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Modeling challenges and potential solutions for integration of emerging DERs in DMS applications: power flow and short-circuit analysis

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Abstract We aim to systematically review challenges imposed by emerging distributed energy resources (DERs) to model in two basic distribution management system (DMS) online applications—power flow and short-circuit analysis, as well as to offer a systematic review of potential solutions. In the last decade, electronically coupled DERs became increasingly popular. DERs can employ a wide range of control strategies for power, current, or voltage control, in both normal and faulted conditions. Therefore, DERs cannot be modeled with the traditional PQ (load or generator bus), and PV (generator bus) bus types used for modeling synchronous and induction machines in online power flow calculations. Moreover, because fault currents of DERs are limited to predefined maximal values, electronically coupled DERs cannot be represented with traditional voltage source behind impedance models for online short-circuit calculation (SCC). However, most of the DMS software packages still use the traditional models to represent all DER types, including those that are electronically coupled. This paper shows that there will be high calculation errors in such practice, which makes the system model be an inadequate representation of the system. And this will lead to serious errors in managing, control, and operation of distribution systems. Nonetheless, potential solutions to the challenges are systematically reviewed. Finally, calculation results on a distribution test system with all DER types are used to prove the claim.

Keywords Distributed energy resources (DERs), Distribution management system (DMS), Power flow modeling, Short-circuit modeling

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1 Introduction

In order to properly monitor, control, optimize, and maintain the secure operation of the systems, distribution system operators use distribution management system (DMS) software packages. DMS consists of supervisory, control and data acquisition (SCADA) system for monitoring, control, and data acquisition and a broad collection of power system applications including planning, optimization, and control. DMS power applications are used in both offline and online operational modes. The offline mode is mainly used for planning and optimization purposes, whereas the online mode is used for the real-time monitoring, control, and maintenance of the secure operation of the distribution system. DMS power applications, in the online mode, need to satisfy two important features when large-scale distribution systems are considered: high speed and high accuracy.

Two basic DMS power applications in online mode are power flow and short-circuit calculation (SCC), and almost all other DMS applications are based on either the power flow or SCC results. Power flow is used for calculating the state of the system without contingencies—normal operational state, and most of the other applications that are used for different calculations on the normal operation of the system, such as state estimation, voltage and reactive power optimization, optimal configuration, supply restoration, etc. are based on one or more power flow calculations. On the other hand, SCC is used for calculating the faulted system state. Results obtained by SCC are required for numerous other power applications, such as relay settings and coordination, protection equipment selection, bus-bar design, etc. Therefore, it is essential for DMS to contain efficient and accurate power flow and SCC to have fast calculations and reliable results. Both the speed and the accuracy of the DMS calculations are highly dependent on the system model. Thus, the system model needs to be accurate and not too complex in case of limiting the use in online applications.

For many decades, energy was produced in bulk by large power stations, and then carried through transmission lines to passive distribution systems. Highly efficient models of traditional power systems in both normal [1–5] and faulted conditions [5–10] have been developed. However, in the last two decades, power systems have faced a shift from traditional to current systems in which, besides the bulk production, energy is produced by smaller energy resources connected to distribution systems. At first, distributed energy resources (DERs) were based on the same technology as traditional AC, synchronous and induction, machines for bulk production, but with much smaller size. Therefore, modeling of these systems, at that time, was not a serious challenge, as models for traditional AC machines have been well developed, standardized and widely used in power industry for decades [1–8]. In the normal operational state, these machines can be set to inject constant real and reactive power or to inject constant real power and to keep constant voltage magnitude. Therefore, they have been modeled with single-phase PQ and PV bus types [1–5]. In the faulted system conditions, traditional AC machines completely lose their control, and the response of which depends on their physical characteristics. The fault currents of the machines can be as high as 30 times the rated currents. And they have been modeled as voltage sources behind sub-transient, transient, or steady state impedances [6–8].

However, in the last decade, the connection of DERs to the distribution system through power electronic devices has become increasingly popular [11–14]. In addition to completely electronically coupled DERs (inverter based DERs—IBDERs), DERs can be partially electronically coupled—doubly-fed induction machines (DFIMs). The DFIM technology allows the stator of the machine to be directly connected to the system, while the rotor is decoupled from the system by a back-to-back converter [15–17]. The DFIMs are mainly used in the wind generation industry, where the percentage of wind turbines based on this technology is almost 80% [16]. The IBDERs are widely used for DERs such as photovoltaics, direct-drive wind turbines, micro-turbines, fuel cells, battery energy storage systems, and flywheels [11–13]. These emerging DERs can employ a wide range of control strategies for power, current, or voltage control, in both normal and faulted operational states [13–15].

In the normal operational state of unbalanced distribution systems, unlike the traditional AC machines, IBDERs and DFIMs can control and block their negative and zero sequence currents [18–26]. Also, they can maintain the symmetrical voltages at their points of common couplings (PCCs) in unbalanced conditions [18–26]. Moreover, these DERs can be bi-directional [15–17]. Therefore, as IBDERs and DFIMs can implement different and more complex control strategies, they cannot be represented with the traditional bus types PQ and PV used for modeling traditional AC machines.

In the faulted state of the system, unlike traditional AC machines, IBDERs and DFIMs in some cases can maintain the control of the fault currents to values not higher than 1.5 times the rated currents [27–33]. These currents are multiple times lower than the fault currents injected by traditional AC machines. Additionally, controllers integrated in DFIMs and IBDERs can implement a wide range of fault current control strategies to specify the real to reactive power ratios. These features greatly benefit the system because of the reduction of stress to system elements caused by large fault currents, and by providing better voltage recovery through reactive power injections during the faulted state. Thus, the response of emerging DERs to faults in the distribution system is completely different from that of traditional AC machines. Additionally, fault ride through (FRT) requirements for DFIMs and IBDERs are introduced into the distribution codes [34–38]. The requirements strictly define how DFIMs and IBDERs should react in the cases of voltage drops at PCCs, caused by faults anywhere in the system. Most of them require that these DERs stay connected to the system throughout the fault state and inject as much reactive power as possible to facilitate faster voltage recovery.

It is clear that the emerging DER technologies impose numerous challenges to modeling and calculations for current distribution systems, in both normal and faulted conditions. Traditional models for modeling all types of

DERs are mostly applied by DMS software packages, including DFIMs and IBDERs, in both normal and faulted conditions [39, 40]. Models that inaccurately represent the distribution system are used and lead to high errors in calculated results, with a negative effect on the control and secure operation of the system. DMS software packages are a critical part for managing and controlling distribution grids. Inaccurate results caused by using inappropriate models could lead to incorrect decisions made by operators which may eventually lead to serious system faults. Examples of serious negative consequences due to inappropriate models can be found in [41–44]. And the consequences include inaccurate input into the other, more advanced power applications, the false tripping of the protection equipment, prolonged fault clearing times, as well as wrong results of the fault location applications. Therefore, following the most recent literature on modeling and analysis of emerging technologies is crucial for DMS software developers, in order to integrate the appropriate models in their calculations and bridge the gap between new DER technologies and traditional modeling practices. We aim to point out challenges that exist in the integration of DER technologies with distribution system operations, and systematically present a list of potential solutions that could be implemented to avoid consequences caused by using inappropriate models.

There are various high-quality review papers addressing the operational challenges of distribution systems that include the connection of DERs [45–54]. In [46–48], challenges imposed by integration of high penetration of renewable DERs were systematically reviewed. Reference [49] also presents integration challenges and an overview of the market and economic influence of renewable DERs. In [50], an extensive review of distribution automation is presented, and consequently a list of challenges and possible solutions imposed by new technologies is provided. Reference [51] deals with control and automation challenges imposed by renewable generation to the modern power grids, and the focus of the paper are transmission systems. In [52], the need for new distribution system control and planning algorithms of emerging active distribution systems are thoroughly discussed. In [53], the impact of photovoltaic DERs on the voltage regulation is discussed. Finally, in [54], the operational challenges imposed by DERs in both normal and faulted conditions are discussed. In [55–62], the distribution system planning challenges imposed by DERs were discussed. In [55–57], new methods for optimal reactive power planning in modern distribution systems are proposed. These references are focused on integration of intermittent energy resources and their influence on reactive power planning in distribution systems. Reference [58] proposes an optimal placement strategy of energy storage units in distribution systems with high penetration of intermittent distributed generators (DGs). However, the focus of that research is on the market and cost benefits of optimal placement. A similar study is presented in [59], but for optimal placement of energy storages in microgrids. References [60–62] present comprehensive review studies of planning techniques for integration of high penetration of DGs into distribution systems.

