Overview of Increasing the Penetration of Renewable Energy Sources in the Distribution Grid by Developing Control Strategies and Using Ancillary Services

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***Abstract*— Increasing the renewables energy resources in the distribution network is one of the main challenges of the distributed system operator due to instability, power quality and feeder capacity problems. This paper proposes a solution for further penetration of distributed energy resources, by developing control strategies and using ancillary services. Besides the penetration issues, the control strategies will mitigate power quality problems, voltage unbalance and will increase the immunity of the grid by provision of fault ride through capabilities.**

***Keywords*— ancillary services, control strategy, power quality, voltage unbalance, voltage control component**

I. Introduction

To meet the European 20-20-20 targets, the share of renewable energy needs to be 20% of the total energy use in 2020 [1].This ambitious objective needs a significant increase of the number of distributed renewable energy sources (DRES) at the low voltage (LV) grid and installation of wind or solar power plants at the medium voltage (MV) level. Consequently, distribution system operators (DSOs) face the challenge to connect and integrate an ever increasing amount of renewable energy sources, but still to guarantee the high level of power quality to their customers. Grid operators today already face problems to dispatch the distribution grid with the currently installed DRES [2]. Thus, the connection of new production units, including many wind farms, risks to be cancelled (or at the least significantly delayed) because it requires expensive and time-consuming investments to extend the capacity of the network.

At the LV network, the penetration of DRES is currently limited by emerging voltage unbalance that is caused by the high number of the (mainly) single-phase connected DRES. Moreover, the DSO does not know the DRES locations nor the phase they are connected to which complicates the problem and prohibits a centralised solution [3,4]. In addition to the energy-based electricity markets, on a technical level ancillary services (AS) are needed for the secure operation of the power system [4]. Ancillary services are grid support services required by the transmission or distribution system operator to maintain the integrity and stability of the transmission or distribution system as well as the power quality. These services typically include regulation of frequency, active power reserves, voltage and reactive power control, black-start capability and islanding.

II. Hiererhical control

A solution to this problem is to add smart control strategies to the inverters of single renewable energy resources (RES) as it shown in Fig. 1. The control strategy can be split on three timescales: local control (response time in order of 1ms) will be implemented at the physical layer, the fast control (response time of in order of 1 min or longer) at the middleware layer, which involves agents and aggregators, and the slow control (response time in order of 1 hour or longer) will be implemented at the service layer. The distribution network will be kept stable in the event of disturbances by using the local control strategy (which is the main focus of this article) that uses local parameters (e.g., voltage, available power) as input. On this short time scale, communication with remote entities is avoided to maximise the reliability of the system. The fast control, which typically uses communication, will solve voltage problems, dynamic load flow, system stability and congestion. The slow control will help with solving multi-objective optimisation problems based on forecasting data for example.

The fast control strategy uses both local parameters (e.g., voltage and available power measured at the inverter itself) and parameters supplied externally (e.g., measured values of current in the distribution feeder connecting also other DRES). The local control will be targeting voltage unbalance mitigation, over/under voltage control and grid support in case of disturbances and faults. This control strategy thus enables an intelligent control of the voltage profile and improves the reliability of distribution grid in times of disturbances and grid faults.

Acknowledgement of EU for funding INCREASE

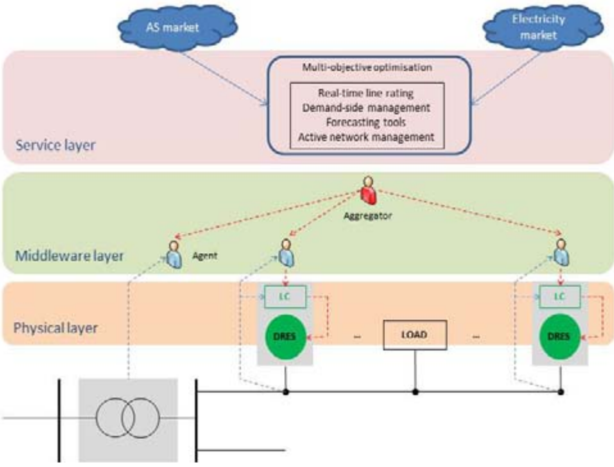

Fig. 1 Hierarchical structure of the smart control [4]

