Low-voltage Ride-through Response of Renewable-Penetrated Distribution Networks

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Abstract—**Low voltage ride-through (LVRT) is a grid code that enables distributed energy resources (DERs) to stay connected under voltage sags. However, a DER is exposed to being tripped if it does not meet the LVRT requirement. For a renewable-penetrated distribution network (RPDN), the lost amount of DER capacity over a voltage sag is the so-called LVRT response of an RPDN. Besides the behavior of DERs during the transient undervoltage condition, their trip may have a negative impact on transmission system security. This paper addresses a general mathematical model for analyzing the DERs' behavior during the transient condition. The proposed model is implemented to obtain the RPDN's LVRT response to different voltage sags. This LVRT response is defined as such that concerns the uncertainty in the output power of renewable resources. Furthermore, the expected ride-through capability index is introduced to capture the generation availability due to meeting the LVRT requirements. The studied RPDN shows the lowest capability is for voltage sags with depth and duration greater than 0.70 pu and 0.4 sec, respectively. Also, with 40% and 20% reductions in solar and wind generation compared to their nominal values, the maximum LVRT response of the RPDN decreases from 2420 kW to 1852 kW. Also, the ERC of 66% is achieved for the RPDN, stating the expected loss of 34% of the total DER generation.**

I. Introduction

With the increase in penetration of distributed energy resources (DERs), traditional power systems with centralized energy delivery structures are shifting to decentralized-generation power systems. Renewable sources like photovoltaic (PV) and wind turbine (WT) generators have attracted the favorites in recent decades, leading to their growth in power systems. Apart from the outweighed advantages of DERs, their high penetration level in the distribution sector can encounter the system to different difficulties. DERs trip under any voltage sag was mandatory in previous standards. Low voltage ride-through (LVRT) was introduced as a grid code to cope with this problem, which permits the DER to stay connected by inserting reactive current into the network. However, it cannot guarantee to keep on all the DERs within the network. Successful ride-through of a DER implies meeting the LVRT requirement. Otherwise, they have to be tripped. Apart from the issues like the power quality requirements [1], IEEE 1547 defined three response categories in 2018; Category I for fossil fuel synchronous generators, Category II for inverter-based DERs and Category III for high-penetrated photovoltaic (PV) networks [2].

LVRT capability curves for Category II DERs is shown in Fig. 1. As it is seen, the curve consists of five performance zones and Category II DERs, including all the inverter-based renewable generators, have higher LVRT capability rather than Category I DERs. Two regions of mandatory and permissive operation allow DERs to ride through the undervoltage conditions. When the PCC voltage of a DER falls within the shall trip region, it does not permit operation and trips the DER for at least several minutes [3]. The regions with the yellow color include three performances of ride-through, trip, or momentary cessation.