However, there are no references in the available literature that systematically review on challenges of modeling and distribution system calculations imposed by integration of emerging DERs. Moreover, systematic review of potential solutions to the existing challenges imposed by emerging DER models does not exist in literature. These challenges were tackled in [63, 64], with no results and potential solutions. Thus we present this paper as modeling and DMS calculations are crucial for the efficient and secure management of distribution systems.

The rest of the paper is organized as follows. In Section 2, the backgrounds of power flow and SCC applications are reviewed. In Section 3, the possible control strategies integrated in different DERs in both normal and faulted conditions are summarized. Consequently, the modeling challenges imposed by the control strategies of emerging DERs are summarized in the latter part of Section 3. In Section 4, potential solutions for the challenges are reviewed. In Section 5, the calculation errors made by using traditional modeling for current distribution systems are shown on a standard test system. Numerical verifications are presented for both normal and faulted states. The paper is concluded in Section 6.

2 Background of basic power applications and traditional DER modeling

2.1 Traditional power flow model and calculation

The control strategies of traditional AC machines in symmetrical states can be listed as follows: ① In the case of synchronous machine, the real power is controlled to be: $P_k < 0$, $P_k = 0$, $P_k > 0$; they can be generators, compensators, or motors, respectively. In any of these three modes, the reactive power can be controlled to be $Q_k < 0$, $Q_k = 0$, $Q_k > 0$ by AC machines, as well as the phase voltage magnitude; ② In the case of induction machines, the real power is specified to be positive (generator) or negative (motor). The reactive power is always negative and it depends on the magnetizing impedances and phase voltage of the machines.

Control strategies of traditional AC machines are modeled with the traditional bus classification, consisting of three types of single-phase buses, as show in Table 1: θV (slack bus), PQ and PV. This classification determines the power flow model and its solution procedure [65].

The angles and magnitudes of phase voltages, as well as the injected real and reactive phase powers are marked with θ, U, P, and Q, respectively. Due to the symmetry of the considered systems, any three-phase state variable can be represented with any of its single-phase variables. The second column of Table 1 consists of specified phase variables of different bus types.

The slack bus is the bus with specified voltage angle and magnitude. The generator buses, depending on their control strategies, can be of PQ type, when the real and reactive powers are controlled (specified), or of PV type, when their real powers and voltage magnitudes are controlled (specified).

In power flow calculations, traditional load buses are with specified real and reactive powers—PQ bus types. These powers are specified as constants or functions of voltage magnitudes and frequency [66–75]. In most cases, they are polynomial functions of 2^{nd} degree in voltages—load ZIP models (Z stands for constant impedance, I stands for constant current, or load linearly dependent on voltage, and P stands for constant power) [69–73]. Other types of exponential functions of voltages can be found in [66–68, 71–73, 75]. Linear functions of voltages are presented in [74]. Frequency dependent loads are presented in [68, 73–75] with the frequency dependency expressed by multiplying the load function of voltage as a linear function of a frequency deviation.

The third column of Table 1 consists of the unknown phase variables that are listed in the real-valued network state vector $\boldsymbol{X}_{\mathrm{S}}$, which consists of phase voltages (complex representatives $\hat{U}$, or their real-valued pairs of voltage magnitudes U and angles θ).

The calculation of the vector was first based on the generic Newton-Raphson iterative method [65]. Fast decoupled power flow, an efficient derivative of the Newton-Raphson method, appeared soon after [76] was applied to the calculation of the power flow model for transmission systems with high X/R ratios of the series branches. Updates of the aforementioned methods for calculation of unbalanced power flow in phase domain are proposed in [77] and in the sequence domain in [78].

Table 1 Traditional single-phase bus classification

Bus type	Specified operation variable	Unknown state variable
θV	θ, U	
PQ	P, Q	θ, U
PV	P, U	θ

Backward/forward sweep (BFS) procedures with compensation for loops and generators of PV type appeared around 2 decades ago [79–82] for calculation of radial and weakly-meshed active systems. These procedures are branch-oriented and they are also based on the traditional bus classification θV, PQ, and PV.

However, as stated in the Introduction, the nature of distribution systems has been significantly changed in the last 2 decades. This change is mainly caused by the high penetration of DERs that include DGs, energy storage (ES) systems, or hybrid bidirectional units (DG-ES). In addition to traditional AC machines, DERs include IBDERs (accumulators and flywheels in consumption mode, the same appliances in generation mode, wind and other types of turbines, and photovoltaic panels), DFIMs, etc. Thus, distribution systems transitioned from passive to the active systems, incorporating IBDERs and DFIMs with particularly complex control strategies. These control strategies cannot be accurately represented with the traditional single phase bus classification θV, PQ and PV. This issue is discussed in Section 3.1.

2.2 Traditional short-circuit model and calculation

When the SCC is considered, regardless of the method used for the calculation of the faulted system state, the traditional fault modeling is based on the four decompositions shown in Fig. 1. The fourth decomposition—from the phase domain to the sequence domain is optional [83–85].

As the pre-fault state of the system is known from power flow or state estimation, the SCC is reduced to a calculation of the Δ-circuit state. The main characteristic of the Δ-circuit is that it is passive except at the short-circuit location [5–7] where the injected (fault) currents are non-zero. The AC components of the fault currents are obtained using superposition of the calculated Δ-circuit state and the known pre-fault state. Dynamical sub-transient and transient states exist because of AC machines, and they are approximated as steady-states in the online mode of SCCs

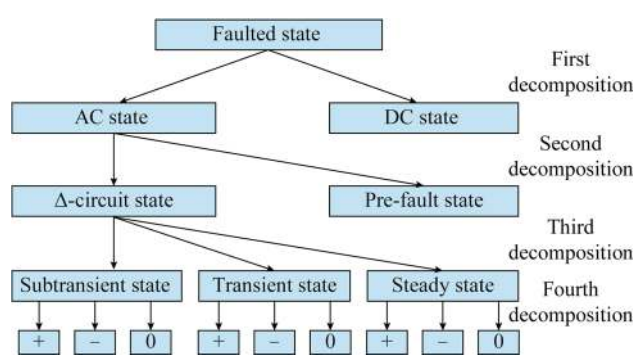

Fig. 1 Four decompositions of faulted system model

[5–7, 81, 83–87]. Thus, the modeling and calculation of AC states for the sub-transient, transient and steady-state time sequence are performed in the complex domain.

The traditional AC machines completely lose the control during the fault, and their fault response depends on the physical characteristics through sub-transient, transient, and steady-state impedances. The models consist of a voltage source behind impedance, and have been well-established in the last decades [3, 6–10].

However, with the emergence of IBDERs and DFIMs, the traditional modeling and calculations for SCCs are not sufficient. As these DERs are decoupled from the system by power electronics, they can maintain the control of the fault currents. Therefore, they cannot be modeled as traditional AC machines. Because of a wide range of possible fault current control strategies integrated in these DERs, there is a need for development of new models, suitable for online SCC of large-scale distribution systems. Moreover, their influence cannot be nulled in the Δ-circuit. Thus, the traditional concept of the passive Δ-circuit cannot be used for SCC for systems with DFIMs and IBDERs [88]. These issues are discussed in Section 3.2.

3 Control strategies implemented in different DERs

The layout of the DER(k) connected to the three-phase bus k is presented in Fig. 2. It can be a traditional AC machine, DFIM, or bidirectional IBDER. Vectors $\hat{\boldsymbol{V}}_k$, $\hat{\boldsymbol{I}}_k$, $\boldsymbol{P}_k$ and $\boldsymbol{Q}_k$ (dimensions 3×1), denote phase voltages, injected currents, and real and reactive powers, respectively.

The sequence domain circuits for DER(k) can be represented as in Fig. 3 [89].

Depending on the way of the connection to the system, DERs can be divided into four types [88, 90].

1) Type 1: synchronous machine directly connected to the system, e.g. small and medium scale hydro turbines, gas turbines, etc.
2) Type 2: induction machine directly connected to the system, e.g. micro-scale hydro turbines, wind turbines with fixed speed, internal combustion engines, etc.
3) Type 3: DFIM, wind turbines with partially variable speed.

