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Compilation of the FRT grid code in grid-connected power plant under unbalanced conditions

Abstract: - The increasing development of distributed generation sources and the advancement of various technologies have led to great attention being paid to utilizing these sources with different capacities and voltage levels. Therefore, in recent years, the development of standards and requirements such as the Grid Code has received more attention in various countries. In addition to using the generations of these resources to provide the required activities, the ability of these resources to improve grid stability and reliability, especially the fault ride-through capabilities, should also be used. Engineers, legislators, and academics' primary focus has been developing grid codes with an emphasis on balanced conditions. However, more than 98% of the faults in the grid are unbalanced, especially single-phase faults. Therefore, in addition to a detailed study of the gaps in the grid codes of different countries covering unbalanced conditions, this study proposes an approach to develop grid codes under unbalanced conditions and, in particular single-phase faults in the IEEE sample system. Simulation results are evaluated under both balanced and unbalanced conditions for better validation

Keywords: Grid code; Unbalance condition; Distributed generation; Grid connection; unbalanced

I. INTRODUCTION

The American Energy Agency has listed the presence of DGs in the power grid as an important factor in providing ancillary services such as improving power quality, reactive power control, etc. Code grid integration systems to connect distributed production resources to the network in the event of an fault is one of the essential requirements. The grid of the considered codes should provide the ability of FRT and maintenance of distributed generation resources in the grid connected state during voltage drop. Different theories have been proposed to increase the FRT capability of DG connected to the grid so that, based on the new grid codes, converters connected to the grid should be able to face different faults in the grid. Voltage stability by injecting reactive power and providing active power in the event of a fault is one of the goals of keeping DGs connected to the grid. Balanced conditions have been investigated in many references, which have resulted in voltage stability and system fault resolution by providing two-stage control. By using the linear approximation of the nonlinear DG model, the amount of generated power has been reduced during the occurrence of a fault, and by providing a nonlinear controller, the amount of voltage in the DC link has been kept constant during the operation of the system. The deep voltage drop has led to the passage of intense transient currents through the power electronic converter and the increase of the capacitor voltage on the DC side, so the transients imposed on the power electronic converter must reach the minimum necessary value so that the DG can during and after from fixing the fault while connected to the network and play an important role in the stability of the network. A large group of faults that occur in the power grid are asymmetric faults. Asymmetrical voltage sags are milder than symmetric voltage sags in terms of the intensity of the transient effect on the transient response at the moment of the fault occurrence, but due to the presence of the negative sequence component of the voltage, during the entire duration of the fault, oscillations with a frequency twice the network frequency appear in the transient response. In the case of voltage imbalance, real/reactive power and capacitor voltage can be controlled by controlling the positive sequence currents of the

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converters on the DG side and the grid side. If by controlling the negative sequence currents of the converters, it is possible to remove some of the adverse effects that the grid voltage imbalance has on the operation of the generator, and the use of negative sequence current control eliminates the output power ripple with a frequency twice the network frequency.

Nowadays, the leading countries in the field of renewable energies are developing some grid codes that are related to the study results of each country's system and sometimes several countries to supply some part of their energy. Until 2017, when the German grid code development committee presented VDE-4120, VDE-4110, and VDE-4105 at high-voltage, medium-voltage, and low-voltage levels, respectively [1-3], all developed grid codes by different countries and committees assumed balanced conditions as a criterion for connecting renewable resources to the grid. One of the main reasons that most of the studies are conducted based on the balanced three-phase fault in the grid codes, was the high short-circuit level of the three-phase fault compared to other faults. However, over time, the problems with unbalanced conditions and the inapplicability of developed codes led to the continuous updating of the grid codes at shorter intervals. The purpose of this review is to provide practical tips for grid code developers, power system operators, engineers in contractor design and system study departments, and consulting firms. It also includes important information on the evolution of published articles in this field, a thematic study of the interests of academic researchers worldwide in this field, the classification of the significant journals in this field with the most published articles, and the comparison of the share of developed grid code in research by the academic community for academic researchers. The review of published articles in IEEE journals indicates that the academic community pays great attention to the study of unbalanced conditions and the provision of key solutions to overcome this problem and exploit the potential of these resources. Therefore, it is necessary for legislative departments and the Ministry of Energy to act as facilitators and seriously pursue the relationship between industry and academia to close the relatively large gap (between developed grid codes and academic research) that has been created and lead to the development of a comprehensive grid code.

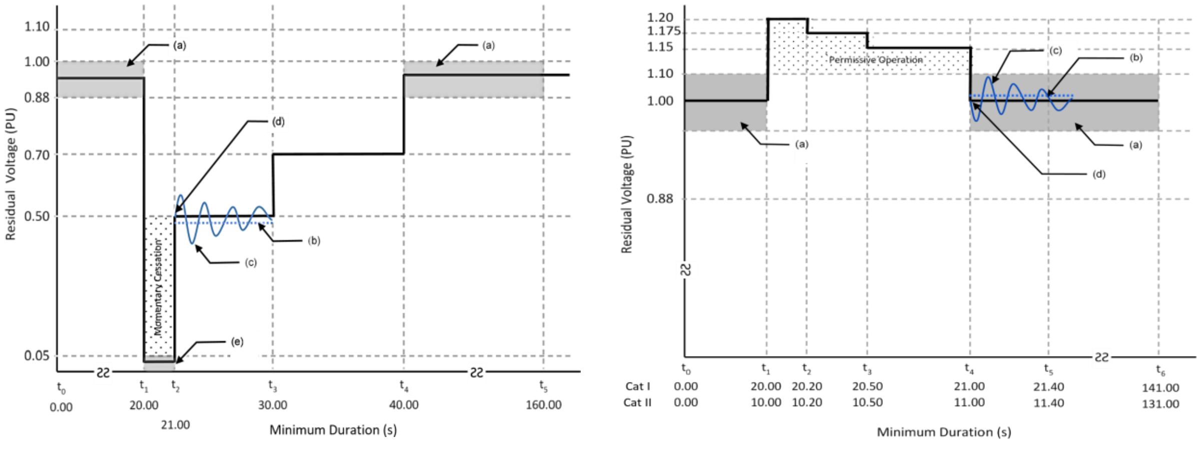
Unbalance conditions (imbalance faults, unbalanced grid, and unbalanced load) are an important issue in power systems. Therefore, the development of a grid code with dynamic response capabilities and requirements for unbalanced conditions is very important for power system operators. Maintaining the connection of renewable resources to the grid sets the stage for improving the stability, reliability, and operation of the system. In the category of imbalance, several grid codes were developed, with titles such as Measurement of unbalanced quantities in the power system, which have mention the value of harmonic voltage distortion and the percentage of imbalance (the ratio of negative to positive voltage sequence) less than 0.1%. The values for low voltage grid are 1 and 0.4%, respectively [4]. E.ON does not address the issue of imbalance, nor does it mention the percentage of imbalance [5]. The reference [6-7] to the Danish Grid Code does not address the issue of imbalance and harmonics and cites the standards IEEE 1459, IEC 61000-3-13, and IEC 61000-3-14 [8-9]. In these standards, the basis for discussing imbalance is the calculation of the imbalance coefficient, and the suggested numerical value is 2%.