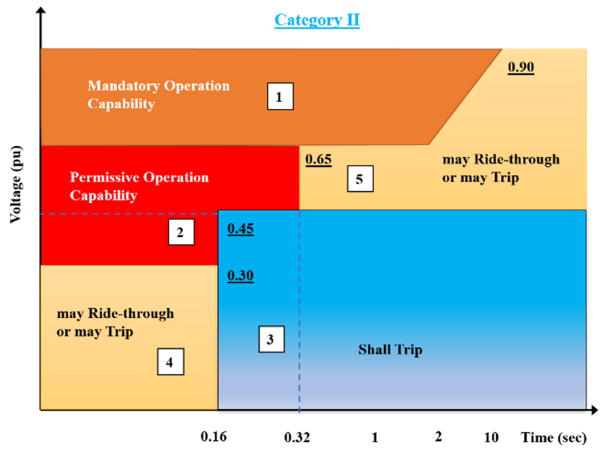

Fig. 1. Abnormal operation performance of Category II DERs

Besides the grid codes that define the LVRT requirements to keep on the DERs, numerous works have been carried out about the control strategies of DERs to inject reactive power and the ways to enhance their LVRT capability [4-7]. This LVRT-based control is applied to both the converter and inverter of the DER [8]. Furthermore, LVRT enhancement of DERs concerning their transient stability issues may be of importance, which was addressed in [9-11]. In comparison to individual grid-connected DERs, LVRT-based control strategies of microgrids are different. These strategies, such as droop control methods [12], controls based on the neural network [13], and coordinated control methods for the unbalanced voltage conditions [14] were proposed. Moreover, the LVRT improvement of microgrids with weak grid connections and the relevant control methods were discussed in [15]. The penetration level of DERs in distribution networks affects their LVRT performance [16,17], but increasing this level may further impact the operation of the whole power system.

By considerable simplifications and PV aggregation method, [18] gave an outline of the positive impact of DERs' LVRT ability on the performance of the whole power system for faults with the origin of high voltage grid. A general mathematical framework was proposed by [19], irrespective of dynamic stability issues, to determine the DERs unable to meet the LVRT requirements during the voltage sag (leading to their trip). Authors in [20] introduced a novel framework to study the impact of active distribution networks' LVRT response on transmission system security. LVRT response stands for the lost amount of DER capacity in response to the voltage sags. The authors of the two last papers pointed out an essential topic, especially the latter one that investigated a transmission system security assessment based on the LVRT performance of active distribution networks.

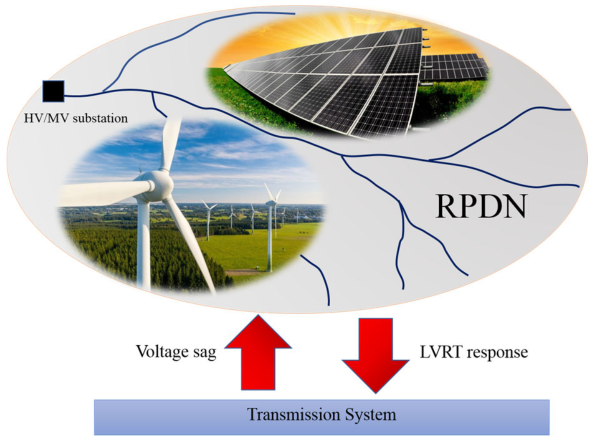

Fig. 2. Graphic of an RPDN's LVRT response to voltage sag

The DERs within an active distribution network have different responses to the voltage sags originating from transient faults of the transmission sector. Depending on the category, network configuration, DER capacity and the sag characteristic, the DERs may stay on or may be tripped. The LVRT response of an active distribution network to a voltage sag is defined as the tripped DER capacity amount in response to a certain voltage sag [20]. This paper discusses the LVRT response of renewable-penetrated active distribution networks (RPDNs). RPDNs stand for distribution networks with a high capacity of renewable energy resources. From the analytic viewpoint, LVRT response is of importance as it is required in the security assessment of the transmission system. High amounts of the lost DER capacity can expose the transmission system to a security violation. Hence the transmission system operator needs the response values to evaluate the system security. Fig. 2 shows an RPDN graphic with sag as the input and LVRT response as the output.

The security assessment is not the topic of this paper. Nevertheless, the authors' main goal is to study the LVRT response of RPDNs from an analytic perspective. RPDNs' LVRT response is formulated through a general mathematical framework, on the basis of dynamic modeling. A system of differential algebraic equations (DAE) is constructed to reveal the DERs behavior under the transient situation and get the RPDN's LVRT response to the input voltage sag. This mathematical model is concerned with the generation uncertainty of renewable resources to enhance the validity of obtained response values.

Also, this paper opens up another topic that can be so applicable to RPDN operators. The so-called expected ride-through capability (ERC) is an index specific to the RPDNs introduced by the authors. This index provides a suitable outlook on the RPDN's LVRT capability for the distribution network operator. The ERC is similar to a reliability index and gives an expected percentage of DER generation capacity that the RPDN operator can rely on. An RPDN can have a low ERC indicating that the network is vulnerable to losing a high amount of distributed generation in response to probable voltage sags. In conclusion, this paper's main contributions are bolded below.