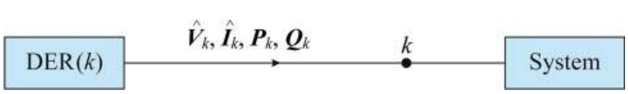

Fig. 2 DER(k) connected to three-phase bus

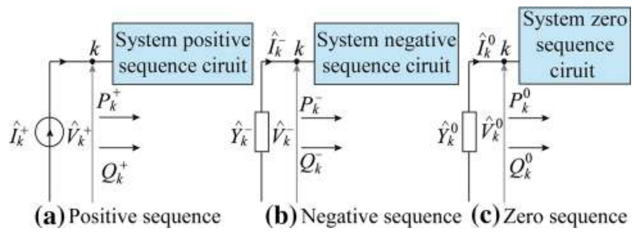

Fig. 3 Sequence domain Norton circuits for DER(k)

4) Type 4: IBDER, e.g. photovoltaics, wind turbines with fully variable speed, energy storages, plug-in electric vehicles, fuel cells, etc.

The three different ways of connecting DERs to the system are presented in Fig. 4.

The possible control strategies implemented in different DERs are explained as follows, in Section 3.1 for the normal system state, and in Section 3.2 for the faulted system state.

3.1 Control strategies of DERs in normal operation state

Due to the unbalanced nature of distribution systems, caused by single phase laterals, single/two-phase and unbalanced three-phase loads, single and three-phase DERs, and un-transposed structure of three wire and four wire three-phase distribution lines, emerging DERs can employ a wide range of control strategies in the

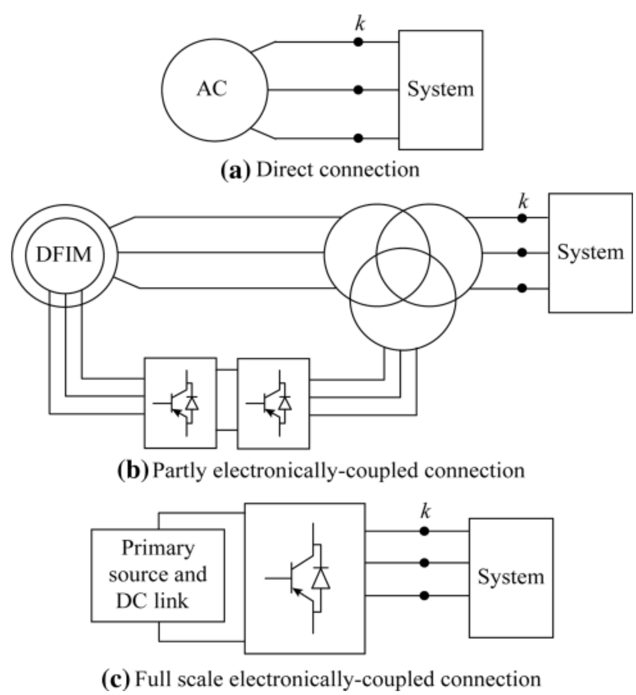

Fig. 4 Three ways of connecting DER(k)

unsymmetrical operation. Considerable limitation in the traditional modeling of DERs is that by including only single-phase, positive sequence models do not correctly represent the control strategies in unsymmetrical operation.

For traditional AC machines in unbalanced systems and in unsymmetrical states, the variables shown in Table 2 are considered.

Control strategies of synchronous machines in unsymmetrical states are as follows: setting the three-phase real power $P_{k\Sigma}$ and positive sequence voltage magnitude U_k^+, or three-phase reactive power $Q_{k\Sigma}$ in all three modes—generator, compensator or motor, and the subscript Σ points to three-phase values. The known values are three-phase real powers $P_{k\Sigma} > 0$, $P_{k\Sigma} = 0$, $P_{k\Sigma} < 0$, respectively; the same relations hold for the known three-phase reactive powers $Q_{k\Sigma}$, for each of three operation modes of synchronous machines. In case of induction machines, the three-phase real power $P_{k\Sigma}$ is set; it can be positive (generator) or negative (motor); the three-phase reactive power $Q_{k\Sigma}$ is negative and depends on parameters of the machine (the known magnetizing impedances and voltage of machines). The windings of both types of AC machines are usually delta or ungrounded wye connected; thus, the corresponding admittances $\hat{Y}_k^0$ from Fig. 3 are equal to zero in most cases.

Even for systems with only traditional AC machines, the traditional single-phase bus classification θV, PQ, and PV is not sufficient for unbalanced power flow purposes. Namely, the new busses with specified three-phase real and reactive powers need to be introduced. The set of control strategies of traditional AC machines in unsymmetrical states are considered by introducing new three-phase bus types in [89] and include: ① $(\theta V)_\Sigma$ (three-phase slack bus), ② $P_\Sigma Q_\Sigma$ and ③ $P_\Sigma V$. The positive sequence voltage magnitude of the $(\theta V)_\Sigma$ bus is controlled, and its phase angle is specified. The three-phase real and reactive powers are controlled in the $P_\Sigma Q_\Sigma$ bus type. The three-phase real power and positive sequence voltage magnitude are controlled in the $P_\Sigma V$ bus type. The models in [89] significantly increased the accuracy of the traditional power flow model and its calculation procedure for modeling the AC machines in unsymmetrical operation.

However, when IBDERs and DFIMs are considered, the bus types need to be further expanded, as with the aforementioned types, their control strategies are only partially covered [18–22, 91–101]. IBDERs and DFIMs are connected to the system via voltage sourced converter (VSC). VSC is voltage or current controlled and can be equipped with voltage regulator and real power controller or *dq*-current controllers [19, 91, 92]. The objective of DER controllers is to achieve either constant three-phase power regulation or voltage regulation. There are two types of VSC configurations [19]: a three- and four-wire configuration. When three-wire configuration VSC is realized, no zero-sequence current is exchanged at the PCC of DER. When in a three or four-wire VSC, there is no active control of negative-sequence current components, then the negative-sequence admittance is present and negative-sequence current is not necessarily nulled, as shown in Fig. 3.

Detailed control strategies for IBDERs and DFIMs are examined in literature, and it is concluded that besides control strategies that can be integrated in the traditional AC machines, IBDERs and DFIMs can employ the following five additional and important control strategies [18–22, 91–102]: ① control of three-phase real and reactive power providing symmetrical positive sequence voltages; ② control of three-phase real power and positive sequence voltage magnitude providing symmetrical (positive sequence) voltages; ③ control of three-phase real and reactive power with additional control of negative sequence current; ④ control of three-phase real power and positive sequence voltage magnitude with additional control of negative sequence current; and ⑤ control of three phase real power and positive sequence current magnitude. These advanced control strategies sense positive sequence voltage and current components at the PCCs of IBDERs and DFIMs, and then provide special VSC switching processes [91]. The control of zero sequence currents is the same as for AC machines [12], [18–22]. Finally, the distributed slack bus is proposed in [23, 103, 104] for microgrids in autonomous operation.

The above discussion shows that the traditional bus classification θV, PQ, and PV is far from sufficient for modeling and analysis of unbalanced power flows in distribution systems with IBDERs and DFIMs, and new bus types, as proposed in recent literature, requiring proper representation of these emerging DERs and their advanced control strategies. The recently proposed bus types are systematically listed and explained in Section 4.1.

Table 2 Phase domain variables associated to the three-phase DER(k)

Basic variable	Derived variable
P_{ka}, Q_{ka}, U_{ka}, θ_{ka}	$\hat{I}_{ka} = (P_{ka} - jQ_{ka})/(U_{ka}e^{-j\theta_{ka}})$
P_{kb}, Q_{kb}, U_{kb}, θ_{kb}	$\hat{I}_{kb} = (P_{kb} - jQ_{kb})/(U_{kb}e^{-j\theta_{kb}})$
P_{kc}, Q_{kc}, U_{kc}, θ_{kc}	$\hat{I}_{kc} = (P_{kc} - jQ_{kc})/(U_{kc}e^{-j\theta_{kc}})$

3.2 Control strategies of DERs in faulted system state

Regarding IBDERs and DFIMs, fault responses are quite different from for traditional AC machines, which will be explained thoroughly in the following.