In some cases where single-phase loads are connected to the system, imbalance factor value is 3%. Apart from mentioning these cases, the issues related to fault ride-through in unbalanced conditions and the requirements of the grid code in the imbalance fault condition are not considered. In the EN50160 standard and CIGRE WG36-05 report, the imbalance is classified as the percentage of even and odd harmonics (multiplier 3 and others). Here, the highest limit for the fifth harmonic is 6% and the lowest limit for the even and odd harmonics is 0.2% and a multiplier of 3, which includes harmonics 10, 25, and 21 [10-11]. The European standard and grid code EN 50438:2013 did not address the imbalance issue, and no suggestion was made. However, in the update of the standard EN 50549:2019, when discussing imbalance in the negative and zero sequences current section, no suggestion was made, and the DSO was asked to choose the best protection setting. As a result, the total imbalance current of single-phase distributed generation plants connected to the distribution grid should be up to 16 Amperes [12-13]. The Italian Grid Codes CEI 0-16 and CEI 0-21 were developed in the low voltage sector and did not contain sections related to imbalance [14-15].

The Federal Energy Regulatory Commission, did not address the imbalance in No. 661, No. 2003, and No. RM02-1 001, did not address the discussion of imbalance and only refers only to the relevant cases under balanced conditions [16-18].

According to the systematic studies and the development of grid codes in the committees of different countries, different topics were important in the articles of different authors. In this article, which includes a review of all IEEE journal articles, we first introduce grid codes and their explanation and finally consider the challenges of grid codes under unbalanced conditions. Before turning to the section on reviewing the articles and categorizing the subsections of the survey, we extract and provide an overview of the issues that arise with unbalanced grid codes. To summarize the introductory section, all cases of imbalances are listed in the vertical column of a table, the name of the grid code developing country is given in the horizontal column, and the extent of grid code coverage of each country is indicated in the imbalance section.

In Figures 1, the conditions related to LVRT and HVRT according to IEEE 1547.1-2020 are mentioned for compiling the FRT grid code. So that in each figure, the symbols (a) to (e) represent (a) any voltage between 1.00 p.u. and 0.88 p.u. is permitted, (b) average of the rms voltage throughout excursion, (c) example of positively damped voltage oscillations allowed during testing, (d) DER shall restore output within 0.400 seconds following momentary cessation, i.e., following time t2 and (e) any voltage less than 0.05 p.u. is permitted.



(A) (B)

II.

Fig 1. The LVRT (a) and HVRT (b) test condition for compiling of grid codes

In Table 1, the grid codes and standards of 34 countries were analyzed for imbalance faults. The mentioned grid codes in published articles in 2008 were examined for imbalance, with a focus on them by academic research.

Table 1.Review grid codes and standards used in articles emphasizing asymmetric faults

Table Coloring Guide			
🟡	The item in question is generally .presented with numbers	🔴	The item in question is not mentioned .in the standard
🟢	The item is presented in the form .of calculation formulas	🟠	The item in question has been .thoroughly examined
🩷	According to and GB/T 14549 GB/T 19963	🟣	According to IEC 60034-1 , IEC 63000-3-3,11
🟩	According to IEEE 1453	🔵	It was only a general reference and there are no technical details about it

`year	Grid Code	Reference	Asymmetric faults			
			1-phase Fault	2-phase Fault	1-phase Connected	Positive/Negative Sequence
2011	VDE-4105	[1]	🔴	🔴	🔴	🔴
2017	VDE-4110	[2]	🔴	🟠	🔴	🟠
2017	VDE-4120	[3]	🔴	🟠	🔴	🟠
2010	IEEE 1459	[4]	🔴	🔴	🔴	🟠
2006	E. ON	[5]	🔴	🔴	🔴	🔴
2016	DENMARK -PV	[6]	🔴	🔴	🔴	🔴
2016	DENMARK-WIND	[7]	🔴	🔴	🔴	🔴
2008	IEC61003-13	[8]	🔴	🔴	🔴	🟢
2011	IEC61003-14	[9]	🔴	🔴	🔴	🟢
2010	EN50160	[10]	🔴	🔴	🔴	🟠
1981	CIGRE	[11]	🔴	🔴	🔴	🟠
2013	EN50438	[12]	🔴	🔴	🔴	🟠
2019	EN50549	[13]	🔴	🔴	🔴	🟠
2016	CEI0-21	[15]	🔴	🔴	🔴	🔴
2005	Order 661	[16]	🔴	🟡	🔴	🔴
2004	Order 2003	[17]	🔴	🔴	🔴	🔴
2005	Order RM02-001	[18]	🔴	🔴	🔴	🔴
2006	SPANISH	[19]	🔴	🔴	🔴	🔴
2017	U.K	[20]	🔴	🔴	🔴	🔴
2014	IRELAND	[21]	🔵	🔵	🔴	🔴
2019	HYDRO QUEBEC	[22]	🔴	🔴	🔴	🔴
2007	NORDIC	[23]	🔴	🔴	🔴	🔴
2013	ENTSO	[24]	🔴	🔴	🔴	🔴
2009	CHINA	[25]	🔴	🔴	🔴	🩷
2019	MEXIC	[26]	🔴	🔴	🔴	🔴
2018	AUSTRALIA	[27]	🔴	🔴	🔴	🔴
2021	N.A	[28]	🔵	🔵	🔵	🔵
2016	IRENA	[29]	🔴	🔴	🔴	🔴
2002	SWEDEN	[30]	🔴	🔴	🔴	🔴
2014	GREEK	[31]	🔴	🔴	🔴	🔴
2018	IEEE 1547	[32]	🔴	🔴	🔴	🔴
2016	Regulation 2016/631	[33]	🔴	🔴	🔴	🔴
2010	INDIAN	[34]	🔴	🔴	🔴	🔵