- Constructing a general DAE system to model the response of RPDNs to different voltage sags
- Addressing the LVRT response of RPDNs by considering the inherent uncertainty of renewable generation
- Discussing the ERC index and introducing the corresponding formula.

The paper is organized into four sections. A thorough introduction was presented in the first section. In the following, Section II provides the mathematical formulation and gives a complete explanation of the LVRT response and the ERC index. The proposed approach is validated in Section III, and the final discussion is addressed in Section IV.

II. Mathematical Formulation

The studied RPDN includes fossil-fuel synchronous generators as the Category I DERs and inverter-based renewable generators as the Category II DERs that play the key role. Their DAE equations are formulated as follows.

A. Fossil-fuel synchronous generators

LVRT analysis of an RPDN with different LVRT categories of DERs implies time-variant modeling of the RPDN performance during the abnormal voltage condition. Considering a certain voltage sag on the substation, synchronous-based DERs have a general DAE model as (1).

$$\begin{cases} \dfrac{d\mathbf{x}_{sg}}{dt}=f_{sg}\left(\mathbf{x}_{sg},\mathbf{z}_{sg},\mathbf{u}_{sg},t\right) \\ 0=g_{sg}\left(\mathbf{x}_{sg},\mathbf{z}_{sg},\mathbf{u}_{sg},t\right) \end{cases} \tag{1}$$

In this system of DAE, $\mathbf{x}_{sg},\mathbf{z}_{sg},\mathbf{u}_{sg}$ are respectively the vector of differential, algebraic and input variables and t is the time. Also, subscript 'sg' denotes the synchronous generator.

B. Inverter-based renewable resources

About the inverter-interfaced DERs, the general model of the DAE system is given in (2). In this system of equations, subscript 'ig' denotes the inverter-interfaced generator and superscript '12' denotes the positive-negative sequences. Also, (3)-(6) represent the control strategy of these DERs by determining the amount of reactive current injection in each time step and with respect to the PCC phase voltage [20].

$$\begin{cases} \frac{d\mathbf{x}_{ig}^{12}}{dt}=f_{ig}\left(\mathbf{x}_{ig}^{12},\mathbf{z}_{ig}^{12},\mathbf{u}_{ig}^{12},t\right) \\ 0=g_{ig}\left(\mathbf{x}_{ig}^{12},\mathbf{z}_{ig}^{12},\mathbf{u}_{ig}^{12},t\right) \end{cases} \quad (2)$$

$$v^{min}=\min\{\lfloor v^a\rfloor,\lfloor v^b\rfloor,\lfloor v^c\rfloor\} \quad (3)$$

$$Q^*=\begin{cases} 0 & v^{min}\geq 0.9 \\ q\left(0.9-v^{min}\right)S^* & 0.2\leq v^{min}<0.9 \\ S^* & v^{min}<0.2 \end{cases} \quad (4)$$

$$P^*=\left(S^{*2}-Q^{*2}\right)^{1/2} \quad (5)$$

$$\begin{bmatrix} i_d^{ref,1} \\ i_q^{ref,1} \\ i_d^{ref,2} \\ i_q^{ref,2} \end{bmatrix}=\begin{bmatrix} v_d^1 \\ v_q^1 \\ -v_d^2 \\ -v_q^2 \end{bmatrix}\frac{P^{ref}}{v_\alpha-v_\beta}+\begin{bmatrix} v_d^1 \\ -v_q^1 \\ v_q^2 \\ -v_d^2 \end{bmatrix}\frac{Q^{ref}}{v_\alpha+v_\beta} \quad (6)$$

In these equations, v^{min} is minimum phase voltages of the DER PCC, P^*, Q^* and S^* are respectively the reference reactive, active and apparent power injection amounts and q is a constant value equal to 1.438. The matrix equation in (6) sets the reference current values in dq frame and for positive and negative sequences i_{dq} based on the reference active and reactive powers and the voltages in dq frame. Also, $D_1=\left(v_d^{*,1}\right)^2+\left(v_q^{*,1}\right)^2$ and $D_2=\left(v_d^{*,2}\right)^2+\left(v_q^{*,2}\right)^2$.