3.2.1 Fault currents injected by emerging DERs

Unlike traditional AC machines, IBDERs and in some cases DFIMs can maintain the control of their fault currents [27–33]. For DFIM, this strongly depends on the method used for the protection of the rotor side converter. DFIM is partially electronically coupled, as its rotor is coupled to the system through the power converter, whereas its stator is directly connected to the system [27–30]. DFIM is usually equipped with the protection device known as a crowbar, which short-circuits the rotor terminals to protect the converter if a severe fault is detected [15], [27–30]. If this happens, the model of DFIM becomes the same as the induction machine model, with the crowbar resistance added to its circuit. This model is used in most of the recent literature regarding the SCC of distribution systems with DFIMs [28–30], as well as in international standards for fault calculations [105–107]. However, if the fault is not that severe, e.g. if it occurs far from the DFIM, the crowbar will not react and the converter will continue to control the injected fault current [15–17, 28–30]. Finally, if a more up-to-date protection scheme is used where the converter is active throughout the entire fault period, the converter will continue to control the current even in cases of severe faults. This type of converter protection is known as a chopper [15]. In the last two cases, DFIM will maintain the control of its injected fault current and it cannot be modeled as a traditional AC machine. In these cases, DFIM model will depend upon the control strategy implemented in the power converter. Therefore, using the induction generator models for representing DFIMs in all cases, as suggested in most of the recent literature [28–30] and in international standards for fault calculations [105–107], would introduce high calculation errors, which is discussed in Section 4.2, as well as in the result section.

IBDERs are fully decoupled from the grid by three-phase inverters. This technology is used by most of the emerging DERs such as photovoltaics, direct-drive wind turbines, micro-turbines, fuel cells, batteries for energy storage, and flywheels [17]. The electrical model of the IBDER is completely dependent on the control strategy implemented in the inverter. When a fault occurs in the system, IBDER switches to a current-limiting mode with a predefined current limit [15–17]. Controllers are set either to inject only positive sequence currents or (less often) to control both positive and negative sequence currents, while zero sequence currents are always blocked [15–17]. The current limit is predefined and integrated in the inverter, and does not exceed 1.5 times the rated currents. Thus, for IBDERs the traditional models represented by ideal voltage sources behind impedances are completely inadequate and cannot be used in any case. This is also discussed in Section 4.2 as well as in the results section.

The control strategies implemented in IBDERs and DFIMs are provided by the manufacturer or dictated by the FRT requirements of the specific country. As the number of IBDERs and DFIMs constantly increases, more and more countries have started introducing the FRT requirements to their distribution codes [34–38]. Therefore, it is most likely that in the near future, manufacturers will be required to tune the control strategies of DERs in accordance with the specific FRT requirements, and the fault models for DERs should be developed in accordance with the FRT requirements.

3.2.2 FRT requirements for emerging DERs

Distribution codes require from electronically coupled DERs to stay connected to the system during the fault, and to support the distribution system by injecting reactive power throughout the duration of a fault [34–38]. The Irish and the German distribution codes require IBDERs and DFIMs to provide reactive current at their PCCs with a contribution of at least 2% of the rated current per percent of the voltage drop [34–37]. It means that if the voltage drops to 50%, the reactive current should be 100% of its rated value, and the requirement is presented in Fig. 5. However, these DERs must control their fault current responses within strictly defined current limits to protect vulnerable power electronic devices [13–15]. The current

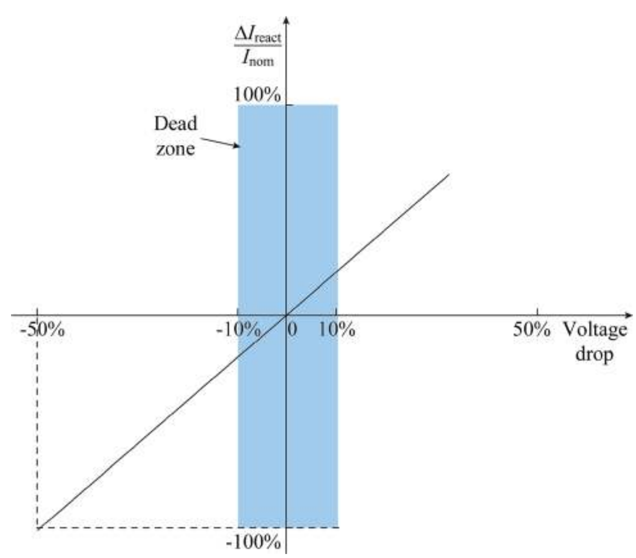

Fig. 5 Requirements for a reactive current injection

limit differs with different manufacturers, but does not exceed 1.5 times the rated current. Therefore, in cases of severe voltage drops (more than 75%), their reactive currents cannot exceed this limit.

Two main FRT requirements regarding electronically coupled DERs are as follows [31, 34–38].

1) To remain connected to the system throughout the duration of the fault.
2) To inject reactive power into the system to support voltage during a system fault.

It is clear that new models for electronically coupled DERs need to be adopted and standardized, in order to have a good approximation of fault responses. In [33, 108–110], the fault models for electronically coupled DERs for dynamical simulations were proposed, and validated on small systems. These models simulate DERs with high precision, but they are too complex. Therefore, calculations with these models would be particularly time consuming, and cannot be used for DMS online calculations implemented on large-scale systems where results are expected in a matter of milliseconds. Moreover, the international standards for fault calculations [105–107] do not provide suitable models for emerging DERs, as they use the traditional induction machine models for representing DFIMs, and provide only brief and inaccurate instructions for modeling IBDERs without considering the FRT requirements. However, in the recent literature, several promising solutions for IBDER and DFIM models have been proposed [88, 90, 111–115], and the proposed models cover several different cases of IBDER and DFIM operation. Therefore, if properly integrated in DMS calculations, these models would be able to represent emerging DERs with high precision in any operating mode, and in that way, avoid inaccurate results. These emerging models will be systematically reviewed and explained in the next section.

4 Systematic review of potential solutions to modeling challenges imposed by emerging DERs

4.1 Normal unsymmetrical operational state

As stated in Section 3.1, new unbalanced power flow models for distribution systems that contain emerging DERs should be adopted. These methods require a new classification of bus types, so the traditional single-phase bus classification θV, PQ, and PV needs to be significantly extended. To accurately represent IBDERs and DFIMs, as well as traditional AC machines in unsymmetrical states, nine control strategies of emerging DERs with corresponding new three-phase bus types that accurately represent these strategies are discussed as follows, and presented in Table 3.

1) $(\theta V)_{\Sigma}$: first variant of the three-phase slack bus. The supply point of the distribution system from the (sub)transmission system that is usually replaced by its Thevenin equivalent with the same form as the models of AC machines. This bus type is introduced in [89]. The positive sequence voltage component of this bus is controlled. Also, this component is the reference variable for angles of all other state variables, so its angle is specified. As it is presented in Table 3, the associated unknown state variables are the complex-

Table 3 New bus type classification

Bus No.		Bus type	Specified operation variables	Unknown state variables
Traditional bus types	1	θV	$\theta,\ U$	
	2	PQ	$P,\ Q$	$\theta,\ U$
	3	PV	$P,\ U$	θ
	4	$(\theta V)_{\Sigma}$	θ^{+}, U^{+}	$\hat{U}^{-}, \hat{U}^{0}$
Three-phase bus types introduced in [89]	5	$P_{\Sigma}Q_{\Sigma}$	P_{Σ}, Q_{Σ}	$\theta^{+}, U^{+}, \hat{U}^{-}, \hat{U}^{0}$
	6	$P_{\Sigma}V$	P_{Σ}, U^{+}	$\theta^{+}, \hat{U}^{-}, \hat{U}^{0}$
	7	$P_{\Sigma}Q_{\Sigma}V_{sym}$	$P_{\Sigma}, Q_{\Sigma}, \hat{U}^{-}=0, \hat{U}^{0}=0$	θ^{+}, U^{+}
	8	$P_{\Sigma}V_{sym}$	$P_{\Sigma}, U^{+}, \hat{U}^{-}=0, \hat{U}^{0}=0$	θ^{+}
Three-phase bus types introduced in [102]	9	$P_{\Sigma}Q_{\Sigma}I$	$P_{\Sigma}, Q_{\Sigma}, \hat{I}^{-}$	$\theta^{+}, U^{+}, \hat{U}^{-}, \hat{U}^{0}$
	10	$P_{\Sigma}VI$	$P_{\Sigma}, U^{+}, \hat{I}^{-}$	$\theta^{+}, \hat{U}^{-}, \hat{U}^{0}$
	11	3θV	$\theta_a,\ U_a,\ \theta_b,\ U_b,\ \theta_c,\ U_c$	-
	12	3PQ	$P_a,\ Q_a,\ P_b,\ Q_b,\ P_c,\ Q_c$	$\theta^{+}, U^{+}, \hat{U}^{-}, \hat{U}^{0}$
Three-phase bus types introduced in [100, 101, 116–118]	13	$P_{\Sigma}I$	P^{+}, I^{+}	$\theta^{+}, U^{+}, \hat{U}^{-}, \hat{U}^{0}$

valued negative- and zero-sequence voltages of this three-phase bus.