III. THEORETICAL BACKGROUND

The developed grid codes are generally derived from the actual conditions of the grid and power system and use a standard or special instruction to satisfy the constraints and operating conditions. These constraints are mainly set by the grid operators of different countries and the standards development committee. In this regard, the grid code development committee has generally developed grid codes based on the standards and the results of system studies, taking into account numerous parameters, each of which significantly impacts the characteristics of the power system. These codes not only served as guidelines for the operation of the grid under various conditions and faults but also took into account the expansion of renewable energy as one of the main challenges for the power systems from the point of view of whether they remain connected to the grid or disconnected from it. When faults occur, grid codes are crucial. According to the above aspects, the steps to develop grid codes can be categorized as follows:

1- To develop grid codes, it is necessary to obtain the desired information about the grid, its structure, and topology changes (system studies step)

It is necessary to obtain complete information about the grid in terms of equipment and control structure and, if possible, the desired grid data from the studied areas power system.

Developing a grid code for a certain period (e.g., five years) is necessary. Therefore, grid development plans should be obtained in a specific time frame so that the developed network code is consistent with future development plans.

Changes in topology mean disconnecting and connecting switches, disconnecting and connecting a line, adding new feeders, changing the capacity of transformers, etc.

2- Standards for balanced and unbalanced conditions should be derived.

Concerning the grid under study, the reference standard for the study of unbalance must be defined (IEC and IEEE).

The numerical value of the unbalanced factor (the ratio of the modulus of the negative-sequence to the positive-sequence components) must be determined based on standard definitions.

It is assumed that at the time of design, implementation, and testing of the grid under study, all devices complying with the standard have developed with the maximum unbalances according to the standard and are within the allowable limit.

3- The maximum unbalance caused by power generation sources is determined by assuming the maximum unbalance specified in the standard at both ends of each load on the grid and by performing system studies. (Combination of steps 1 and 2)

Performing load flow assuming unbalanced loads (e.g., in an unbalanced grid, the voltage at one of the busses should be equal to the maximum unbalance specified in the standard)

In the discussion of single-phase connection to the distribution grid in the presence of dispersed single-phase PV generation sources, the PV capacity is determined by not exceeding the maximum unbalance limit (worst case).

The conditions for performing the above study are carried out in the first step in a distribution grid with unbalanced generation and unbalanced loads or micro grids.

Perform unbalanced load flow studies using DIGSILENT Power Factory software with unbalanced load flow, provided that none of the standard conditions are violated.

4- It should be noted that the grid codes result from a combination of system studies in compliance with the restrictions and limitations specified in the standard. However, the purpose of their use is to facilitate the Gird integration of power generation, consumption and transmission systems. The Grid Codes are used so that stakeholders are aware of their legal obligations without conducting system studies and referring to the standards.

According to the Grid Codes development steps, system studies must ask two important questions: According to the catalogue, the first question is whether the new power plant is operating under unbalanced conditions, and the second question is to identify the main short-circuit factor or factors that cause the power plant to fail. Considering the above questions, the grid code development committees should use the simulation results as a criterion for developing the grid code.

In the grid code, the voltage of the busses indicates which critical power plant has been taken out of the circuit, and we consider this voltage and proceed in the same way to identify the critical power plant whose failure causes a blackout. Critical events are the main factors that cause a power plant to go out of the circuit. Depending on operating experience, faults and events such as line failures and other factors may be used as criteria for investigation. From the point of view of active power, the grid code is frequency control; from the point of view of reactive power, it is voltage control; and discussions on power quality, harmonics, and flicker are also added to special studies in the field of distribution grids. Our goal is that after identifying the critical event and the critical power plant, the FRT characteristics are relaxed until this critical power plant is no longer out of the circuit. Generally, the system studies of the different parts are performed until the weakest power plant is identified and the slope characteristic of the fault ride-through requirement curve is not less than this value so that the said power plant does not fall out of the circuit. After that, the remaining and new power plants must match the characteristics of the developed grid code to be connected to the grid. The algorithm in Figure 2 shows the steps of developing the grid code considering the information about the power system equipment parameters in balance conditions.