C. Inverter-based renewable resources

Network algebraic equations in dq frame are formulated in the matrix form of (7). Here, G and B are the conductance and suseptance submatrices of the reduced network (through Krone reduction), and matrix T (6) is used to transform the output voltage and current vectors of DERs from DQ frame to the dq frame [20]. δ is the difference between the reference frame angle of the DER and the global reference frame.

$$T^{-1}\begin{bmatrix} G & -B \\ B & G \end{bmatrix}^{12} T\begin{bmatrix} V_d \\ V_q \end{bmatrix}^{12}=\begin{bmatrix} I_d \\ I_q \end{bmatrix}^{12} \quad (7)$$

$$T=\begin{bmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{bmatrix} \quad (8)$$

D. Overall DAE system for LVRT analysis of an RPDN

These equations, overall, construct a system of DAE as (9) that is time-dependent, i.e., the trip of any DER due to inability in LVRT requirements changes the structure of the DAE. By matrix equation of (10), the differential and algebraic variables are calculated in each time step through the implicit trapezoidal method. W and U are, respectively, the coefficient and output matrices in time step t.

$$\begin{cases} \frac{d\mathbf{x}}{dt}=f(\mathbf{x},\mathbf{z},\mathbf{u},t) \\ 0=g(\mathbf{x},\mathbf{z},\mathbf{u},t) \end{cases} \quad (9)$$

$$W_t^{12}\begin{bmatrix} \mathbf{x} \\ \mathbf{z} \end{bmatrix}^{12}=U_t^{12} \quad (10)$$

Equation (10) is the linearized form of the overall DAE system and is time-dependent as any DER trip changes the size of matrices. A voltage sag has two characteristics, depth and duration. LVRT response refers to the lost DER capacity of an RDPN over the sag duration as given in (11). LR denotes the LVRT response; ND is the total number of DERs with the RPDN, and C is the DER capacity. Also, α is a binary variable that is 1 if the incapability to meet the LVRT requirement yields the DER trip.

$$LR=\sum_{k=1}^{ND}\alpha_k.C_k \quad (11)$$

It is noteworthy that the proposed LVRT analysis model can solve the problem by integrating the MV distribution networks and its DER-penetrated LV networks. However, since PV cells are the mostly used DERs in the low-voltage level, PV-penetrated low-voltage distribution networks can be modeled in medium-voltage buses in an aggregated way and through their equivalent Thevenin impedance [21].

E. LVRT response concerning the generation uncertainty

In the previous subsection, LVRT response was formulated by considering the lost DER capacity in response to certain voltage sag. However, there is an important point that should not be disregarded. The introduced problem studies the LVRT response of RPDNs from the analytic viewpoint. In other words, the lost DER generation is visible in real-time for the operator, but an analytic approach is adopted herein to use the LVRT response in security assessment problems. LVRT response of an RPDN is affected by renewable generation uncertainty. Containing PV and WT generation units, the LVRT response of an RPDN is rewritten as (12)-(14).

$$LR=\mathbf{A}\times(\mathbf{M}\odot\mathbf{C}) \quad (12)$$

$$\mathbf{A}=[\alpha_1,..,\alpha_{ND}] \quad (13)$$

$$\mathbf{M}=\begin{bmatrix} m_1 \\ . \\ m_{ND} \end{bmatrix},\ \mathbf{C}=\begin{bmatrix} C_1 \\ . \\ C_{ND} \end{bmatrix} \quad (14)$$

Equation (12) models the LVRT response in a vector multiplication form. Symbols × and ⊙ respectively denote the traditional matrix multiplication and Hadamard product. **A** is the vector of aforementioned binary variables α, **C** is the DER capacity vector and **M** stands for the adjustment coefficient vector to give the lost generation vector of DERs according to their inherent uncertainty. Indeed, the adjustment coefficient vector **M** is a factor to model the generation uncertainty of the renewable resources and depends on the forecasting error. Note that m=1 for the Category I DERs and 0<m<1 for the Category II DERs, PV and WT. By this formulation, the generation uncertainty is concerned with the RPDN's LVRT response.