2) $P_{\Sigma}Q_{\Sigma}$: traditional three-phase AC machines as well as IBDERs and DFIMs can be represented with this bus type. In accordance with [89], the control strategy of the DER connected to this bus type consists of specifying the injected three-phase real and reactive powers control. Due to the unsymmetrical system state, the real and reactive powers at the PCC of DER are not equally distributed per phase. Therefore, representing this control strategy with the traditional single-phase PQ bus type, per each phase, would introduce calculation errors. The shortcoming could be omitted by using the $P_{\Sigma}Q_{\Sigma}$ bus type. For the three-phase real and reactive powers are known variables, while the three sequence components of phase voltages are unknown state variables.

3) $P_{\Sigma}V$: traditional three-phase AC machines as well as IBDERs and DFIMs can be represented with this bus type. In accordance with [89], the control strategy of the DER connected to this bus type involves setting the injected three-phase real power and the magnitude of the positive sequence voltage component. Due to the unsymmetrical system state, the real power at the PCC of DER is not equally distributed per phases. Therefore, representing this control strategy with the traditional single-phase PV bus type, per each phase, would introduce calculation errors. The shortcoming could be omitted by using by using the recently-introduced $P_{\Sigma}V$ bus type. For this bus type, the three-phase real power and the positive sequence voltage magnitude are known variables, while the angle of the positive sequence voltage component as well as the complex-valued negative and zero sequence voltage components are unknown state variables.

The possibility to control the phase voltages of IBDERs and DFIMs to be symmetrical in unbalanced networks [19] is a particularly important control strategy. And it cannot be represented with any of the previously introduced bus types. By trying to represent these DERs with the traditional bus types, a high calculation error would be introduced, which is numerically presented in the Results Section of this paper. To avoid this error, two new bus types are proposed in [102] and presented in this paper as follows.

1) $P_{\Sigma}Q_{\Sigma}V_{sym}$: only IBDERs and DFIMs can be represented with this bus type. It is derived from the $P_{\Sigma}Q_{\Sigma}$ type, with additional control of the (positive) symmetry of the voltages, without specifying their magnitude. Both negative and zero sequence voltages are equal to zero. The positive sequence component of phase voltages is an unknown state variable that is described by its angle and magnitude Without introducing $P_{\Sigma}Q_{\Sigma}V_{sym}$, DFIMs and IBDERs with this control strategy cannot be properly represented. Therefore, it is a significantly new bus type for emerging distribution systems.

2) $P_{\Sigma}V_{sym}$: as the previous case, only IBDERs and DFIMs can be represented with this bus type. In accordance with [102], the control strategy is derived from $P_{\Sigma}V$ bus type with additional control of the positive sequence symmetry of voltages and the control of voltage magnitudes. Both negative and zero sequence voltage components are equal to zero as in the $P_{\Sigma}Q_{\Sigma}V_{sym}$ bus type. The angle of the positive sequence voltage component is an unknown state variable.

The possibility to control the negative sequence currents in unbalanced networks [18–20] is the next important control strategy. Like the previous case, it is obvious that none of the existing bus types can accurately represent this control strategy. Moreover, trying to represent it with any of the existing bus types would lead to inaccurate results. This is also clearly illustrated in the Results Section of this paper. To overcome this issue, two new bus types are introduced in [102].

1) $P_{\Sigma}Q_{\Sigma}I$: only IBDERs and DFIMs can be represented with this type. And it is derived from the $P_{\Sigma}Q_{\Sigma}$ type, with additional control of the negative sequence current. The unknown state variables are the same as in $P_{\Sigma}Q_{\Sigma}$ bus type. Without the addition of this bus type, IBDERs and DFIMs with negative sequence current control cannot be properly modeled. Thus, it is crucial to add this new bus type to properly represent distribution systems with emerging DERs.

2) $P_{\Sigma}VI$: as the previous case, only IBDERs and DFIMs can be represented with this bus type. The control strategy is derived from the $P_{\Sigma}V$ bus type with additional control of the negative sequence current. The unknown state variables are the same as in $P_{\Sigma}V$ bus type.

The possibility to control the real power and current in symmetrical states is one more important control strategy of electronically coupled DERs. For this situation, the single-phase bus type PI is introduced in [100, 116, 117]. This provides an indirect control of reactive power support of the grid. This bus type is generalized as three-phase for grids in unsymmetrical states in [101, 118]. In this case, the positive sequence real power and current are controlled variables. Therefore, it is assumed that the positive sequence real power of DER is equal to one third of its three-phase power (P_{Σ}). This bus type is denoted as $P_{\Sigma}I$ as follows.

$P_{\Sigma}I$: only IBDERs and DFIMs can be represented with this bus type. The control strategy of the DER connected to this bus type consists of setting its injected real power and the magnitude of the positive sequence current. Due to the unsymmetrical system state, the real power at the PCC of DER is not equally distributed per phase. For this bus type, the three-phase real power and the positive sequence current magnitude are known variables, while the three sequence components of phase voltages are the unknown state variables.

Reference [102] introduces the second variant of three-phase slack bus—3θV, and the three-phase load bus—3PQ. They are shown in Table 3. These buses are derived from traditional single-phase buses—θV (single-phase slack bus) and PQ. The 3θV bus type is used in a case when a weak distribution grid is connected to the strong (sub)-transmission grid with specified unsymmetrical voltages (infinite three-phase bus). The 3PQ bus type is a three-phase bus, where three (unbalanced) single-phase traditional load buses, as described in Section 2.1, are connected to the distribution grid. The electronically coupled loads, including prosumers and DG-ES, are considered by the other bus types listed in Table 3, depending on the implemented control strategy.

When microgrids are considered, particularly those with autonomous operation, the distributed slack bus (DSB), introduced [23, 104], is based on the droop characteristics *P*–*f* and *Q*–*V* [119, 120] provided in selected DERs. DSB is the fourteenth type of bus classification presented in this paper. It is the third variant of the three-phase slack bus.

With this more complete classification of bus types, the distribution systems with emerging DERs can be accurately represented for unbalanced power flow calculations. Control strategies of emerging DERs are properly modeled and accurately defined by more precise bus types.

Note that without the addition of the recently proposed bus types systematically presented in this paper, unbalanced power flow calculations in presence of emerging DERs would not be possible, as their control strategies cannot be represented with traditional bus types. Namely, by using the results of the traditional power flow calculation, with the traditional single-phase bus classification, for calculating emerging unbalanced networks can introduce high errors. This consequently causes high errors in the results of the other DMS power applications that are based on power flow. The following four DMS power applications are very good examples of the extraordinary sensitivity of their results to errors of power flow calculation: ① state estimation, ② voltage/reactive power optimization, ③ optimal configuration, and ④ supply restoration. Power flow calculation is repeatedly used in the execution of all four applications. The results of the first two applications are very sensitive to the bus voltages and the second ones to the branch currents. The bus voltages and the branch currents are main result of power flow calculation, so the precise power flow results are of the highest importance in order to have correct results of other, more advanced DMS power applications.

In the Results Section of this paper, all bus types from Table 3 are integrated into recently proposed power flow calculation procedure for unbalanced distribution systems [102] to verify the accuracy and to show the urgent need for standardization.

4.2 Faulted system state

As indicated in Section 3.2, electronically coupled DERs have completely different fault responses from traditional AC machines. The fault currents are limited and often have lower values than the fault currents of traditional AC machines. Moreover, IBDERs inject strictly positive sequence symmetrical currents even in cases of unbalanced faults [27–31]. Only in some rare cases of microgrid implementation, inverters can be set to inject negative sequence currents, to be used as signals that the microgrid switched from grid-tied to islanded operation [18, 19]. Therefore, the traditional voltage source behind impedance models cannot be used for modeling electronically coupled DERs, and the new models for IBDERs and DFIMs need to be standardized to have a correct approximation of their fault responses.

In [111], new fault models for IBDERs were proposed. The models consist of controlled current sources, with values equal to 2 times their rated currents, in phase with the voltages at PCCs. And they can be used only in cases that reactive current injection requirements are not imposed, and when it is required that the IBDERs inject purely real power in faulted conditions.

However, most of the grid codes require IBDERs to inject reactive power throughout the duration of the fault, in order to improve voltage recovery time. Therefore, in [31, 112], IBDER models consisting of purely reactive controlled current sources with values limited to 1.5 of the rated values were proposed. These models should only be used in cases when the IBDERs inject fault current that is purely reactive.