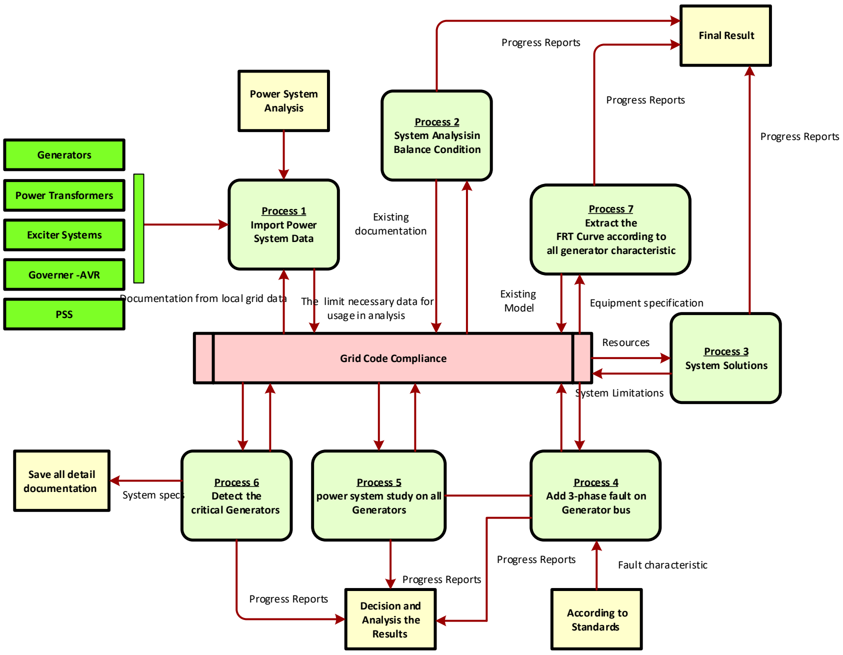


Fig.2 Grid code compliance in balance conditions

The nonlinear equation of oscillation governing this system in Pre fault (equations 1,2), fault (equations 3,4) ,and post-fault (equation 5):

$$\begin{cases} P_m = P_0 \\ P_e = P_{mox} \sin \delta \end{cases} \qquad 1$$

$$P_{mox} = \frac{|E||V_\infty|}{\sum x} \quad , \quad \delta_0 = \sin^{-1} \frac{P}{P_{mox}} \quad , \quad P = P_e = P_m \qquad 2$$

$$\begin{cases} \dfrac{\partial^2 \delta}{\partial t^2} = \dfrac{\omega_0}{2H}\left(P_0 - P_e\right) \\ P_e = 0 \end{cases} \quad with \ : \ \begin{cases} \delta\left(0\right) = \delta_0 \\ \dfrac{d\delta}{dt}\left(0\right) = 0 \end{cases} \qquad 3$$

$$\delta\left(t\right) = \frac{\omega_0}{4H} P_0 t^2 + \delta_0 = f\left(t\right) \qquad 4$$

$$\frac{\partial^2 \delta}{\partial t^2} = \frac{\omega_0}{2H}\left(P_0 - P_e\right) = \frac{\omega_0}{2H}\left(P_0 - P_{mox} \sin \delta\right) \quad with : \ \begin{cases} \delta\left(0\right) = f\left(t = T\right) = \dfrac{\omega_0}{4H} P_0 T^2 + \delta_0 \\ \dfrac{\partial \delta}{\partial t}\left(0\right) = f'\left(t, T\right) = \dfrac{\omega_0}{2H} P_0 T \end{cases} \qquad 5$$

Equation 5 is a nonlinear differential equation with initial conditions. To obtain the function V, we multiply $\frac{\partial \delta}{\partial t}$ the sides of the equation 5. According to $M = 2H$ is the moment coefficient. Now we take the integral from the sides of the relation (6):

$$M \frac{\partial^2 \delta}{\partial t^2} \times \frac{\partial \delta}{\partial t} - \omega_0 \left(P_0 - P_{mox} \sin \delta\right) \frac{\partial \delta}{\partial t} = 0 \qquad 6$$

$$V = \int_{\delta_0}^{\delta} M \frac{\partial^2 \delta}{\partial t^2} . \frac{\partial \delta}{\partial t} - \omega \int_{\delta_0}^{\delta} \frac{\partial \delta}{\partial t} \left(P_0 - P_{mox} \sin \delta\right) = cte. \qquad 7$$

$$V\left(\delta, \dot{\delta}\right) = \frac{1}{2} M \left(\frac{\partial \delta}{\partial t}\right)^2 - \omega_0 \left(P_0 \left(\delta - \delta_0\right) + P_{mox} \left(\cos \delta - \cos \delta_0\right)\right) = E_K + E_P = cte. \qquad 8$$

$$\delta\left(T\right) = \frac{\omega_0 p_0}{2M} T^2 + \delta_0 \ , \ \dot{\delta}\left(T\right) = \frac{\omega_0 P_0}{M} T \qquad 9$$

$$V\left(\delta\left(T\right), \dot{\delta}(T)\right) = \frac{1}{2} M \left(\frac{\omega_0 P_0}{M} T\right)^2 - \omega_0 \left\{ P_0 \left(\frac{\omega_0 P_0}{2M} T^2\right) + P_{mox} \left(\cos\left(\frac{\omega_0 P_0}{2M} T^2 + \delta_0\right) - \cos \delta_0\right)\right\} \qquad 10$$

At time t=T, the time to fix the defect (third stage), with the initial conditions of relation 9, the energy function will be according to relation 10. This relationship shows the sum of kinetic energy and potential when disconnecting and connecting the line, which is a constant value.

$$\nabla V = \begin{bmatrix} \dfrac{\partial V}{\partial \dot{\delta}} \\ \dfrac{\partial V}{\partial \delta} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial E_k}{\partial \dot{\delta}} \\ \dfrac{\partial E_P}{\partial \delta} \end{bmatrix} = \begin{bmatrix} M\dot{\delta} \\ -\omega_0 \left(P_0 - P_{mox} \sin \delta\right) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad 11$$

$$H = \begin{bmatrix} \dfrac{\partial^2 V}{\partial \dot{\delta}^2} & \dfrac{\partial^2 V}{\partial \dot{\delta}\ \partial \delta} \\ \dfrac{\partial^2 V}{\partial \delta\ \partial \dot{\delta}} & \dfrac{\partial^2 V}{\partial \delta^2} \end{bmatrix} = \begin{bmatrix} M & 0 \\ 0 & \omega_0 P_{mox} \cos \delta \end{bmatrix} \qquad 12$$

$$\dot{V} = \frac{dV}{dt} = \frac{dE_k}{dt} + \frac{dE_P}{dt} \qquad 13$$

$$\frac{dE_k}{dt} = \frac{dE_k}{d\dot{\delta}} \times \frac{d\dot{\delta}}{dt} = M\dot{\delta} \times \frac{d\dot{\delta}}{dt} = M\frac{d^2\delta}{dt^2} \times \dot{\delta} = \omega_0\left(P_0 - P_{mox}\sin\delta\right)\dot{\delta} \qquad 14$$