F. Expected ride-through capability of RPDN

It was shown in subsection E that the LVRT response of an RPDN could be formulated in a matrix relation. This matrix relation expresses the lost DER generation of an RPDN for different voltage sags. There is an important question that relates to the LVRT response application for the RPDN operator. The importance of the LVRT response from the perspective of the transmission system was indicated in Section I. Nevertheless, an RPDN operator is responsible for load serving during peak times. Losing a high generation amount of DER capacity without a predetermined strategy may encounter significant difficulties. Thus, this operator needs to assess the expected available DER capacity at peak times.

On the other hand, voltage sags are phenomena with uncertain and random characteristics. This randomness refers to the nature of the transmission level transient fault impacts the assessment. Based on these explanations, the ERC index is introduced to give an outlook on the network's LVRT capability. The ERC states the expected available generation capacity due to the successful ride-through of DERs within the RPDN. Let's rewrite the LVRT response as a function LR(ζ,τ,θ,**M**), in which ζ, τ, and θ are respectively the sag depth, sag duration, and the fault type causing this voltage sag. The voltage sag severity in the single-line-ground fault type is less than those with three phase fault type. Now, the ERC is defined as (15).

$$\mathrm{ERC} = \frac{1}{N_s}\sum_{s=1}^{N_s}\left[1 - \frac{\mathrm{LR}\left(\zeta_s, \tau_s, \theta_s, \mathbf{M}_\omega\right)}{\mathrm{TDC}}\right] \quad (15)$$

