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Factors influencing Oscillations within Meshed HVDC Grids and Implications for DC Voltage Control

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***Abstract*—Since meshed HVDC grids are discussed for offshore wind farms interconnection and onshore long distance transmission use, there is also a research focus on operation of such new type of grids. A major aspect is DC voltage control. Tests on a low voltage meshed HVDC mock-up system showed oscillatory behavior using state of research DC voltage control characteristics. This paper presents an analysis of influencing factors for these oscillations and proposes improvements for the DC voltage control characteristic, for the operation management and shows that converter parameters can invoke oscillations.**

***Index Terms*—DC voltage control, meshed HVDC/MTDC grids, operation management, stability**

I. INTRODUCTION

With an increasing proportion of renewable energy generation in offshore wind farms or huge solar power plants (e.g. in deserts), the distance between consumption and generation increases significantly. A suitable solution for the transmission problem is considered to be an HVDC system. Due to reliability reasons the vision of a meshed HVDC system comes up e.g. in Asia or Europe [1]. The control of DC energy balance is solved for point-to-point connections by one converter controlling active power infeed and the other controlling DC voltage [2]. This method needs to be adapted for meshed HVDC grids covering a lot of GW with remote converter stations since power flows are divided automatically all over the system according to the power infeed and consumption of converters.

Since important physical values for the determination of system state, stability and power flow in AC systems do not exist in DC grids, voltage is the most important variable. Power flows as well as the system state are defined by actual DC node voltages. If there is an energy lack DC voltage decreases and vice versa. Thus, it seems to be suitable to control DC voltage at all converter nodes (or at least at more than one in order not to overload this converter and the connected AC system with DC grid's balancing power) with respect to the requirements at the AC point of common coupling and a given power reference value for the converter. Thereby balancing energy distribution to more than one converter is ensured.

Some voltage control methods have been developed and described in literature. The essence is summarized in [3], [4] and [5]. In general a centralized voltage control is possible if the HVDC grid covers a small amount of power, since balancing power will be small as well. This can be extended with a decentralized backup so that other converters participate in DC voltage control as well if a certain voltage margin is left, i.e. in a case where the central voltage controller can't cover the whole balancing power. The stress for a single AC point of common coupling can be prevented in general if the voltage control is distributed to all converters or even some converters of a DC grid.

In general three different DC voltage control methods exist: Voltage droop control, constant voltage and voltage margin control [3]. All three can be summarized as voltage droop control according to (1) while constant voltage control has a droop constant $k_{\mathrm{DC},i} \rightarrow 0$ and constant power control has a droop constant $k_{\mathrm{DC},i} \rightarrow \infty$. $P_{\mathrm{conv},i}$ is the power reference given to the inner converter control, $P_{\mathrm{conv,ref},i}$ is the power reference provided by e.g. a schedule, $U_{\mathrm{DC},i}$ and $U_{\mathrm{DC,conv,ref},i}$ is the measured voltage and reference voltage respectively.

$$P_{\mathrm{conv},i} = P_{\mathrm{conv,ref},i} - \frac{1}{k_{\mathrm{DC},i}}(U_{\mathrm{DC},i} - U_{\mathrm{DC,conv,ref},i}) \tag{1}$$

Voltage droop control can be extended by a voltage dead band or low droop band, to give respect to a given converter power reference value (see figure 1). Since voltage droop control is the only option with significant and limited droop it is supposed to be the most suitable for DC voltage control.

To test several HVDC operations and control methods a downscaled HVDC mockup was built (see chapter II). It was found that undamped oscillations of the transmitted power occurred in the system. Its basic operation was realized by using a dead band voltage droop control characteristic as shown in figure 1. This paper describes the mockup structure and measured oscillations in chapter II. Afterwards the oscillation causing factors on the equipment side as well as on the control side have been identified using a software simulation. For complexity reduction a point-to-point (P2P) topology was simulated. The results including suggestions for improvement are presented in chapter III.