$$\frac{dE_P}{dt} = \frac{dE_P}{d\delta} \times \frac{d\delta}{dt} = -\omega_0\left[P_0 - P_{mox}\sin\delta\right]\dot{\delta} \qquad 15$$

$$V_{cr}\left(\delta, \dot{\delta}\right) = V\left(\delta_u = \pi - \delta_0, 0\right) = \omega_0\left[2P_{mox}\cos\delta_0 - P_0\left(\pi - 2\delta_0\right)\right] \qquad 16$$

$$V_{cl}\left(\delta\left(T\right), \dot{\delta}\left(T\right)\right) = \frac{M}{2}\left(\frac{\omega_0 P_0}{M}T\right)^2 - \omega_0\left[P_0\left(\frac{\omega_0 P_0}{2M}T^2\right) + P_{mox}\left(\cos\left(\frac{\omega_0 P_0}{2M}T^2 + \delta_0\right) - \cos\delta_0\right)\right] \qquad 17$$

$$\Delta V = V_{cr} - V_{cl} > 0\ ,\ V_{cr} - V_{cl} = 0\ ,\ k = \frac{V_{cr} - V_{cl}}{V_{cr}} \qquad 18$$

The system is stable when first part of relation 18 is established, and the stability margin can be described in third part of relation 18. The greater the value of k, the greater the margin of stability

IV. SIMULATION RESULTS

A. *Validation*

To validate the approach proposed in Section 2, the curves of the grid code requirements according to PRC-024 WECC, PRC-024 ERCOT, and IEEE1547-2018 in the states of voltage variations (voltage rise and fall) ride-through and frequency variations ride-through are shown in Figure 3. Then, the curves of grid requirements according to the IEEE 1547-2018 standard for the simulation of different power plant generators are shown in Figure 4 based on IEEE. In Figures 3 and 4, the voltage and frequency variations curves according to the developed grid codes differ in voltage range, frequency and time and have different slopes. Based on the changes in the slopes of the curves, the areas connected to the grid or disconnected from the grid for distributed generation sources are shown.

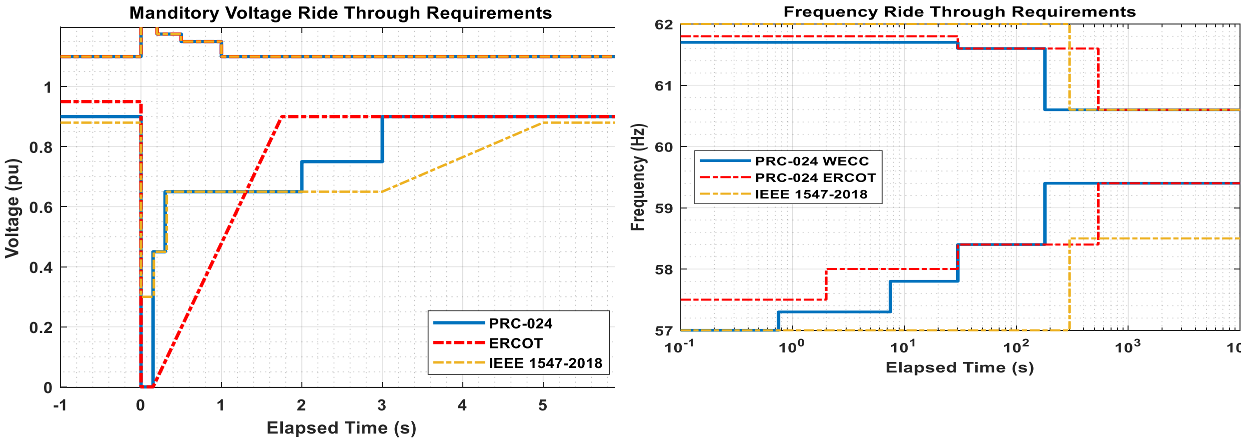


Fig3. Grid code requirements curve based on PRC-024 WECC, PRC-024 ERCOT and IEEE1547-2018 standard

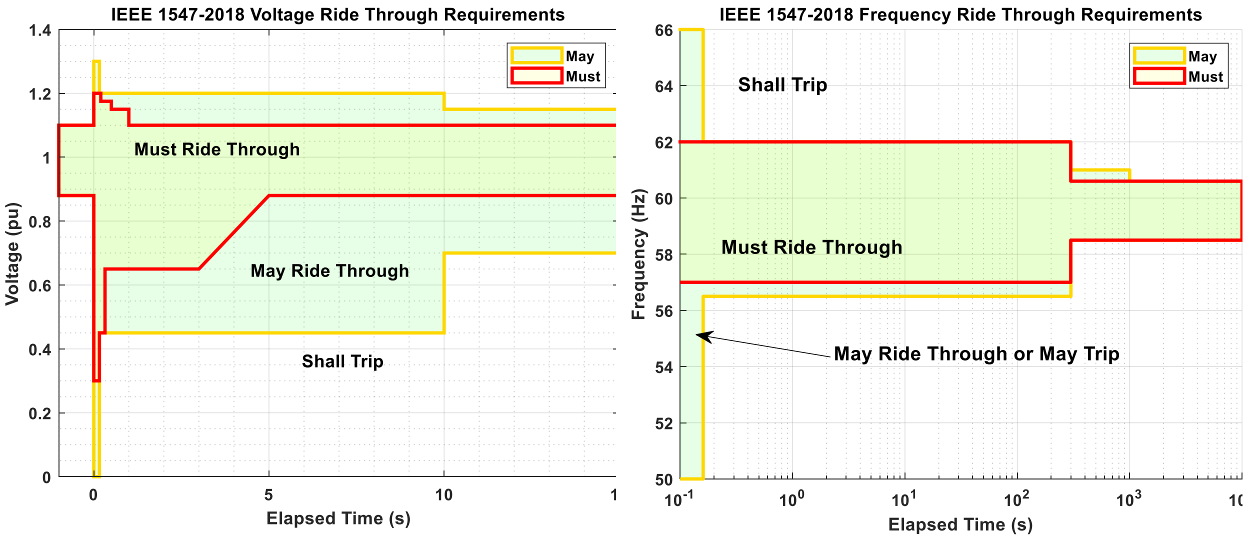
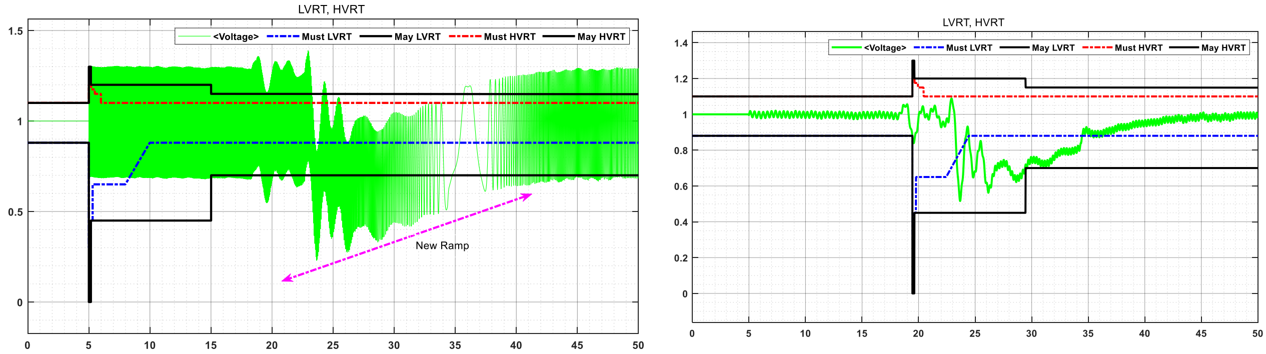