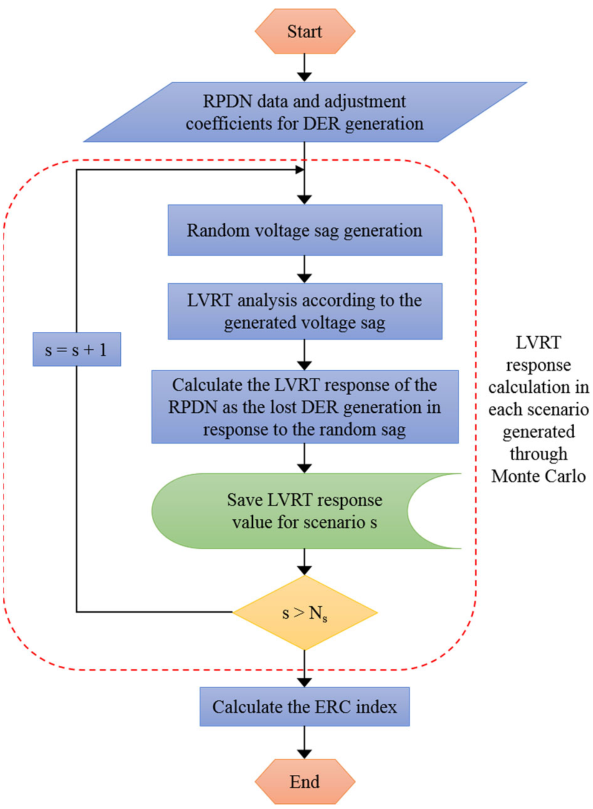

Fig. 3. Flowchart of finding the ERC index for an RPDN

The Monte Carlo scenario generation is used for random sag generation in this definition. This technique is based on random sampling from the probability distribution function and calculates the ERC under a high number of generated sag scenarios. TDC is the total DER capacity with the RPDN, s denotes the Monte Carlo scenario index for random sag generation, and N_s is the total number of generated scenarios. The ERC is a value between [0-1], indicating the expected available generation as a percentage of the whole DER capacity of the RPDN. This available generation refers to the successful ride-through of the DERs over the sag periods. In other words, LVRT responses of an RPDN are calculated under a high number of random voltage sags. Using these responses, the available generation capacity as a ratio of the total DER capacity is calculable for each scenario. Thus, the ERC stands for the generation capacity expected to be available after a probable voltage sag. The higher the ERC index, the more the tolerance of the DERs against the voltage sags. However, the lower ERC values point out an RPDN with weak ride-through performance in response to voltage sags. The overall process of finding the ERC index for an RPDN is provided as a flowchart in Fig. 3.

III. TEST SYSTEM AND RESULTS

The proposed mathematical model is tested on the IEEE 33 bus network as an RPDN in Fig.4, consists of three DER types of WT, diesel engine (DE) and PV. Low voltage side of two buses, 13 and 20, with considerable PV penetration, is modeled as the aggregated load-generation and is added to the feeder through a Thevenin equivalent. Also, the LVRT analysis is conducted for four fault types; 1 (single-line-ground), 2 (double-line), 3 (double-line-ground) and 4 (three phase). Furthermore, the simulation is carried out in MATLAB software, on a Laptop with 4Gb RAM. The required data about the DERs, their internal parameters, the feeder data and the LV connected network data are addressed in [19],[20].

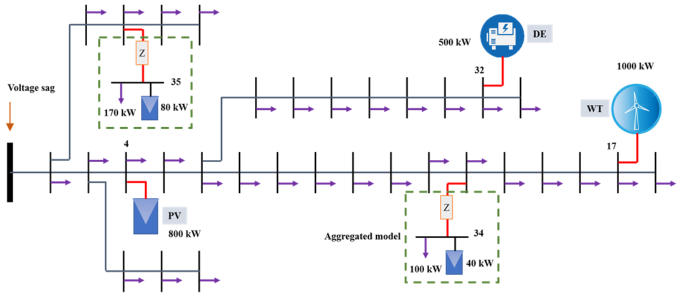

Fig. 4. IEEE 33 bus feeder as the test RPDN

First, to see the behavior of this RPDN under abnormal voltage conditions, LVRT analysis is performed against different values of sag depth and duration. This analysis is carried out according to the IEEE 1547 and considers regions 4 and 5, respectively, as the ride-through and trip performance regions, which looks quite pessimistic. The five DERs are numbered in the sequence of their connected bus numbers. Fig. 5 shows variations in the phase A voltages of the DER-connected buses and phase voltages of bus 4 for a voltage sag with a depth of 0.8 pu, duration of 340 ms, with the origin of fault type 1.

By looking at the figure, two sharp decreases are observed, pointing out that the DER trip violates the LVRT requirements. First, the DER 3 with the category of I is tripped at 160 ms, and then the remaining DERs with higher LVRT capability are tripped at 321 ms. Moreover, Fig. 6 represents the similar voltage variations of phase B for sag type 3 with a depth of 60% and a duration of 800 ms. As it is seen, despite the considerable rise of the PCC voltages rather than the sag depth, the grid code is pessimistically defined, which does not permit the DERs to stay connected.