The DRES with high peak power require three-phase grid-connected inverters. In these inverters, a control strategy can be developed that mitigates voltage phase unbalance by distributing the active power between the phases and also avoid voltage problems. This control strategy enables local voltage control, and the system stability in the event of disturbances will be maintained by using frequency response and the provision of fault-ride through capabilities. Decreasing the voltage unbalance will result in an improved voltage profile allowing a higher penetration of individual DRES in the low voltage network and decreasing the network losses.

The fast control strategy will be implemented by combination of two control strategies – the three-phase damping control strategy [5] and the voltage-based droop control strategy [6]. By doing so, voltage unbalance will be mitigated and due to the droops a soft curtailment will be achieved between the different DRES. The soft curtailment will increase the exchange energy from the DRES to grid and will prevent on-off oscillations of the grid voltage [7,8].

III. THREE-PHASE FOUR-WIRE INVERTER

In order to solve voltage unbalance problems a full-bridge three-phase four-wire topology is used. The DRES are interfaced to the LV grid via a transformerless inverter configuration. There are generally two types of four-wire inverter topologies: three-leg with split dc bus and four-leg. The three-phase three-leg inverter with split dc-bus allows implementation of a three-phase four-wire system with a neutral point. Compared to a three-phase three-wire inverter, it does not require an isolation transformer to create a neutral point and the three-phase voltages can be controlled. Compared to a three-phase four-leg topology, it saves two power switches and also reduces control complexity. A disadvantage of this topology is that the dc-bus capacitors have to be oversized because harmonic currents can flow through these capacitors into the neutral wire. The topology of the three- phase split dc-bus voltage-source inverter which is chosen in this paper is depicted in Fig. 2. The inverter outputs are connected to a three-phase LC filter which attenuates high frequency components resulting from switching. The dc-bus can be

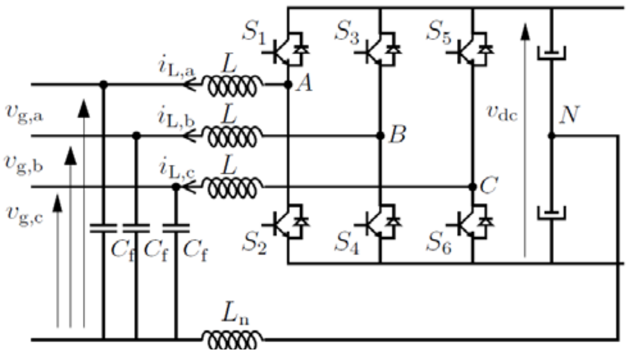

Fig. 2 Topology of the three-phase neutral-point-clamped voltage-source inverter [9]

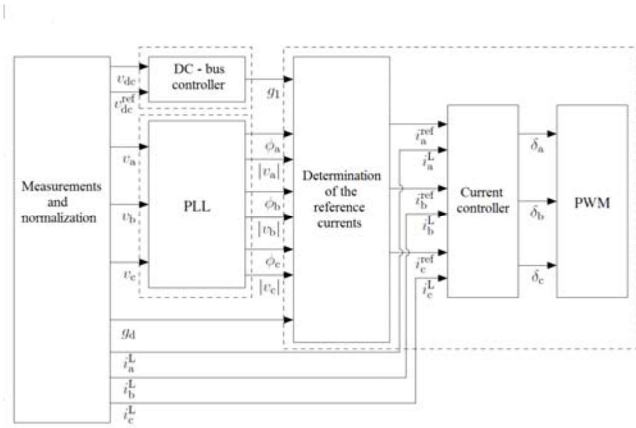

Fig. 3 Damping control strategy for the three-phase neutral-point-clamped VSI [5]

energised by a (small) DRES or power can be taken from the grid.