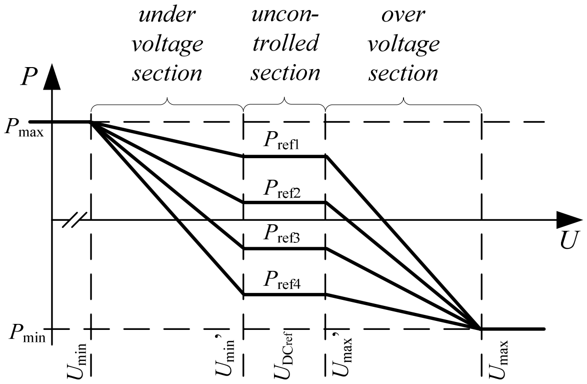

Figure 1. Dead band voltage droop control characteristic for DC voltage control

II. LOW VOLTAGE TEST SYSTEM

A reduced scale model of a meshed HVDC grid was configured at the laboratory of power systems of the University of Applied Sciences of western Switzerland. The scaling factors for the hardware model is shown in TABLE I.

TABLE I Scale of the mockup system and its maximum ratings

	scale	**maximum value**
Voltage	$10^3 : 1$	800V
Current	$10^3 : 1$	6A
Power	$10^6 : 1$	4.8kW

A. Structure

The model represents a meshed HVDC grid with 4 Converters and 6 lines so, that it results in 4 meshes (see fig. 2). It includes overhead (OH) lines as well as cables. For hardware simulations the converters are connected to an interconnected ac system. For the purpose of this paper it can be assumed that there are no restrictions given by the ac connection points.

B. Measurements

Since it was intended to split the balancing power of the DC grid to more than one converter, for the first operation tests of the grid a dead band voltage droop control was applied to all converters. It was found that there can result undamped oscillations between the converters. Those oscillations can also occur within a P2P connection when the dead band droop control is used. In order to make a root cause analysis of the oscillation a P2P connection has been analyzed in a first step. As a test scenario the converter power reference value has been set to 1.1 kW for converter 1 and -0.6 kW for converter 2. The corresponding line parameters (*R* and *L*) are given in table II as well as the converters DC link capacity C_{LE}. Fig. 3 and 4 show the measured voltage at both converters DC nodes of the connection and the line current using the described test scenario. It can be seen that the voltage at the converter nodes is oscillating against each other and in consequence the current is oscillating as well. The oscillation parameters are given in table III and show the oscillation frequency, the minimum and maximum value of the converter node DC voltages, the minimum and maximum line current as well as the differences between the minimum and maximum of each value.

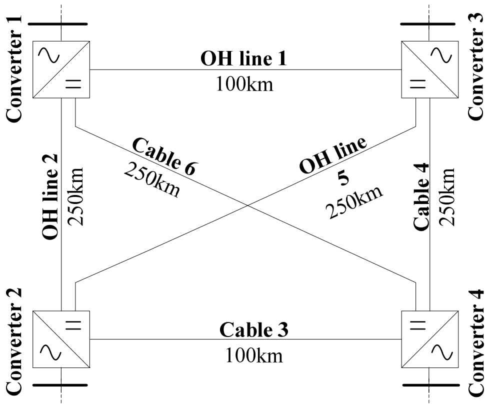

Figure 2 Topology of the HVDC grid

TABLE II Line parameters for test scenario

	***R* [Ω]**	***L* [mH]**	**$C_{LE}/2$ [µF]**
Line 1	3	51	700

TABLE III Oscillation parameters

	Maximum, Minimum	Δ(max, min)	Frequency
U_{conv1}	395V, 410V	15V	40Hz
U_{conv2}	390V, 402V	12V	40Hz
I	0.8A, 2.5A	1.7A	40Hz

The measurements have been repeated with an inductance twice as large than the original with the result of a smaller oscillation frequency of 30Hz and larger oscillation amplitudes of voltages and line current ($\Delta(U_{max}, U_{min}) = 26$ V, $\Delta(I_{max}, I_{min}) = 2.5$ A).

It is important to avoid such significant oscillations in real transmission HVDC grids for similar reason as AC power system oscillations are avoided e.g. by power system stabilizers (PSS) that can damp AC oscillations [7]. This reason is a blocking of transmission capability due to oscillations and thus sub optimal power flows or non optimal use of physical transmission capacity. Additionally an increased equipment stress can be caused as well as oscillation propagation from the DC into the AC system via the converter due to its voltage control characteristic. Thus, oscillations of that kind within the DC grid, maybe also spreading to the AC system causing different negative effects, have to be avoided or well damped.

