs, two industrial loads and a capacitor bank are added to the IEEE test feeder (Fig. 6) as shown in Fig. 13.

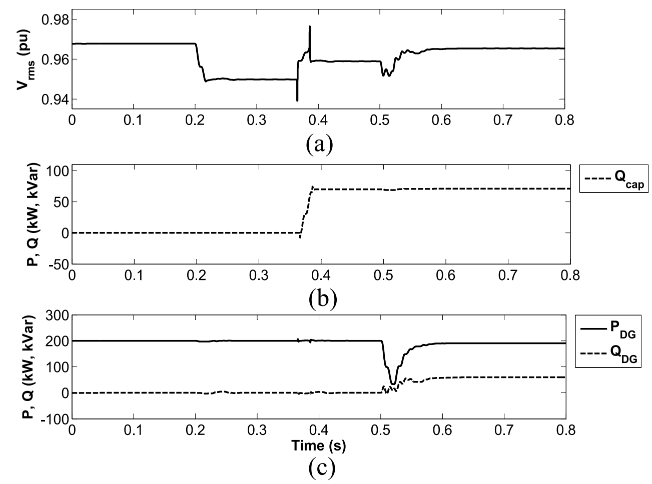

Fig. 9. Operation of capacitor bank and DG, and impact on critical node voltage. (a) RMS voltage at node 33. (b) Reactive power output of capacitor bank. (c) Active and reactive power output of DG.

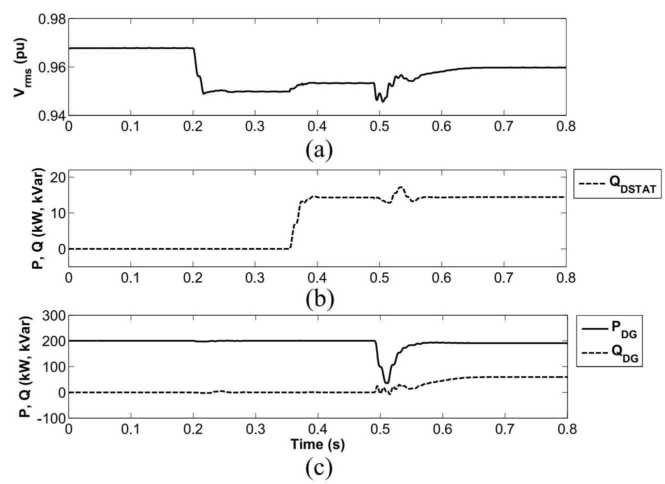

Fig. 10. Operation of DSTATCOM and DG, and impact on critical node voltage. (a) RMS voltage at node 33. (b) Reactive power output of DSTATCOM. (c) Active and reactive power output of DG.

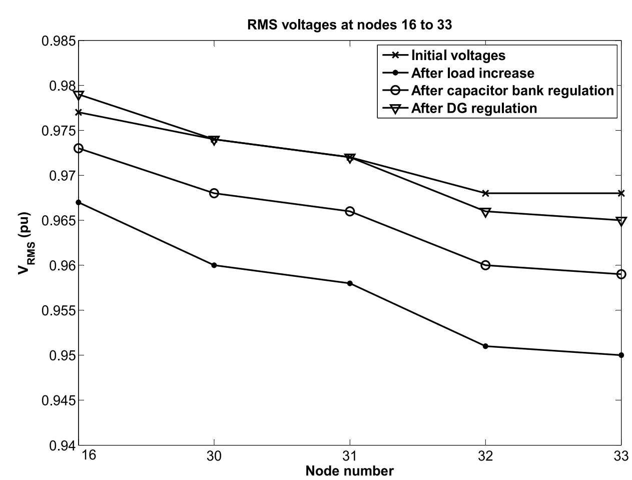

Fig. 11. Impact of regulation on voltage profile in case with capacitor bank.

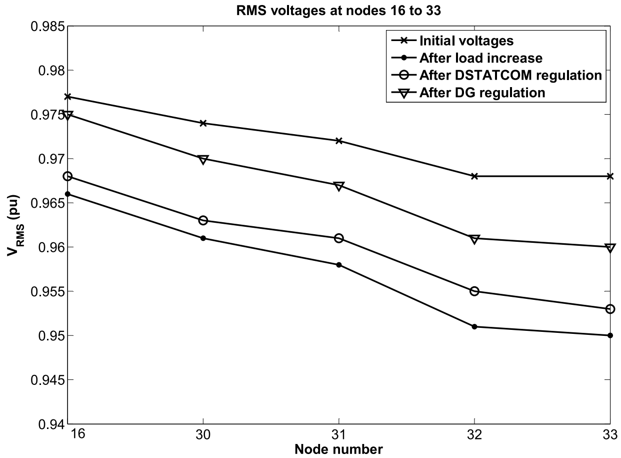

Fig. 12. Impact of regulation on voltage profile in case with DSTATCOM.