III. THREE – PHASE DAMPING CONTROL STRATEGY

A. Voltage unbalance mitigation

The scheme of the proposed three-phase damping control strategy in [9] is depicted in Fig. 3. It has the ability to inject higher currents in the phase(s) with the lowest rms value of the phase voltage by emulating a resistive behaviour towards the negative and zero sequence voltage components. This resistive behaviour can be translated into the following equations:

$$\begin{bmatrix} \underline{i}_0 \\ \underline{i}_1 \\ \underline{i}_2 \end{bmatrix} = \begin{bmatrix} g_d & 0 & 0 \\ 0 & g_1 & 0 \\ 0 & 0 & g_d \end{bmatrix} . \begin{bmatrix} \underline{v}_0 \\ \underline{v}_1 \\ \underline{v}_2 \end{bmatrix} \tag{1}$$

where $\underline{i}_0$, $\underline{i}_1$ and $\underline{i}_2$ are the zero, positive and the negative sequence components of the current, $\underline{v}_0$, $\underline{v}_1$ and $\underline{v}_2$ are the zero, positive and the negative sequence components of the voltages, g_1 is the fundamental conductance, g_d is the fundamental damping conductance of the inverter and it has an opposite sign of g_1 in case of power injection in the grid.

Then (1) can be transformed to phase values according to:

$$\begin{bmatrix} \underline{i}_a \\ \underline{i}_b \\ \underline{i}_c \end{bmatrix} = T^{-1} \begin{bmatrix} g_d & 0 & 0 \\ 0 & g_1 & 0 \\ 0 & 0 & g_d \end{bmatrix} T. \begin{bmatrix} \underline{v}_a \\ \underline{v}_b \\ \underline{v}_c \end{bmatrix} \quad (2)$$

where T is the transformation matrix.

By doing this, the following equations for the phase currents are obtained:

$$\begin{aligned} \underline{i}_a &= \frac{1}{3}.\{\underline{v}_a.(g_1+2.g_d)+a.\underline{v}_b.(g_1-g_d)+a^2.\underline{v}_c.(g_1-g_d)\} \\ \underline{i}_b &= \frac{1}{3}.\{a^2.\underline{v}_a.(g_1-g_d)+\underline{v}_b.(g_1+2.g_d)+a.\underline{v}_c.(g_1-g_d)\} \\ \underline{i}_c &= \frac{1}{3}.\{a.\underline{v}_a.(g_1-g_d)+a^2.\underline{v}_b.(g_1-g_d)+\underline{v}_c.(g_1+2.g_d)\} \end{aligned} \quad (3)$$

with a=exp$^{(i2\pi/3)}$.

Harmonic distortion will not be considered in this paper such that | $\underline{v}_x$| can be written in complex form as:

$$\underline{v}_x = |\underline{v}_x| .\exp(j\theta_x) \quad (4)$$

with $|\underline{v}_x|$ the amplitude of $\underline{v}_x$ and θ_x its phase angle in the respective phases x. If (3) is substituted in (2), the following equations are obtained:

$$\begin{aligned} \underline{i}_a &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_a|.\exp(j\theta_a)+|\underline{v}_b|.\exp\left(j\left(\theta_b+\frac{2.\pi}{3}\right)\right)+|\underline{v}_c|.\exp\left(j\left(\theta_c-\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_a|.\exp(j\theta_a)-|\underline{v}_b|.\exp\left(j\left(\theta_b+\frac{2.\pi}{3}\right)\right)-|\underline{v}_c|.\exp\left(j\left(\theta_c-\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \\ \underline{i}_b &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_b|.\exp(j\theta_b)+|\underline{v}_a|.\exp\left(j\left(\theta_a-\frac{2.\pi}{3}\right)\right)+|\underline{v}_c|.\exp\left(j\left(\theta_c+\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_b|.\exp(j\theta_b)-|\underline{v}_a|.\exp\left(j\left(\theta_a-\frac{2.\pi}{3}\right)\right)-|\underline{v}_c|.\exp\left(j\left(\theta_c+\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \\ \underline{i}_c &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_c|.\exp(j\theta_c)+|\underline{v}_a|.\exp\left(j\left(\theta_a+\frac{2.\pi}{3}\right)\right)+|\underline{v}_b|.\exp\left(j\left(\theta_b-\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_c|.\exp(j\theta_c)-|\underline{v}_a|.\exp\left(j\left(\theta_a+\frac{2.\pi}{3}\right)\right)-|\underline{v}_b|.\exp\left(j\left(\theta_b-\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \end{aligned} \quad (5)$$