Fig 4: Curve requirements of grid code to ride through of voltage and frequency changes according to IEEE1547-2018 standard

B. *Simulation of different power plants to derive grid curves*

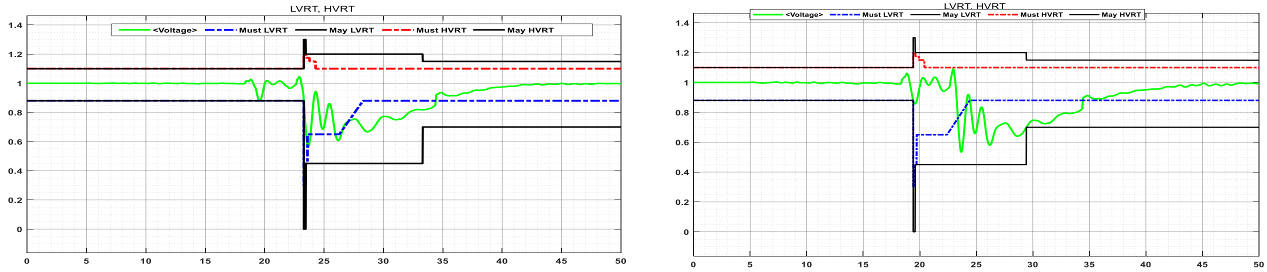
In this context, Figure 5 shows the implementation process of deriving grid code requirements for different types of renewable and non-renewable power plants considering the constraints of the IEEE 1547-2018 standard for gas, hydro, solar, and wind power plants.

It should be noted that in the development of grid codes, many factors, such as the capacity of power plant resources and the characteristics of generators and transformers, as well as the level of short circuits and the type of short circuit, are effective factors in deriving the fault ride-through characteristics. In this section, the results considering a balanced three-phase fault are considered.



Hydropower

Gas power plant



Wind power plant

Solar power plant

Fig 5. Derivation of the grid code requirements curve in different power plants according to the effective voltage in the PCC bus

As shown in Figure 5, the voltage variations based on the voltage rise and drop ride-through curve are within the allowable limits of the IEEE 1547-2018 standard, so the grid code requirements in Figure 3 can be considered acceptable for the simulated power plants. However, due to the hydropower plant's characteristics, the IEEE curves' requirements do not comply with the mentioned changes. If these requirements are followed, the hydropower plant must be disconnected from the grid. This leads to frequency and voltage instabilities in the power system. Therefore, the grid code development committees should reduce the above problems by continuously monitoring and updating the grid codes. As mentioned in Section 3, the occurrence of a critical fault and the determination of the critical power plant is very important for maintaining the stability of the grid and are among the most important studies in the development of grid codes considering the criteria of stability, reliability, and flexibility of the grid against common faults. The results of individual simulations of different power plants with PCC show that the approach to developing the grid code is valid and complies with the standard. The curve of voltage variation is drawn at a balanced three-phase fault. After this validation, subsections 3-3 and 3-4 analyze the results and simulation in the IEEE 118-bus modified system to derive the characteristic curve and grid code development under the balanced three-phase and single-phase fault conditions.

C. Grid code development under balanced conditions (three-phase fault)

The IEEE test grid is selected to implement the proposed approach in a real sample grid. Since the existing grid codes and the focus of their development committee are on balanced conditions, this section first examines the balanced three-phase fault. Due to the importance and the greatest effectiveness of the power plants connected to the grid, the application of the three-phase fault in the generator busses is studied, so the strictest conditions where none of the power plants are interrupted are the criteria for code development. It is also clear that the grid's stability suffers when one of the critical and high-power generators fails. Therefore, a more comprehensive study of other grid parameters, including transient and dynamic stability, is needed. In this study, the case where all generators are connected to the grid is considered an exception in order not to change the conditions of the existing grid, so the connection of new power plants to the grid depends on the stability and improvement of the grid. The schematic diagram of the simulated grid is shown in Figure 6.