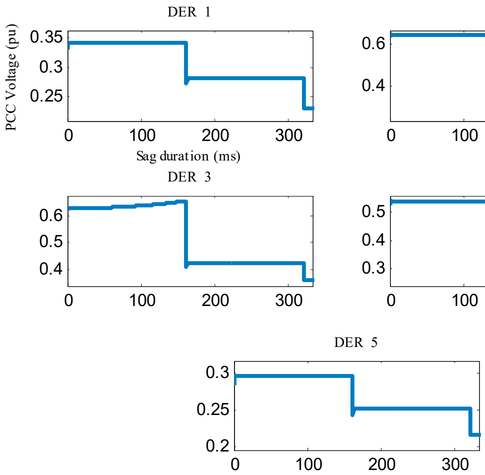

Fig. 5. Phase A voltages of DER connected buses during the sag of type 1 with a depth of 0.80 pu

The DERs behavior against a voltage sag of type 4 with depth and duration of 50% and 340 ms is shown in Fig. 7. Concerning the severity of this sag type, it can be observed that the reactive current injection cannot lead to any considerable raise in PCC voltages. Regarding the previous results, one point is noticeable: the difference in voltage rise of the DER-connected buses. DERs 1 and 5 exhibit resistance against the voltage raise of their PCC, notwithstanding the reactive power injection, and it refers to the close electrical distance to the HV/MV substation. In turn, DER 3 is relatively farther electrically distant, and this feature, besides reactive current injection, helps further raise its PCC voltage.

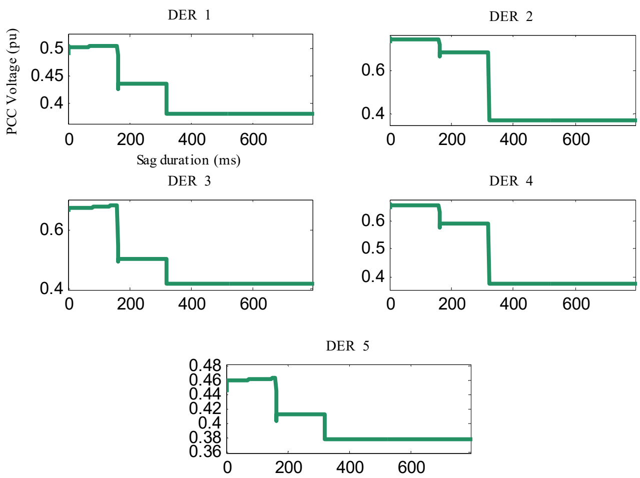

Fig. 6. Phase B voltages of DER connected buses during the sag of type 3 with depth of 0.60 pu

TABLE I gives the LVRT response of the RPDN for different sag depth and duration values with the origin of fault type 1. First, it is seen that the voltage sags of about 100 ms have an LVRT response equal to 0, stating a safe performance margin. An increase in the sag severity from either depth or duration entails the lost DER capacity enhancement.

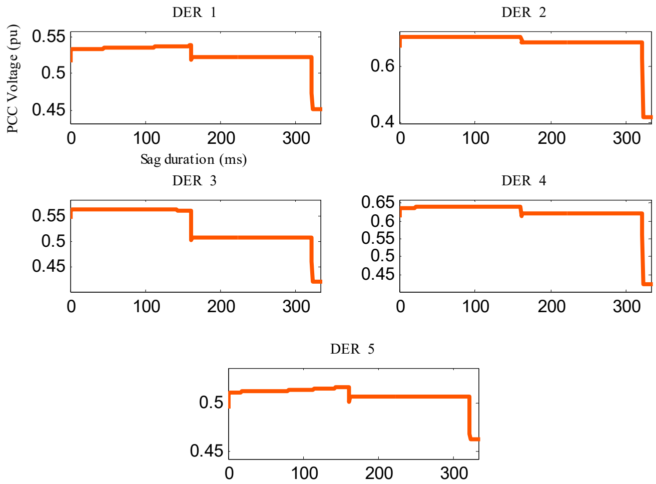

Fig. 7. Phase voltages of DER connected buses during the sag of type 4 with depth of 0.50 pu

TABLE I. LVRT RESPONSE FOR FAULT TYPE 1 IN KW

Sag depth	**Sag duration (ms)**				
	100	***200***	***400***	***600***	***800***
0.25	0	0	0	500	500
0.40	0	0	880	1380	1380
0.50	0	0	1420	1420	1420
0.70	0	1380	2420	2420	2420
0.85	0	1420	2420	2420	2420