The terms in (5) related to g_1 can be interpreted as the steady-state value of the fundamental component of the injected current. These terms are adapted by the bus-voltage

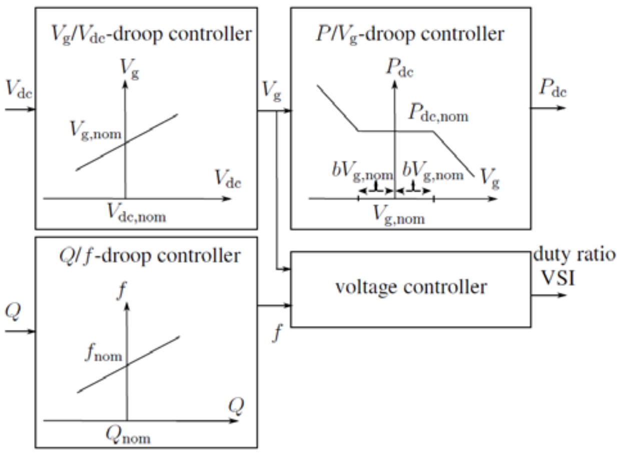

Fig. 4 VBD control: active and reactive power control. Combined operation of the droop controllers to determine the set value of the grid voltage. [6]

controller in order to balance the power exchanged with the grid. Since the bus voltage controller is slow, g_1 is slowly varying. The terms related to g_d emulate the resistive behavior towards the zero and negative sequence voltage components.

B. Fault ride-through capabilities

In order to provide fault ride-through capabilities to this control strategy, a fast reaction is needed. Therefore, the following term is considered:

$$v_x - |\underline{v}_x|.\exp(j\theta_x) \quad (6)$$

By summing (5) with (6), the final equation (7) of the control strategy is obtained:

$$\begin{aligned} \underline{i}_a &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_a|.\exp(j\theta_a)+|\underline{v}_b|.\exp\left(j\left(\theta_b+\frac{2.\pi}{3}\right)\right)+|\underline{v}_c|.\exp\left(j\left(\theta_c-\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_a|.\exp(j\theta_a)-|\underline{v}_b|.\exp\left(j\left(\theta_b+\frac{2.\pi}{3}\right)\right)-|\underline{v}_c|.\exp\left(j\left(\theta_c-\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \\ & \quad + g_d.(v_a-|\underline{v}_a|.\exp(j\theta_a)) \\ \underline{i}_b &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_b|.\exp(j\theta_b)+|\underline{v}_a|.\exp\left(j\left(\theta_a-\frac{2.\pi}{3}\right)\right)+|\underline{v}_c|.\exp\left(j\left(\theta_c+\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_b|.\exp(j\theta_b)-|\underline{v}_a|.\exp\left(j\left(\theta_a-\frac{2.\pi}{3}\right)\right)-|\underline{v}_c|.\exp\left(j\left(\theta_c+\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \\ & \quad + g_d.(v_b-|\underline{v}_b|.\exp(j\theta_b)) \\ \underline{i}_c &= \frac{1}{3}.\left\{ \begin{aligned} & g_1.\left[|\underline{v}_c|.\exp(j\theta_c)+|\underline{v}_a|.\exp\left(j\left(\theta_a+\frac{2.\pi}{3}\right)\right)+|\underline{v}_b|.\exp\left(j\left(\theta_b-\frac{2.\pi}{3}\right)\right)\right]+ \\ & +g_d.\left[2.|\underline{v}_c|.\exp(j\theta_c)-|\underline{v}_a|.\exp\left(j\left(\theta_a+\frac{2.\pi}{3}\right)\right)-|\underline{v}_b|.\exp\left(j\left(\theta_b-\frac{2.\pi}{3}\right)\right)\right] \end{aligned} \right\} \\ & \quad + g_d.(v_c-|\underline{v}_c|.\exp(j\theta_c)) \end{aligned} \quad (7)$$