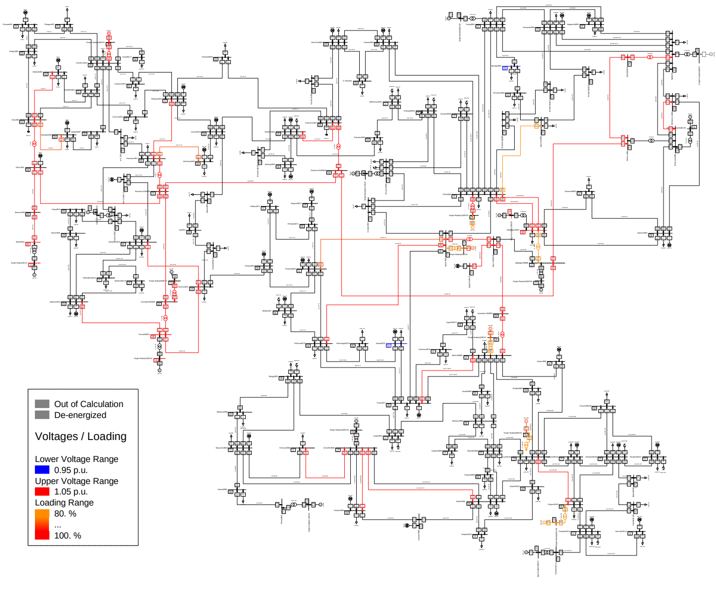


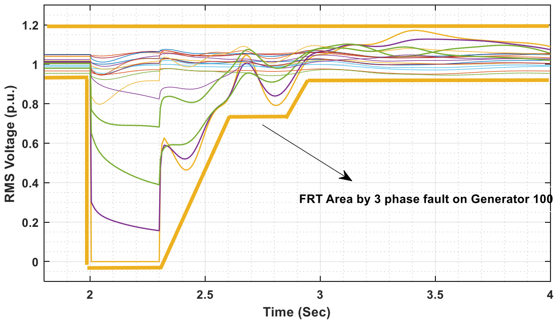
Fig 6: IEEE Extended 118 Bus Network Schematic

IEEE 118-bus modified test system includes 54 synchronous machines with IEEE type 1 excitation system, 20 synchronous compensation machines for reactive power compensation, and 15 motor machines. There are also 172 busses, 185 transmission lines, 76 transformers, and 91 fixed impedance loads, totaling 3668 MW and 1438 MVAR. Table 2 shows the specifications of the generators, the rated capacity, and the voltage levels of each generator. Considering the voltage level, the level of capacity, and the effect that the presence or absence of a power plant has on the stability of the entire grid, the decision process for determining the FRT characteristic can be determined.

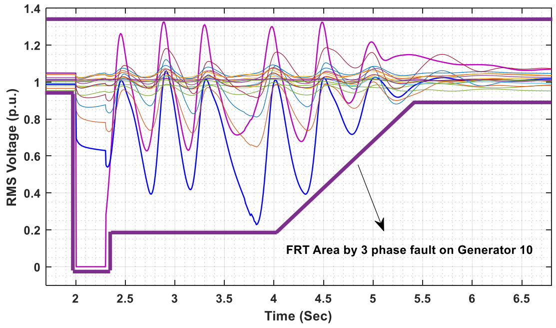
Table 2. Specifications and nominal capacity of generators

	Name	MVA	PF	KV	BUS
1	Gen 10 (590 MVA)	590	0.95	22	B119
2	Gen 100 (330 MVA)	330	0.9	20	B135
3	Gen 103 (100 MVA)	100	0.8	13.8	B136
4	Gen 111 (100 MVA)	100	0.8	13.8	B137
5	Gen 12 (125MVA)	125	0.85	15.5	B120
6	Gen 25 (330 MVA)	330	0.9	20	B121
7	Gen 26 (410 MVA)	410	0.9	24	B122
8	Gen 31 (75 MVA)	75	0.8	13.8	B123
9	Gen 46 (75 MVA)	75	0.8	13.8	B124
10	Gen 49 (330 MVA)	330	0.9	20	B125
11	Gen 54 (100 MVA)	100	0.8	13.8	B126
12	Gen 59 (233 MVA)	233	0.85	20	B127
13	Gen 61 (233 MVA)	233	0.85	20	B128
14	Gen 65 (512 MVA)	512	0.9	24	B129
15	Gen 66 (512 MVA)	512	0.9	24	B130
16	Gen 69 (590 MVA)	590	0.95	22	B131
17	Gen 80 (590 NVA)	590	0.95	22	B132
18	Gen 87 (75 MVA)	75	0.8	13.8	B133
19	Gen 89 (835 MW)	835	0.9	20	B134

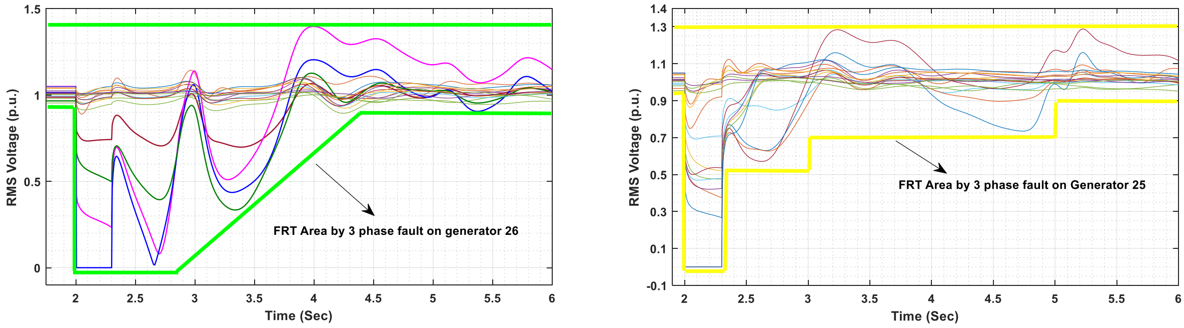
To determine the FRT characteristic under balanced conditions, a three-phase fault generator bus is considered with a time of 0.3 s, corresponding to the maximum operating time of the relays and protection devices. In each of the studies, this generator is taken off the grid according to the worst case and the corresponding diagram so that the curve of FRT can be considered under relaxed conditions; otherwise, in case of instability, the same diagram is used as the final diagram. The characteristic of FRT is considered in this case study. The simulation is done by applying a three-phase fault in 2 s, then the fault is fixed after 0.3 s in 2.3 s, and the total simulation time is 10s.