TABLE II. LVRT RESPONSE FOR FAULT TYPE 4 IN KW

Sag depth	**Sag duration (ms)**				
	100	***200***	***400***	***600***	***800***
0.25	0	0	500	500	500
0.40	0	500	1420	1420	1420
0.50	0	500	2420	2420	2420
0.70	0	1420	2420	2420	2420
0.85	0	2420	2420	2420	2420

TABLE II shows the LVRT responses for voltage sags with similar depth and duration values but fault type 4. It is observed that voltage sags with the origin of fault type 4 increase the LVRT response, which indicates the reduction in the ride-through capability. In the end, deviations of 40% and 20% from the respective nominal output power of PV and WT are considered. By looking at the obtained LVRT responses in TABLE III, a considerable decrease is evident. It refers to the uncertainty concerned with the output power of the renewable units and regarding the lost generation instead of lost capacity.

TABLE III. LVRT RESPONSE FOR FAULT TYPE 4 IN KW WITH GENERATION UNCERTAINTY CONSIDERATION

Sag depth	Sag duration (ms)				
	100	***200***	***400***	***600***	***800***
0.25	0	0	500	500	500
0.40	0	500	1052	1052	1052
0.50	0	500	1852	1852	1852
0.70	0	1052	1852	1852	1852
0.85	0	1852	1852	1852	1852

The ERC index is calculated under 1000 generated scenarios of the voltage sag with different depths, durations, and fault types. Keeping the adjustment coefficients of 60% and 80% for the output power of PV and WT units, the ERC of 66% is obtained. This value states that 1597 kW from the total 2420 kW DER capacity is expected to be available if a voltage sag appears on the HV/MV substation. In other words, the RPDN operator expects to lose about 34% of 2420 kW capacity under a voltage sag occurrence. It should be noted that a part of this generation loss refers to the power deficiency of 40% and 20% for the renewable resources PV and WT.

Notwithstanding, a major part corresponds to the trip of DERs incapable of meeting the LVRT requirements. The obtained ERC index has a special and different meaning for the RPDN owner. The network has a problem from the LVRT perspective and may require a revision in the planning framework. 34% of generation loss is a considerable value albeit the probabilistic nature of the voltage sag occurrence. The ERC of this network can be enhanced by methods like DER relocating or adding DERs in the direction of LVRT capability enhancement.

IV. CONCLUSION

This paper attempted to introduce a method to mathematically model the LVRT response of RPDNs and their generation loss after fault clearance. LVRT response of RPDNs is an essential issue in a DER-penetrated power system since a part of DERs may fail to meet the LVRT requirements, and their trip can endanger the system's security. RPDNs' LVRT response was formulated and the uncertainty subject to the output power of renewable generators was concerned by a matrix relation. It was shown that the RPDN under study was weak against the severe sag voltages and had high LVRT response values, which may not be preferable for the transmission system operator. On the other hand, it is worth mentioning that the severe sags with durations higher than 100 ms are low probable, hence decreasing the risk of DER trips in high capacity amounts.

The newly defined LVRT response gives out the lost DER generation in response to different voltage sags. As the output power of renewable resources is exposed to uncertainty, an adjustment multiplication vector was used to model the generation instead of the capacity (nominal power). This model is helpful, especially for the transmission system operator, to conduct a more accurate LVRT-based security assessment. Besides, the ERC index was proposed in this paper, which captures the expected availability of DER generation due to meeting the ride-through requirement. The ERC as a percentage of the whole DER capacity gives the RPDN operator an outlook on the expected available DER generation at peak hours. This index can play an essential role in future works in the distribution network planning context. Distribution companies seek a cost-effective planning scheme that fulfills other objectives like reliability. However, the ERC index may bring a conflict of objectives. Optimal planning of an RPDN with the orientation of ERC improvement needs considering factors like the DER penetration level, DER category, and DER numbers.

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