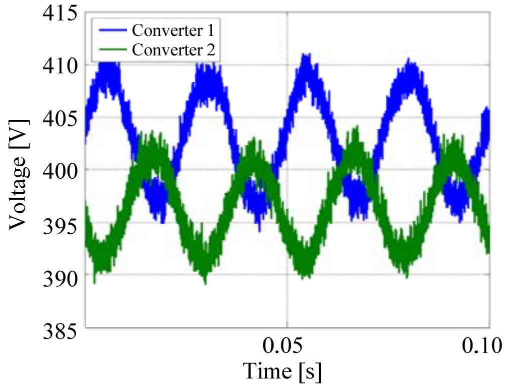

Figure 3. Voltage measurement on a point-to-point connection with a constant power reference value

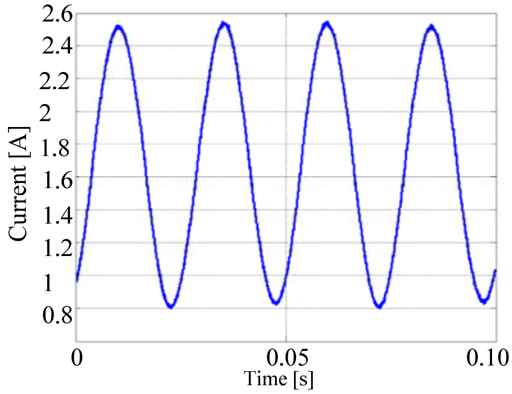

Figure 4. Line current measurement on a point-to-point connection with a constant power reference value

III. OSCILLATION CAUSING FACTORS

The investigated grid was modeled using Matlab Simulink in order to reproduce the converter behavior. The p-v-characteristic was extended with a dead time and a delay (fig. 5). The dead time represents delay due to communication, computing time, measured value acquisition and processing. Converter time constants are represented by the delay, which depends on the internal converter control parameters. It was found that a dead time of 4ms and a delay of 10ms result in the same oscillations as they were measured in the physical model. For all physical tests and simulations in the following subchapters a characteristic as shown in figure 1 was used.

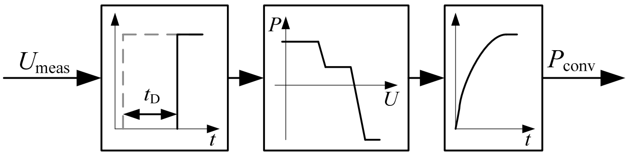

Figure 5. Line current measurement on a P2P connection with a constant power reference value

The stability of the overall system is analyzed using eigenvalues (EVs). When the operating point of the converters is within the uncontrolled section of the p-v-characteristic, EVs are marginally affected by the delay and dead time. If the operating point is on the over- or undervoltage section of the p-v-characteristic the time delay causes an EV shift closer towards the imaginary axis. However, the biggest influence on the EV shift has the considered due to the dead time.

It was found that in the asymptotically stable system the two converter operating points are on the uncontrolled section (dead band) of its p-v-characteristic, i.e. no correction by the voltage control method is necessary. If the system is marginally stable (undamped oscillation with $P_{\text{conv}} < P_{\text{max}}$) exactly one of the two converter operating points is on the over- or undervoltage section of the p-v-characteristic while the other is in the uncontrolled section. Finally the unstable system state is characterized in that way that both converter operating points are oscillating simultaneously on the over- or undervoltage section of the p-v-characterstic, between the minimum and maximum converter power while both signals are phase shifted by 180°. Thus the system is only bounded due to the converter power limits.

A. Dead time and Delay

Thus, delay and especially dead time have the most significant impact on the system stability / oscillations. For each HVDC system a dead time limit can be defined. For values below that limit there is no influence on the oscillation. This limit is dependent on the line inductances and system capacitances values. If these values are increased the critical dead time increases as well. This effect is exemplarily shown for two different node capacity values and its impact on the oscillation frequency in figure 6.