Even more precise IBDER fault models were proposed in [88, 90]. These models are based on German FRT requirements and consist of ideal current sources, where the current values are calculated based on the estimated voltages at the PCCs of IBDERs when the fault occurs. In accordance with German FRT requirements for reactive current injection, as shown in Fig. 5, the reactive component of the IBDERs fault current is calculated based on this voltage, while the active component is calculated based on the known fault current limit as well as on the pre-calculated reactive component [90]. The current limit is considered to be 1.5 of the rated value, in accordance to [27–31]. In this way, the IBDER fault model is fully correspondent to the actual FRT requirements for both magnitude as well as the ratio of active to reactive components. These models can be easily adapted to fit the FRT requirements of any grid code. Therefore, it is suggested that these models should be used when the FRT requirements are strictly imposed.

Finally, in [111–115], IBDER fault models based on FRT requirements are proposed, but with contributions from both positive and negative sequence currents. In these models, the fault currents are also limited to 1.5 of their rated values. These models should be used in microgrid fault studies, where the negative sequence fault current is required as a signal that microgrid has switched from grid-connected, to islanded operation.

It is clear that IBDERs cannot be represented with the traditional voltage source behind impedance models, in any case. Depending on the different grid code regulation, inverters can be set in different ways, but their fault current magnitudes are always limited and do not exceed 1.5–2 times their rated values. Therefore, they always inject multiple times lower fault currents than the traditional AC machines, and their models need to represent the fact appropriately. Moreover, the ratios of the active to reactive components depend on the grid codes of various countries, so these models need to be flexible to be generally implemented. Finally, in the cases of microgrid implementation, inverters can be set to inject negative sequence fault currents, besides the positive sequence currents, which is also an important control strategy that should be appropriately modeled.

On the other hand, DFIMs present quite a different challenge as their fault responses depend on various factors, and therefore, DFIM fault modeling needs to be extremely flexible. This is an issue with the DFIM modeling proposed in the recent literature [23–30] and the international standards [105–107], as these references propose to model DFIMs like the induction machines. They do not consider the fact that the DFIM behavior in faulted conditions depends on the severity of the fault and on converter protection. Therefore, this practice could lead to inaccurate results in the cases when DFIM manages to control its fault current and could eventually lead to inaccurate setting and coordination of the protection devices in the system.

To avoid the aforementioned issue, an SCC algorithm is proposed in [88], in which a part for deciding which DFIM models should be used based on the location and the severity of the fault and on the converter protection scheme is integrated. The fault severity is estimated based on the voltage drop at the PCC of DFIM, caused by the fault. If this voltage drops below the predefined value, and if the crowbar is used for the converter protection, the DFIM is modeled like an induction machine. However, if the voltage at the PCC of DFIM stays above the predefined value, the DFIM will maintain its current control. In this case, it is modeled as a current source with the value of pre-fault current of the DFIM. Finally, if chopper protection is used, the DFIM will manage to control its fault current regardless of the fault severity. In this case, it is modeled the same as the IBDER.

Another issue introduced by the connection of electronically coupled DERs is that the traditional way of using the passive Δ-circuit [5–9, 81, 83–85, 87] for modeling and calculation of faulted distribution systems is not valid in the presence of these DERs. Namely, faulted systems have traditionally been solved by decomposition to the passive Δ-circuit state and the known pre-fault state, as shown in Fig. 1. Thus, the entire calculation reduces to the calculation of the passive Δ-circuit. This is not possible with electronically coupled DERs because the fault currents cannot be nulled in the Δ-circuit. Specifically, IBDERs in all cases and DFIMs in case of the chopper protection are modeled with current sources, where their values exceed the pre-fault currents. Therefore, when the decomposition to the pre-fault state and the Δ-circuit state is performed, the values cannot be nulled in the Δ-circuit. This issue is discussed in detail in [88], and consequently the Generalized Δ-circuit concept was proposed that allows the integration of DFIMs and IBDERs into the fault calculations. In the Generalized Δ-circuit, the differences between the

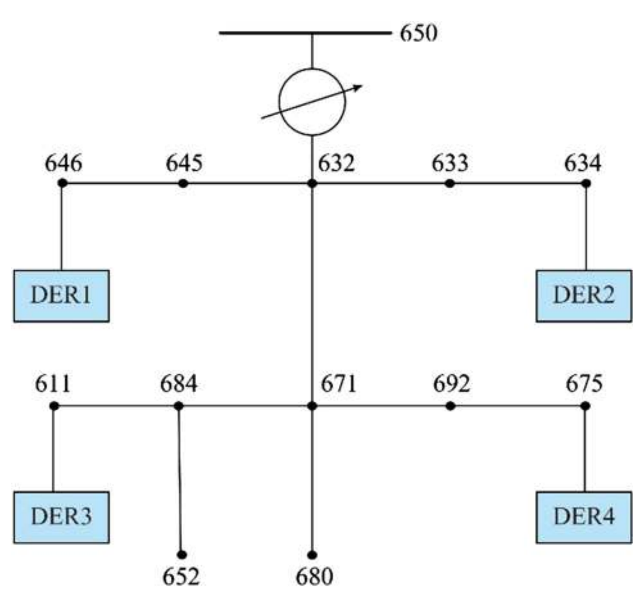

Fig. 6 Modified IEEE 13-node test feeder

fault currents and the pre-fault currents of these DERs are defined as excess currents. These currents are injected into the busses where controlled DFIMs and IBDERs are connected to the Generalized Δ-circuit and in that way their contribution is fully recognized.

The calculation error that can be introduced by using inappropriate models for electronically coupled DERs is discussed in the next section to point out the urgent need for global standardization of the recently-proposed models.

5 Numerical tests and discussion

All numerical tests were carried out on a PC, Intel i3—2330 M, 4 GB RAM. All calculation procedures were in-house developed and programmed in FORTRAN 2008.

The modified IEEE 13-node test feeder shown in Fig. 6 was used for numerical verification. The feeder was modified as follows: ① all two-phase and single-phase sections are replaced with three-phase sections, and the lengths are saved, but the sequence parameters are taken from 4-wire configuration of IEEE 4-node test feeder; ② the switch 671–692 and transformer 633–634 are replaced with sections that are equal to the modified section 692–675 and 650–632, respectively; ③ the turn ratio of voltage regulator is fixed to one; ④ buses 646, 634, 611, 675 are modified from load to generator buses: a synchronous generator (DER1), induction generator (DER2), DFIM (DER3), and IBDER (DER4) were connected to buses 646, 634, 611, and 675, respectively; their injected powers are equal to the load powers with opposite directions; these powers are assumed to be the rated power of generators; the rated voltages are equal to 4.16 kV; the negative sequence admittances of generators: $Y^i = 25\%$ and zero sequence admittance: $Y^0 = 0\%$.

Table 4 New types of three-phase buses of unbalanced power flow

Case	Generator bus type			
	646	634	611	675
1	PQ	PQ	PQ	PQ
2	$P_\Sigma Q_\Sigma$	$P_\Sigma Q_\Sigma$	$P_\Sigma Q_\Sigma$	$P_\Sigma Q_\Sigma$
3	$P_\Sigma V$	$P_\Sigma V$	$P_\Sigma V$	$P_\Sigma V$
4	$P_\Sigma Q_\Sigma I$	$P_\Sigma Q_\Sigma I$	$P_\Sigma Q_\Sigma I$	$P_\Sigma Q_\Sigma I$
5	$P_\Sigma VI$	$P_\Sigma VI$	$P_\Sigma VI$	$P_\Sigma VI$
6	$P_\Sigma I$	$P_\Sigma I$	$P_\Sigma I$	$P_\Sigma I$
7	$P_\Sigma Q_\Sigma V_{sym}$	$P_\Sigma Q_\Sigma V_{sym}$	$P_\Sigma Q_\Sigma V_{sym}$	$P_\Sigma Q_\Sigma V_{sym}$
8	$P_\Sigma V_{sym}$	$P_\Sigma V_{sym}$	$P_\Sigma V_{sym}$	$P_\Sigma V_{sym}$
9	$P_\Sigma V$	$P_\Sigma Q_\Sigma V_{sym}$	$P_\Sigma Q_\Sigma$	$P_\Sigma Q_\Sigma I$

5.1 Power flow verification

In Table 4, all bus types that are used for representing different DERs for this verification are presented. As shown in this table, nine different cases were examined, to clearly verify our claims for the need of introducing new bus types for an accurate representation of the emerging DERs. Each case is explained in detail as follows.