The last term out of the curly brackets can vary faster, as it reacts on every deviation of the fundamental grid voltage from the reference value [9]. Therefore, it can be stated that the damping control strategy provides voltage support by injecting higher currents in the phase(s) where the fault is presented.

IV. VOLTAGE- BASED DROOP CONTROL

The voltage-based droop control (VBD) developed in [6] is applicable for islanded mode and further adaptation will be made for grid connected mode. This control strategy is based on two control algorithms, with their operation dependent on the rms grid voltage as shown in Fig. 4 In a voltage band around the nominal grid voltage $V_{g,nom}$, only the V_g/V_{dc} droop control strategy is applied, keeping the generated power constant and where V_g is drooped with the DC-bus voltage V_{dc}. If the grid voltage exceeds this band, a P_{dc}/V_g droop controller is turned on in addition to the V_g/V_{dc} droop controller. Opposed to the conventional P/V droop control, which is only implemented in dispatchable DRES, the P_{dc}/V_g droop controller is implemented in both the renewable and dispatchable DRES.

The V_g/V_{dc} droop control strategy delays changing the output power of the generators by slightly varying V_g. All electrical equipment in the grid is designed to withstand some voltage deviation from its nominal value. Still, the variations of V_g need to remain in a tolerated voltage band (for example 0.9-1.1 $V_{g,nom}$) [10]. Therefore, it is necessary to also control the active power of the DRES.

In the low-voltage, thus resistive, grids, there is a linkage between active power and grid voltage. Hence, a P_{dc}/V_g droop controller is used that changes P_{dc} according to V_g, while avoiding communication and central controllers. Changing P_{dc} can be done in several ways. For instance, P_{dc} can be decreased by storage charging, by lowering the generated power P_{gen}, load increase or by using dump loads. For an increase of P_{dc}, battery discharge, demand-side management (potentially driven by the emerging smart grid concept) or an increase of P_{gen} can be incorporated in the control. The method of changing the power delivered to the dc-link does not inherently change the control method and can be determined according to the specific application. For PV panels for example, the control of the dc-dc converter, e.g., a chopper, including maximum power point tracking (MPPT), is not considered. The P_{dc}/V_g droop controller only operates when the terminal voltage exceeds a certain threshold voltage, which is determined by the adjustment voltages $V_{g,up}= V_{g,nom}(1+b)$ and $V_{g,low}= V_{g,nom}(1-b)$ (see). In case these adjustment voltages are not exceeded, P_{dc} remains unchanged and only the V_g/V_{dc} droop control strategy is used. This operating mode is called constant-power operation. The total width of the constant-power band equals $h = 2b = V_{g,up} + V_{g,low}$. The parameter '$b$' is called 'the constant-power band width' and a symmetrical constant-power band ($h = 2b$) is considered. Summarised, the P_{dc}/V_g droop controller operates according to:

$$P_{dc} = \begin{cases} P_{dc,nom} - K_p\left(V_g - (1+b)V_{g,nom}\right) & \text{if } V_g > (1+b)V_{g,nom} \\ P_{dc,nom} & \text{if } (1-b)V_{g,nom} < V_g < (1+b)V_{g,nom} \\ P_{dc,nom} - K_p\left(V_g - (1-b)V_{g,nom}\right) & \text{if } V_g > (1-b)V_{g,nom} \end{cases} \quad (8)$$

where P_{dc} is the current power from the renewable source, $P_{dc,nom}$ is the nominal power from the renewable source, K_P is the droop coefficient, V_g is the rms value of the grid voltage and b is a constant.