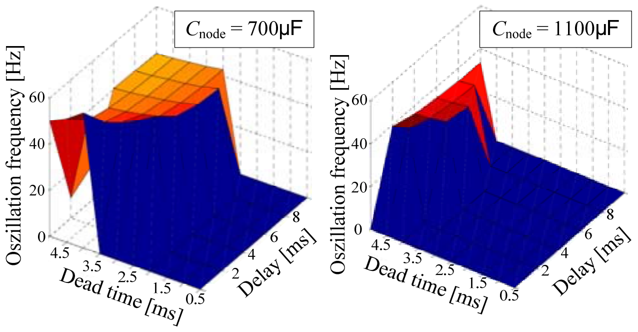

Figure 6. Current oscillation frequency as a function of converter's dead time and delay for two node capacity values

B. Converter reference values

If the reference values for the converters are well matched, no converter will leave the dead band or at least will stay close to the dead band e.g. if losses are not well considered during converter power reference value calculation. The worse the reference values are matched the more the operating points will reach outside the dead band. If this fact is combined with a delay and dead time both converters oscillate with even higher amplitudes the worse the reference values are matched (see figure 7).

Consequently, in real systems one needs to have one instance that calculates converter power reference values with special attention to p-v-characteristic coordination. This is valid for P2P connections as well as for multi terminal HVDC grids if more than one converter controls DC voltage. Converter reference values do not affect oscillation frequency, i.e.

if the converter reference values are not well matched (including system losses) the oscillation frequency will be the same - independent of the difference in the absolute power reference values.

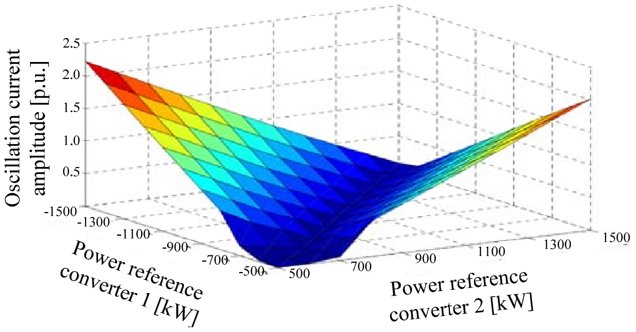

Figure 7. Current oscillation amplitude as a function of power reference values of a P2P connection

C. Parameters of the p-v-characteristic

A marginally stable or unstable system state is characterized by one or both converters having an operating point on the under-/ overvoltage section or at the converter power limits. If the dead band section is modified to a section with a small droop (see fig. 8) and thus becomes a controlled section as well, some operating points do not reach a marginally stable or unstable operating point. Thus small power imbalances in the HVDC system do not cause undamped oscillations as it is illustrated in fig. 8.

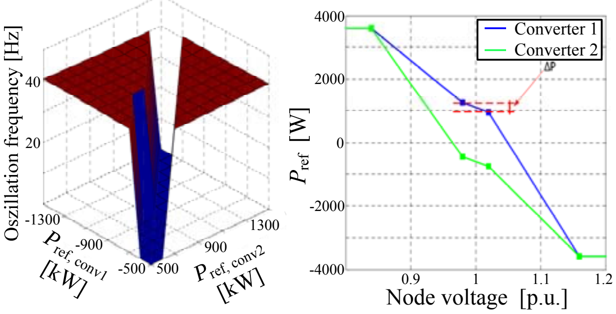

Figure 8. Oscillation frequency (left) as a function of power reference values of a P2P connection with a undead band DC voltage control (right)

The p-v-characteristic was further modified as it is proposed in [8] and shown in figure 8. This characteristic is a continuous undead band voltage droop. This further modification of the p-v-characteristic leads to an extension of the area where uncoordinated converter power reference values do not cause marginally stable or unstable oscillations (see fig. 9).

D. Line parameters

An HVDC system including converter and line capacitances as well as line inductances and resistances can be compared to an LC pi-section. The resonance frequency of a line is given by:

$$f_R = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

As simulations confirm, the oscillation frequency decreases with increasing inductances and capacitances with a negligible impact of the resistances.