TABLE II
RMS VOLTAGE AT NODE33 DURING REGULATION (CAPACITOR BANK CASE)

Time	RMS voltage (pu)
Before load increase	0.968
After load increase	0.950
After capacitor bank regulation	0.959
After DG regulation	0.965

TABLE III
RMS VOLTAGE AT NODE 33 DURING REGULATION (DSTATCOM CASE)

Time	RMS voltage (pu)
Before load increase	0.968
After load increase	0.950
After DSTATCOM regulation	0.953
After DG regulation	0.960

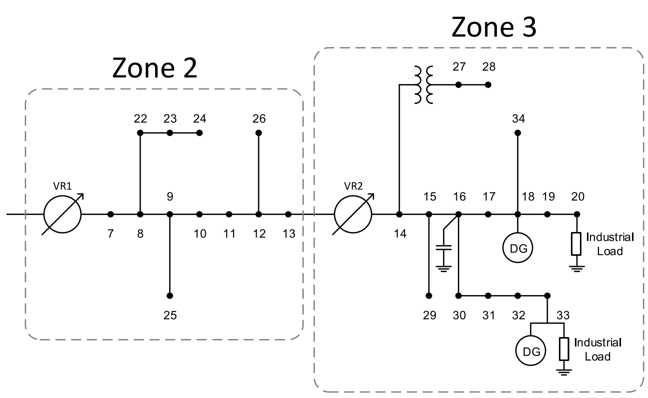

Fig. 13. Added devices for adaptive zoning simulation.

At t = 0.2 s, the two industrial loads are increased by 50% each, causing the voltage to drop below the lower regulation limit (set to 0.95 pu in this simulation) in both Zones 2 and 3. Available conventional shunt devices are activated before VRs change tap settings, i.e., the switched capacitor bank at node 16 is connected. Next, the upstream VR (VR1) increases tap settings until voltage at node 13 is within regulation limits. The downstream VR (VR2) adjusts voltages in Zone 3. In this case, the DGs are not required to contribute to voltage regulation. The output of the capacitor bank, the tap settings of VR1 and VR2, as well as the subsequent impacts on voltages at nodes 13 and 20 are shown in Figs. 14 and 15. The voltages at nodes 13 and 20 during the regulation sequence are listed in Table IV.

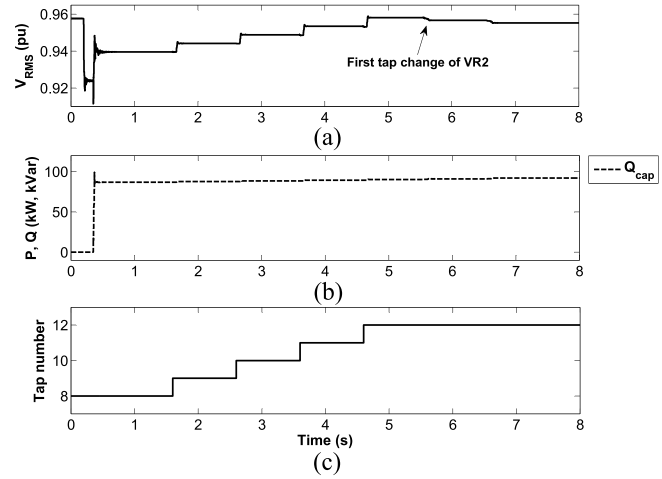

Fig. 14. Operation of capacitor bank and VR1, and voltage at node 13. (a) RMS voltage at node 13. (b) Reactive power output of capacitor bank. (c) VR1 tap setting.

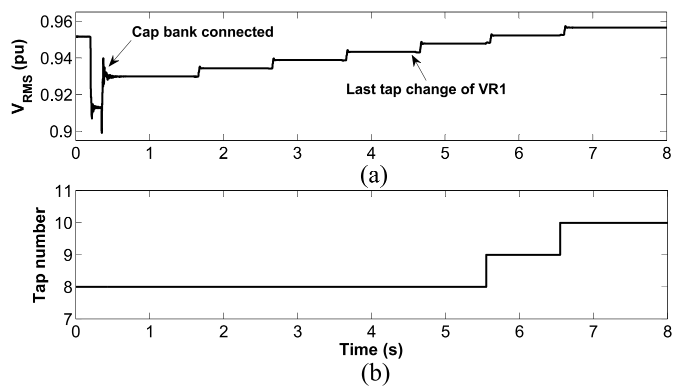

Fig. 15. Operation of VR2 and voltage at node 20. (a) RMS voltage at node 20. (b) VR2 tap setting.

TABLE IV
RMS VOLTAGE AT NODES 13 AND 20 DURING REGULATION

Time	RMS voltage node 13 (pu)	RMS voltage node 20 (pu)
Before load increase	0.958	0.952
After load increase	0.923	0.913
After capacitor bank regulation	0.940	0.930
After VR1 and VR2 regulation	0.955	0.967

It should be noted that optimal operation of cascaded VRs is a well-debated topic and that in some cases VRs might work in opposite order from the case described here.