The droop K_P is generally determined according to the ratings of the units, such that $P_{dc,nom}/K_P$ is equal for each DRES. The index 'nom' refers to nominal values, but is not necessarily equal to the rating of the unit. In the dispatchable DRES, $P_{dc,nom}$ is generally determined according to unit scheduling in the electricity markets. This is often based on (but not necessarily equal to) the ratings of the units, which in turn corresponds to the operating point with optimal efficiency. Hence, $P_{dc,nom}$ can vary in time. For the renewable DRES, $P_{dc,nom}$ generally is the instantaneous maximum power point (MPP), hence, also not constant in time.

By setting a proper b, the VBD control enables an automatic priority allocation for the primary control. Based on the terminal voltage, an example of this priority list for power changes is: 1) dispatchable DRES, 2) storage, 3) highly controllable loads, 4) less dispatchable DRES (including local storage, deviating from the MPP, and local load changes), 5) less controllable loads, 6) load shedding of the other loads. The combined operation of the V_g/V_{dc} and P_{dc}/V_g droops is shown in Fig. 5. This figure shows that if V_g, calculated according to the V_g/V_{dc} droop control, exceeds the upper adjustment voltage $V_{g,nom}+V_{g,up}$, the P_{dc}/V_g droop controller decreases P_{dc}, and it increases P_{dc} if V_g is lower than $V_{g,nom}$-$V_{g,low}$. In these two

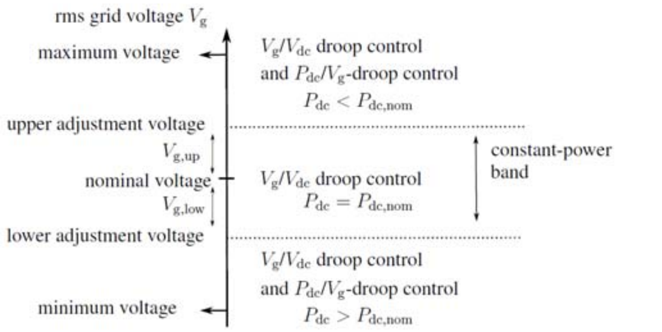

Fig. 5 P_{dc} control as a function of V_g: adjustment voltages $V_{g,up}$ and $V_{g,low}$ [6]

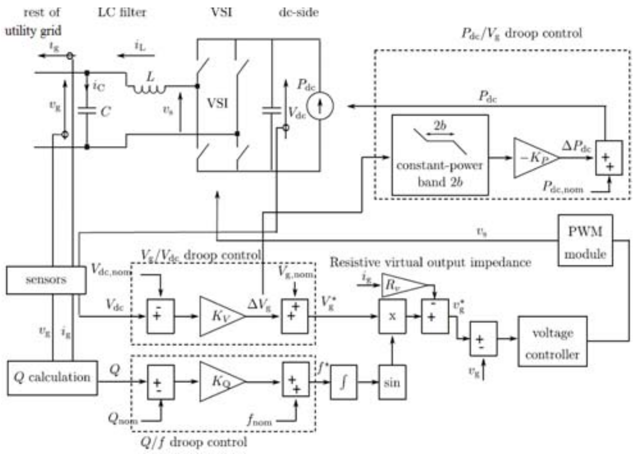

Fig. 6 VBD control: P_{dc}/V_g droops, Q/f droops, V_g/V_{dc} droop controller and constant-power bands. [6]

conditions, the two droop controllers operate together. Otherwise, with only the V_g/V_{dc} droop controller, P_{dc} remains equal to $P_{dc,nom}$. An overview of the VBD control strategy is given in Fig. 6.