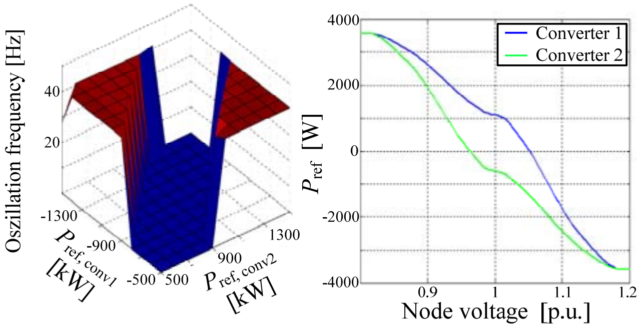

Figure 9. Oscillation frequency (left) as a function of power reference values of a P2P connection with a continuous undead band DC voltage control (right)

If the oscillation amplitude is considered there is a negligible impact of the resistance if the line inductance or capacity exceeds a certain value. For smaller values the resistance has a significant impact. Hence the oscillation amplitude becomes smaller the higher the line resistance will be.

If two or three level voltage source converters (VSC) are considered they have a significant impact on the overall system capacity. Regarding systems composed of OH lines or short cables the line capacitances can be neglected against converter capacitances (node capacitance). The slower the converter and its control are, the larger the node capacity needs to be. If the node capacity is too small for a given delay and dead time node voltage can even collapse. With an increasing capacity value the system become at first unstable, then marginal stable (continuously oscillating) and finally stable. This can also be seen from the eigenvalue plot in figure 10. Unstable in this context means that converter power is oscillating between its minimum and maximum possible values, while marginally stable is an oscillation between smaller power values. Since the eigenvalues' real parts also decrease with increasing node capacitance values also damping is increased. This means that an HVDC system is more stable the larger the node capacitances are and thus they are comparable to the inertia in ac systems. At this point it is important to mention that large capacitances would significantly feed fault currents even if this topic is out of scope of this paper.

The necessary size of node capacitanceto stabilize the system do not exclusively depend on delay and dead time constants of the converters but also on the line inductances since its comparable behavior to an LC resonator. The eigenvalue dependence on the line inductance is shown in figure 11 for an increasing value. This eigenvalues can contribute to oscillations if a certain inductance value is exceeded and if further increased cause instabilities until an extreme value is reached. When the value is increased even further the eigenvalue can becomes stable again even if the eigenvalue can still cause undamped oscillations. If the unstable line inductance values are combined with large capacity values, the eigenvalues move back towards the stable complex plane.

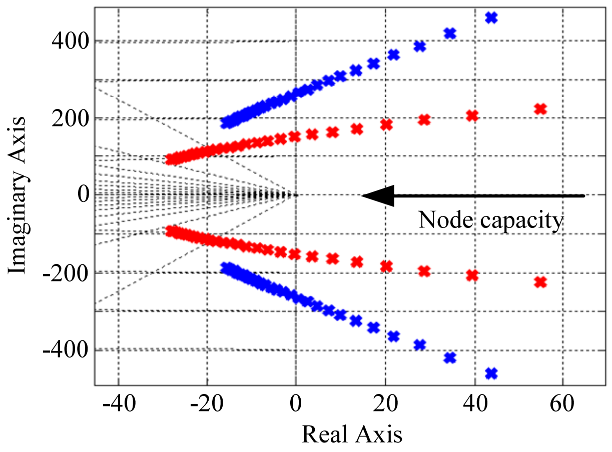

Figure 10. Eigenvalues with increasing node capacitance

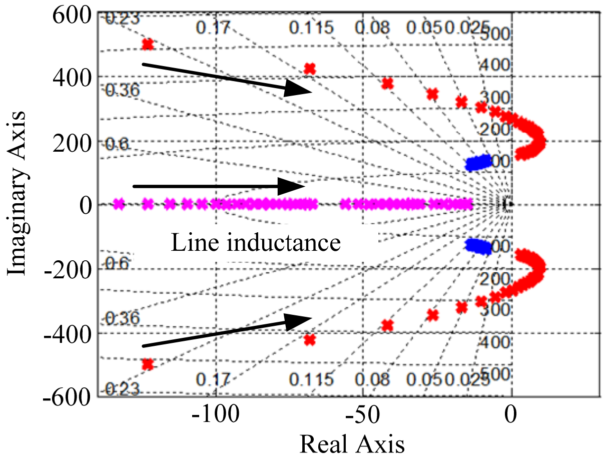

Figure 11. Eigenvalues with increasing line inductance

E. *Line length and types*

For comparative analysis different line technology parameters shown in table IV are used which are over head lines (OH line), XLPE cables and gas insulated lines (GIL).