C. Important Findings

The most important findings from the study of the proposed control are as follows.

1) A reactive compensation device located at the critical node can successfully be coordinated with a DG located further away within the same zone to regulate voltage.

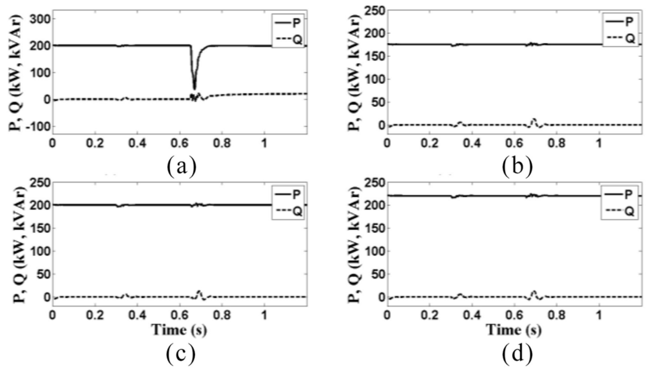

Fig. 16. Operation of DGs 1–4 in system with high DG penetration. DG (a) 1, (b) 2, (c) 3, and (d) 4 power output.

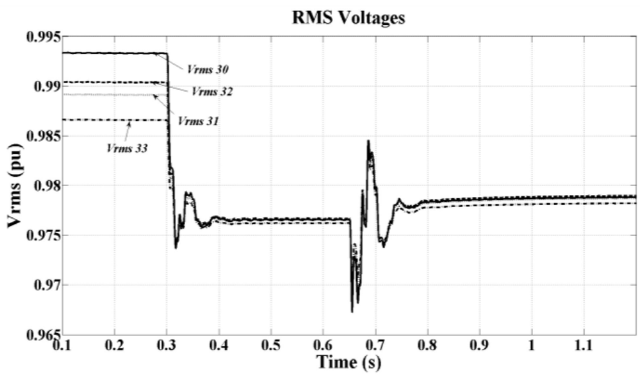

Fig. 17. RMS voltages at nodes 30–33 in system with high DG penetration.

2) DGs can successfully contribute to voltage regulation and can be switched to voltage reference (V_{ref}) mode without causing serious voltage drops/spikes/transients.
3) A conventional reactive compensation device in at least one of several zones can minimize the use of VRs and avoid voltage regulation from DGs.
4) Adaptive zoning leads to an efficient voltage profiling while minimizing system losses.

VI. Conclusion

In this paper a decentralized, adaptive zone-based Volt/VAR management solution is proposed, which coordinates active participation of DGs with conventional voltage regulation equipment. It is shown that DGs can successfully contribute to voltage regulation in the distribution grid, and this reduces the negative impacts on distribution system operation that prevent an increased DG penetration.

By decentralizing Volt/VAR management into control zones, complexity, and requirements for data handling capability are minimized. The proposed concept of adaptive zoning ensures optimized use of regulation equipment when voltage patterns are similar in adjacent zones and reduces network losses. It adds modularity and allows deployment to be scaled up from small parts of the grid to a grid-wide solution.

Appendix I

In order to show the ability of the system and the control scheme to handle high DG penetration, simulation results of Zone 5 (Fig. 6) with an industrial load at node 33 and four DGs connected to nodes 30–33 are shown in Figs. 16 and 17. DG 1 is connected closest to the industrial load, i.e., to node 33, DG 2 is connected to node 32, DG 3 to node 31, and DG 4 to node 30. Deadbands and voltage regulation limits differ from the simulations presented in Section V-A.

Appendix II

Example controller settings for two zones and combining of the two zones are shown in Table V.

TABLE V
Example Controller Settings

	Set Voltage	Bandwidth	Time Delays	Line Compensation
Alternative-1 Two Zones in **series** (Zone1 upstream)	Zone 1 : V pu Zone 2: kV pu Where 0.9 <k< 0.98	Zone 1 :±10% Zone2: ±k*10% Where 0.95 <k< 1	Zone 1 : 5s Zone2: 2.5-3.75s (50-75%)	Zone 1 : From substation to start of zone 2 Zone2: From start of zone 2 to end of feeder
Alternative-2 Two Zones in **series** (Zone1 upstream)	Zone 1 : V pu Zone 2: kV pu Where 0.9 <k< 0.98	Zone 1 :±k*10% Zone2: ±10% Where 0.95 <k< 1	Zone 1 : 2.5-3.75s Zone2: 5s (50-75%)	Zone 1 : From substation to start of zone 2 Zone2: From start of zone 2 to end of feeder
Two Zones in **parallel**	Zone 1 : V pu Zone 2: V pu	Zone 1 :±10% Zone2: ±10%	Zone 1 :5s Zone2: 5s	Zone 1 : From substation to end of feeder 1 Zone2: From substation to end of feeder 2
Combining two zones	Zone 12 V pu	Zone 12 :±10%	Zone 12 :5s	Zone12:From substation till end of feeder(s)

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