The adjustment voltages $V_{g,up}$ and $V_{g,low}$ depend on the flexibility of the power source, which is depicted in . This figure shows that the P_{dc}/V_g function is abstract and can be modified according the characteristics of the source. For example, a distinction can be made between variable and non-variable power sources. For variable, controlled (often non-renewable) power sources, a narrow constant-power band can be handled such that the dispatchable units decrease their output power with increasing voltage and vice versa for low voltages. Therefore, small variations of V_g from $V_{g,nom}$ address the P_{dc}/V_g droop controller to change P_{dc}. This enables to fully exploit the power control capability of the power source. In this way, less voltage variation in the grid is obtained as the power source acts dynamically to limit the voltage changes by changing its output power. After a small load change compared to the scheduled (nominal) load, only these units will act in the power sharing by changing their output power. The less dispatchable DRES will not act as long as their voltage is inside the constant-power bands.

For non-variable or slightly-variable power sources (often intermittent renewable or combined heat and power units with

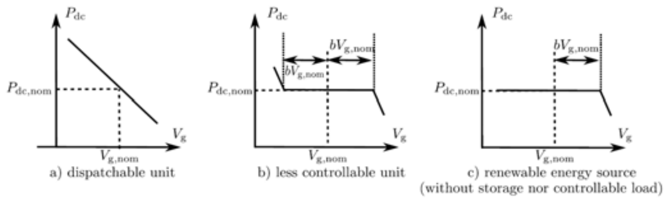

Fig. 7 Fully dispatchable versus fully undispatchable DRES. Dispatchable units have a small constant power band; fully undispatchable DRES have a very wide constant-power band. [7]

heat as primary driver), a wide constant power band can be applied. The variable intermittent, often renewable units deliver nominal power to the network in case the voltage is in the constant-power band. Further, in case the terminal voltage exceeds this band, the power of the DRES is changed, e.g., by including small storage elements, load response, or by abandoning the MPP. E.g., if only a renewable source is present, the power band is characterised according to Fig. 7(c) as only a power decrease is possible. Fig. 7(b) represents, for example, a combination of a renewable energy source and a controllable load. The power can decrease by the renewable source through deviation from the maximum power point, and a power increase is equivalent with a load decrease (load shifting). By properly setting the constant-power band widths, changing the output power of the less dispatchable power sources is delayed to more extreme terminal voltages compared to the dispatchable DRES. It is only addressed to limit too large voltage variations in the grid. Because of the increasing share of renewable energy sources, active dispatching of these units in small-scale grids will be required, e.g. to avoid over-voltage tripping. This control strategy makes this possible without inter-unit communication, while still delaying the power changes of the renewables. Note that the width of the constant power band should be lower than that of the voltage margins. Otherwise, these units will not contribute in the voltage support and the power sharing.

In conclusion, by setting the value *b*, the priority in which the units react on load variations is automatically set, dependent on variations of the voltage from its nominal value. For small variations, the dispatchable DRES and storage elements (small b) will react. Only for more extreme voltages, the other units, such as controllable loads or renewables will react as well. Hence, with a proper combined usage of V_g/V_{dc} and P_{dc}/V_g droop controllers in the VBD control, a higher degree of renewables (contributing in voltage support) and a more efficient usage of the renewable energy (other grid elements such as the loads can act on the voltage as well) can be expected.

As VBD control is a primary control strategy, dealing with the stability of the grid, further optimisation can be made by using a secondary controller, e.g., to return to the MPP by changing the consumption or by coordinating the DRES to achieve fuel savings.

V. Conclusions

The control algorithms for three-phase-grid connected inverters for DRES to avoid voltage unbalance and overvoltage problems in LV networks can easily be implemented for all future DRES implementation. Moreover, the control strategy can be added to existing controllers as well. In this way, by using control strategies only, the power quality and the stability during disturbances in LV will be improved. Furthermore, the loss of energy due to hard curtailment will be decreased which will increase the exchanged energy to the grid. In general the penetration of DRES will increase, without changing of the existing infrastructure of the existing LV-networks which will be cost effective for benefit for DSO’s.

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