TABLE IV Line parameters of different line technologies

	R’ [mΩ/km]	L’[mH/km]	C’[nF/km]
OH line [6]	28	0.86	13.8
Cable [9]	19	0.73	183
GIL [9]	9.4	0.22	54

As it is explained before resistances, inductances and capacitances of the DC grid have a fundamental impact on the oscillation behavior. With an increasing line length these parameters change as well. Thus the oscillation frequency (see fig. 12) and amplitude (see fig. 13) decreases with increasing line length. Since the distributed line inductance *L*’ and resistance *R*’ are the smallest when considering GILs they have the highest oscillation frequency. Even if the difference between *R*’ and *L*’ of cable and OH line technology is significant the difference in oscillation frequency is very low since cables’ *C*’ is much higher than that of OH lines. Very low line resistances of high temperature superconducting cable technology is very low there would result a very low damping effect and due to smaller line capacitances a less stable system behavior (see figure 10).

According to equation (1) the resonance frequency is as smaller the bigger *L* and *C* becomes. As can be seen from fig. 13 there is a peak for cables around 50 km line length and a small peak for GIL between 100 and 150 km which indicate the resonance points. The resonance point for the OH line occurs for shorter distances and cannot be seen in fig. 13. Since the converter induced DC link capacitors (700 µF each) and especially the DC inductance of the converters (0.55 H each, PWM converter) are major compared to the line parameters they have a significant impact. At the resonance point of the cable setup both converter operating points lie on the over- or undervoltage section of the p-v-characteristic. However, an onshore HVDC overlay grid will be mainly built up with OH lines due to its faster installation time and lower costs. Short sections will probably be realized with one of the underground technologies (GIL or cable) due to environmental or visual reasons.

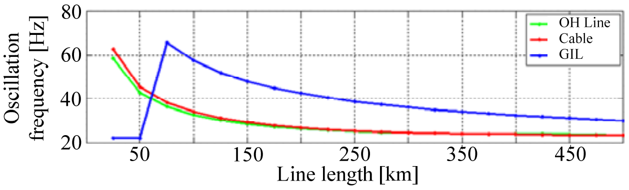

Figure 12. Oscillation frequency with increasing line length and different line technologies with a dead time of 4ms and a delay 10ms

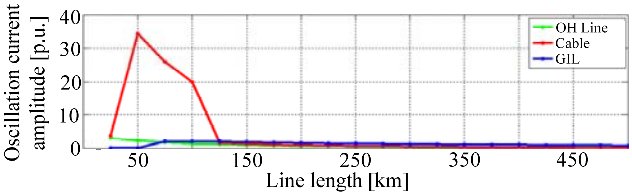

Figure 13. Oscillation amplitude with increasing line length and different line technologies with a dead time of 4ms and a delay 10ms

IV. CONCLUSION

As worldwide several efforts are made towards a meshed HVDC overlay grid to transmit remotely generated renewable electricity to centers of load, suitable operation methods need to be developed. To determine the ac systems state, its stability and power flows several variables are necessary. In DC grids the necessary measure is reduced to a single one which is DC node voltage. Thus it is essential for system stability and operation to have an adequate control method for DC node voltages. Even if several methods are presented in literature, voltage droop control seems to be the most reasonable one, more than ever if it is extended by a functionality respecting given converter power reference values (integrated voltage dead band or smaller droop for a certain voltage band).

A reduced scale HVDC grid was build at the University of Applied Sciences of Western Switzerland to test several operation and control methods. During the first tests it was found that undamped and even unstable oscillations between converters can occur. This paper identifies oscillation causing factors on the equipments side as well as on the control side. For the analysis of influencing factors, a P2P topology is simulated. Afterwards the identified improvements have been applied to a meshed HVDC system with the same positive effects. The following impact factors have been found: dead time and delay of the inner converter control, inconsistent converter power reference values, parameters and shape of p-v-characteristic for DC node voltage control, equipment parameters (capacitances and inductances) as well as line length and type. The biggest impact was identified by the delay time of the inner converter control combined with DC grid capacitances (converter output and lines) and secondly the shape of the p-v-characteristic since oscillations occur when converter operating points change between piece wise linear defined sections. Thus the system behavior was approved using an undead band voltage droop control and the most significant impact was achieved using a continuously defined undead band voltage droop control.

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