Case 1: the three-phase state is symmetrical in positive sequence. It corresponds to the traditional single-phase power flow. The magnitude of the phase voltage of the slack bus 650 (traditional single-phase θV bus type) is equal to 4.16 kV with an angle equal to zero. The real and reactive powers of all single-phase PQ buses are equal to one third of the sums of given (three-phase, two-phase, single-phase) powers of the corresponding original buses. The control strategies of all DERs are assumed to control real and reactive powers, and they are represented with the traditional PQ bus types in this case. The magnitudes of phase voltages and currents of DERs are presented in Table 5.

Case 2: the three-phase state is unsymmetrical. The symmetry from the Case 1 is disturbed by the loads' real and reactive powers of phases a, b and c. The real and reactive powers of phase a loads are increased for 100%, loads of phases b are saved, and the loads of phases c are nulled. DERs are the same as in the previous case, with the same three-phase powers. However, in this case, the power are not equally distributed per phases, because of an unsymmetrical state of the system. Therefore, in this case, DERs need to be represented with $P_\Sigma Q_\Sigma$ bus types introduced in [89]. The results are presented in Table 6. To illustrate the calculation error that would be made if the

Table 5 Magnitude of phase voltage and current of DERs for Case 1

Phase	Voltage magnitude							
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	I_{DER3} (A)	I_{DER4} (A)
a	4.159	4.191	4.125	4.123	36.816	68.058	26.301	133.909
b	4.159	4.191	4.125	4.123	36.816	68.058	26.301	133.909
c	4.159	4.191	4.125	4.123	36.816	68.058	26.301	133.909

Table 6 Magnitude of phase voltage and current of DERs for Cases 2 and 3

Phase	Voltage magnitude				Current magnitude			
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	I_{DER3} (A)	I_{DER4} (A)
a	3.552	3.660	3.337	3.355	40.614	74.887	27.216	156.202
b	4.289	4.310	4.340	4.360	33.732	63.496	27.216	119.674
c	4.403	4.407	4.461	4.485	38.821	69.997	25.513	138.360

Table 7 Results for unbalanced network where all DERs are represented with single-phase bus types

Phase	Voltage magnitude				Current magnitude			
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	I_{DER3} (A)	I_{DER4} (A)
a	3.575	3.684	3.375	3.398	42.842	77.425	32.161	165.832
b	4.285	4.305	4.331	4.350	35.742	66.261	25.062	129.537
c	4.393	4.397	4.446	4.467	34.860	64.871	24.413	126.109

Table 8 Magnitude of phase voltage and current of DERs for Cases 4–6

Phase	Voltage magnitude				Current magnitude			
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	$I_{DER3\ (A)}$ (A)	I_{DER4} (A)
a	3.526	3.631	3.294	3.308	37.579	69.244	26.901	136.95
b	4.300	4.322	4.357	4.378	37.579	69.244	26.901	136.95
c	4.411	4.417	4.475	4.501	37.579	69.244	26.901	136.95

Table 9 Magnitude of phase voltage and current of DERs for Cases 7 and 8

Phase	Voltage magnitude				Current magnitude			
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	I_{DER3} (A)	I_{DER4} (A)
a	4.097	4.134	4.066	4.086	222.885	83.237	146.714	216.816
b	4.097	4.134	4.066	4.086	73.586	64.728	8.988	124.836
c	4.097	4.134	4.066	4.086	90.354	59.785	78.986	69.154

traditional PQ bus types were used for modeling DERs in this case, Table 7 is presented, in which all DERs are modeled with the single-phase PQ bus types, per each phase. The results are noticeably different if we compare the results obtained in Tables 6 and 7. Therefore, it can be concluded that in unbalanced networks with unsymmetrical states, even the traditional AC machines cannot be represented with single-phase PQ bus types, as it would lead to inaccurate results.

Case 3: this case is derived from Case 2 with the modification of all DER buses from $P_{\Sigma}Q_{\Sigma}$ to $P_{\Sigma}V$ type introduced in [89]. The magnitudes of positive sequence voltages of all DERs are taken from the results of Case 2, as shown in Table 6. The results of this case are the same as the results from Case 2, which verifies the validity of models of $P_{\Sigma}Q_{\Sigma}$ and $P_{\Sigma}V$ bus types.

Case 4: this case is derived from Case 2, but with all DERs switched to IBDERs with the control strategy where the currents can be symmetrical controlled in unsymmetrical network state. Therefore, IBDERs cannot be represented with traditional single-phase bus types, or with the bus types previously introduced in [89]. They need to be represented with the $P_{\Sigma}Q_{\Sigma}I$ bus type, introduced in [102], with $\hat{I}^{-} = \hat{I}^{0} = 0$ ($\hat{Y}^{-} = \hat{Y}^{0} = 0$) from Fig. 3. The results are presented in Table 8. The magnitudes of phase voltages are changed compared to the previous case, and the magnitudes of symmetrical phase currents are mutually equal, which verifies the validity of $P_{\Sigma}Q_{\Sigma}I$ bus types. Again, if we

Table 10 Magnitude of phase voltage and current of DERs for Case 9

Phase	Voltage magnitude				Current magnitude			
	U_{DER1} (kV)	U_{DER2} (kV)	U_{DER3} (kV)	U_{DER4} (kV)	I_{DER1} (A)	I_{DER2} (A)	I_{DER3} (A)	I_{DER4} (A)
a	3.784	4.129	3.579	3.593	39.207	272.8380	29.582	136.436
b	4.201	4.129	4.241	4.263	35.090	36.0183	24.143	136.436
c	4.275	4.129	4.336	4.361	38.331	86.8530	27.074	136.436

compare the results from Tables 8 and 5, it can be concluded that in Case 1 also, the traditional single-phase DER modeling is inadequate for representing IBDERs with this control strategy. Moreover, if we compare results from Tables 6 and 8, it is obvious that the results are different, and therefore these IBDERs cannot be represented with $P_{\Sigma}Q_{\Sigma}$ bus type introduced in [89], but they need to be modeled with the $P_{\Sigma}Q_{\Sigma}I$ bus type introduced in [102].

Case 5: this case is derived from Case 4 with the following modifications—instead of the controlled 3-phase reactive powers, the magnitudes of positive-sequence voltages of all generators are maintained equal to the values calculated in Case 4. Therefore, the generator busses need to be represented with the $P_{\Sigma}VI$ bus type ($\hat{I}^{-} = \hat{I}^{0} = 0$) introduced in [89]. The results are the same as in Case 4 as shown in Table 8, which verifies the validity of the models of $P_{\Sigma}Q_{\Sigma}I$ and $P_{\Sigma}VI$ bus types.

Case 6: this case is also derived from Case 4 with the following modifications—instead of the controlled 3-phase reactive powers, the magnitudes of positive-sequence currents of all generators are maintained equal to the values calculated in Case 4. Therefore, the generator busses need to be represented with the $P_{\Sigma}I$ bus type ($\hat{I}^{-} = \hat{I}^{0} = 0$) introduced in [89]. The results are the same as in Cases 4 and 5, as shown in Table 8, which verifies the validity of the models of $P_{\Sigma}Q_{\Sigma}I$, $P_{\Sigma}VI$ and $P_{\Sigma}I$ bus types.

Case 7: this case is also derived from Case 2 but with all DERs switched to IBDERs with the control strategy where they control their voltages to be symmetrical in the unsymmetrical network state. Therefore, in Case 7, all DERs need to be represented with the $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$ bus type introduced in [102]. The results are presented in Table 9. The magnitudes of phase currents are changed by incorporating this bus type, and the phase voltages are symmetrical, which verifies the validity of the $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$ bus type. By comparing the results from Table 9 with the results from Tables 5, 6, 7 and 8, the conclusion is like that in the previous case. Namely, IBDERs with this control strategy cannot be represented with neither the traditional single-phase bus types, or with $P_{\Sigma}Q_{\Sigma}$ bus type. Rather, they need to be modeled with $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$ bus type.

Case 8: this case is derived from Case 7 with the following modifications: instead of the controlled 3-phase reactive powers, the magnitudes of symmetrical (positive sequence) voltages of all generators are maintained equal to the values calculated in Case 7. Therefore, the generator busses need to be represented with the $P_{\Sigma}V_{\mathrm{sym}}$ bus type introduced in [102]. The results are the same as in Case 7, as shown in Table 9. This verifies the validity of the models of the $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$ and $P_{\Sigma}V_{\mathrm{sym}}$ bus types.

Case 9: this case is derived from Case 2 as well, but it is assumed that every DER employs different control strategy selected from Table 4: bus 646 (DER1)—$P_{\Sigma}V$, bus 634 (DER2)—$P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$, bus 611 (DER3)—$P_{\Sigma}Q_{\Sigma}$, and bus 675 (DER4)—$P_{\Sigma}Q_{\Sigma}I$. The results for this case are presented in Table 10. The phase voltages of DER_2 are symmetrical, and the currents of DER4 are also symmetrical. This additionally verifies the validity of $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$ and $P_{\Sigma}Q_{\Sigma}I$ bus types, introduced in [102]. The results for this case show that different DER control strategies, whether DERs are based on traditional AC machines, as shown in Cases 2 and 3, IBDERs, or DFIMs with additional control strategies to control their voltages or currents to be symmetrical in the unsymmetrical network state, as shown in Cases 4 to 9, can significantly affect the calculation results.

Based on the numerical results, we can find that the traditional single-phase bus classification is far from sufficient for accurate modeling of the emerging systems. From Cases 2–9, the traditional single-phase bus classification cannot be applied for an accurate calculation of unsymmetrical operations of three phase DERs, even for systems with only traditional AC machines. In order to properly take AC machines into account, the traditional bus classification has to be extended by the following three-phase bus types: $(\theta V)_{\Sigma}$ (three-phase slack bus), $P_{\Sigma}Q_{\Sigma}$ and $P_{\Sigma}V$, as shown in Cases 2 and 3 [89]. Moreover, Cases 4–9 show that in order to take emerging DERs into account as well, the aforementioned bus classification has to be further extended, at least by three-phase bus types recently introduced in [102]: $P_{\Sigma}Q_{\Sigma}V_{\mathrm{sym}}$, $P_{\Sigma}V_{\mathrm{sym},}$ $P_{\Sigma}Q_{\Sigma}I$, $P_{\Sigma}VI$, $3\theta V$, and 3PQ, as well as by $P_{\Sigma}I$ bus type [100, 101, 116–118].

From the comparison of the results presented in Table 5 and results presented in Tables 6, 7, 8, 9 and 10, it is obvious that the grid voltages and branch currents are drastically different. This proves the claim from the end of the Section 4.1 that the results of the traditional power flow calculation of emerging unbalanced networks can be highly erroneous. And this highly influences the errors of results of other DMS power applications based on the power flow results.

For further understanding of implementing new bus types in a power flow calculation of large-scale systems, reference [102] provides a good basis.

5.2 SCC verification

For SCC, the transient parameters were used for all DERs. For DFIM, firstly the crowbar protection was assumed. The threshold voltage for the reaction of crowbar was assumed as 70% of the rated voltage at the PCC of DFIM, in accordance with [88]. For the DFIM modeling, the algorithm from [88] was used for determining which model should be used. For the IBDER, it is assumed that the German FRT requirements are imposed, thus the models from [90] were used. Three-phase short-circuits were simulated at busses 671 and 680. The results are presented in Tables 11 and 12 for short-circuits at buses 671 and 680, respectively. The fault current values injected by all four DERs are shown in the tables, as well as their percentage values, compared to the rated values.

Finally, Table 13 shows the results for the case same as for Table 11, but with the chopper used for converter protection of DFIM.

From the presented results, it can be concluded that the synchronous and induction machines in the transient time period inject fault currents that range from 4.60 to 6.53 of the rated currents, depending on the location of the fault. Note that for the sub-transient period, these values are several times higher and can be as high as 30 times the rated currents [1, 5, 6].

Regarding the DFIM, its fault current differs greatly depending on the protection method of converter as well as if it managed to maintain the control or not. For the short-circuit at bus 671 and the crowbar protection as shown in Table 11, the voltage at the PCC of DFIM dropped below the threshold value, which was used for determining the fault severity. In this case, the crowbar reacted and the DFIM lost its fault current control. Therefore, the fault response of DFIM was similar to the induction machine, and its fault current is equal to 5 times its rated value. However, for the short-circuit at bus 680 and the crowbar protection shown in Table 12, the voltage at the PCC of DFIM remained above the threshold value. In this case, the crowbar did not react, and the DFIM maintained its pre-fault current control. Therefore, the fault current magnitude of DFIM was the same as for the rated current. Finally, for the short-circuit at bus 671 and the chopper protection shown in Table 13, the DFIM managed to maintain the predefined fault current control strategy, regardless of the fault severity. In this case, the fault current of DFIM is the same as for the IBDER, and its magnitude is 1.5 of the rated current.

The fault modeling of DFIM is particularly complex, and should be carefully performed. Modeling DFIMs with the induction machine models in all cases, as suggested in [28–30] as well as in international standards [105–107] can cause extremely high errors. As shown in Tables 12 and 13, when the DFIM manages to maintain the fault current control, its current magnitude is between 1 and 1.5 of its rated value, and therefore multiple times lower than when the induction machine model is used. This error could consequently cause an inaccurate setting and coordination of the protection equipment in the distribution system, which can be a disastrous condition as the fault would not

Table 11 Calculation results for three-phase short-circuit at bus 671 (crowbar protection for DFIM)

Fault current	Value (A)	Magnitude (A)	Percentage of rated current (%)
I_{DER1}	59 − j188	261	653
I_{DER2}	170 − j198	297	593
I_{DER3}	103 − j171	200	500
I_{DER4}	36 − j48	60	150

Table 12 Calculation results for three-phase short-circuit at bus 680 (crowbar protection for DFIM)

Fault current	Value (A)	Magnitude (A)	Percentage of rated current (%)
I_{DER1}	53 − j176	184	460
I_{DER2}	− 130 + j157	203	508
I_{DER3}	36 − j17	40	100
I_{DER4}	36 − j48	60	150

Table 13 Calculation results for three-phase short-circuit at bus 671 (chopper protection for DFIM)

Fault current	Value (A)	Magnitude (A)	Percentage of rated current (%)
I_{DER1}	59 − j188	261	653
I_{DER2}	170 − j198	197	493
I_{DER3}	36 − j48	60	150
I_{DER4}	36 − j48	60	150

be cleared and would then cause significant damage of system equipment. For this purpose, using a decision-making algorithm similar to [88] for modeling DFIMs is highly advised, in this way the highly undesirable operating condition explained above would be avoided.

Regarding the IBDER, its fault current is always controlled and dictated by the predefined control strategy (Tables 11, 12, 13). Therefore, its value is always limited and does not exceed 1.5 of the rated current value. Thus, in this case also, using the traditional models would introduce high calculation errors. Therefore, the models with controlled current sources need to be used. Moreover, depending on if the FRT requirements are imposed or not, ratios of active to reactive components of the fault currents of IBDER should be appropriately calculated [88, 90, 111–115], as discussed in Section 4.2.

In [95], a comparison of the SCC method with the models based on the FRT requirements, and the method that uses traditional models, on several large-scale systems is performed and the errors in traditional modeling are clearly shown.

6 Conclusion

This paper is intended as a review paper on the state of the art in DER modeling and what is required of DER models in order that they are useful for future power system planning and operations studies. A large number of the latest papers available in the literature have been reviewed, and a systematic list of challenges for the modeling of DERs is provided and based on this, potential solutions are identified.

Unlike synchronous and induction machines, electronically coupled DERs can implement a wide range of control strategies in both normal and faulted conditions. Therefore, their responses completely differ from the responses of traditional AC machines, and they cannot be represented with the same models.

In the normal operational state, the traditional single-phase bus classification needs to be significantly extended in order to accurately represent emerging DERs in unsymmetrical states, which was thoroughly discussed in the paper. And a list of eleven new three-phase bus types introduced in the recent literature was presented. Finally, a complete list of fourteen bus types is presented and explained—thirteen in Table 3 and the DSB. It is shown that by using these bus types, emerging distribution systems can be represented with high precision, and the calculation errors caused by traditional modeling would be avoided.

Regarding the faulted state of the system, unlike synchronous and induction machines, electronically coupled DERs can control their fault currents. Therefore, these currents are significantly lower than the fault currents of traditional AC machines, and they cannot be represented with the same models. Thus, it is shown in the paper that the calculation error caused by using traditional modeling for current systems could be significant and induce serious issues. Consequently, by using the recently proposed models, based on the FRT requirements, this error would be avoided. Moreover, the traditional way of solving short-circuit problems, by using the passive Δ-circuit cannot be performed in presence of emerging DERs. Therefore, a new concept of Generalized Δ-circuit is explained. It is shown that by using this concept, emerging DERs can be successfully processed in SCC.

In summary, this paper shows that traditional DER modeling can cause high errors when representing emerging distribution systems, and there is an urgent need for changing this distribution system modeling practices in the near future.

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