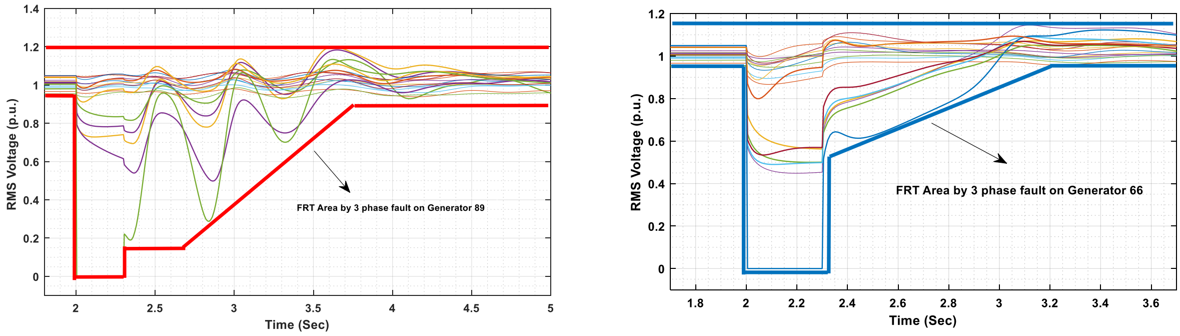
Generator 100



Generator 10



Generator 26 Generator 25



Generator 89 Generator 66

Fig 7. Changes in the voltage curves of the generator buses under the application of a three-phase fault in the candidate generator bus

According to the number of generators and their busses from Table 1, for brevity, only the diagram for the worst-case conditions of the generators is given, on which the criterion for developing the grid code for the IEEE sample grid is based. According to the output of DIGSILENT Power Factory and the results of the simulation of the three-phase short-circuit that occurred in generators No. 10, 100, 25, 26, 66, and 89, there are significant changes in the voltage curve, and consequently, there is a need for a grid code.

The changes in the voltage curves of the generator buses when there is a three-phase fault in the bus of the candidate generators, are shown in Figure 7. Based on the different curves of the mentioned generators compared to 13 other generators, the criterion of code development is selected for these generators. Based on the results in Figure 7, the voltage and fault requirements curve in Figure 8 is derived for each of the generators in Figure 7. Finally, the diagram related to the combination of generators 25 and 89 is selected as the final curve of grid code requirements in the IEEE 118-bus grid.

According to Figure 8, the black curve is derived and developed as the final grid code of the IEEE 118-bus extended grid under a balanced three-phase fault. It should be noted that in this section, according to the final derivation of the black curve as the curve for the fault ride-through requirement, each distributed generation source of any capacity must be connected to the grid according to the said curve and be in the state of being connected to the grid or disconnected from the grid. In the following, the simulation was carried out with the inclusion of two distributed generation sources with a lower and a higher capacity than the existing IEEE grid power plants. In the first case, with a lower capacity source, the voltage variations are within the allowable limits, and there is no need to change the developed curve. However, in the second case, where the distributed generation source has a higher capacity, the voltage variations have responded to the black curve, and there is a need to develop a new grid code for this case or disconnect one of the existing generators from the grid. This issue should be determined by the grid code development committee considering other dynamic parameters

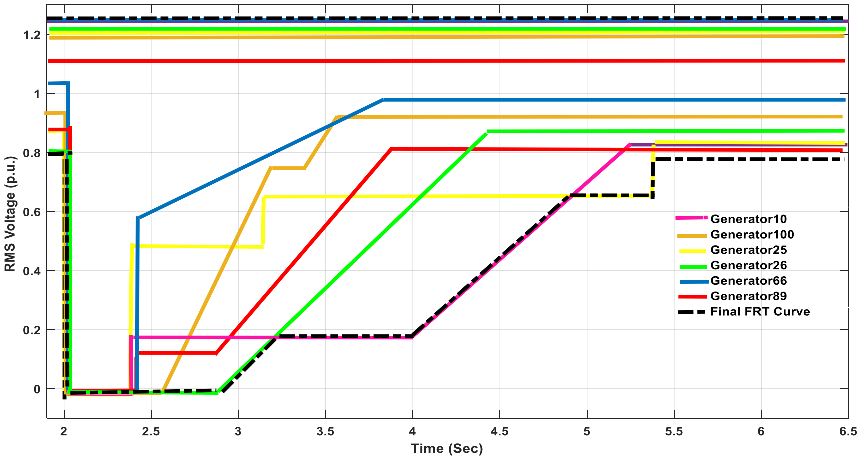


Fig 8. Extracted grid code requirement curve in IEEE 118-bus grid candidate generators

D. *Grid code development under unbalanced conditions (two-phase and single-phase fault)*

Considering that most of the grid faults are of unbalanced type, the algorithm and process of extracting the grid code according to the unbalanced error have been investigated and simulated in this section. The algorithm of Figure 8, which is developed from the algorithm of Figure 1, has two basic changes compared to the balanced state; firstly, the second stage process has balanced and unbalanced power system analysis, and the fourth stage process has three sections, including balanced three-phase faults, two-phase

Furthermore, a single-phase fault, which should be evaluated at the end of the analysis of each of these faults according to the processes of steps 5 and 6, and after saving the results and executing process 8, the output curve of the FRT in the unbalanced state will be published to extract single-phase and two-phase faults.

According to the algorithm approach of Figure 9, the simulation results of generator 26 are shown in Figure 10. As was shown in sections 3-3 on how to obtain the FRT curve in the balanced state, in this section, the output results under single-phase, two-phase and three-phase faults are shown in Figure 10. It should be noted that the FRT curve, according to the grid conditions and the parameters of different equipment and their positive and negative sequences, is influenced by the unbalanced error, which is sometimes dominated by the single-phase error. In Figure 9, the two-phase error directly affects obtaining the FRT curve's slope.

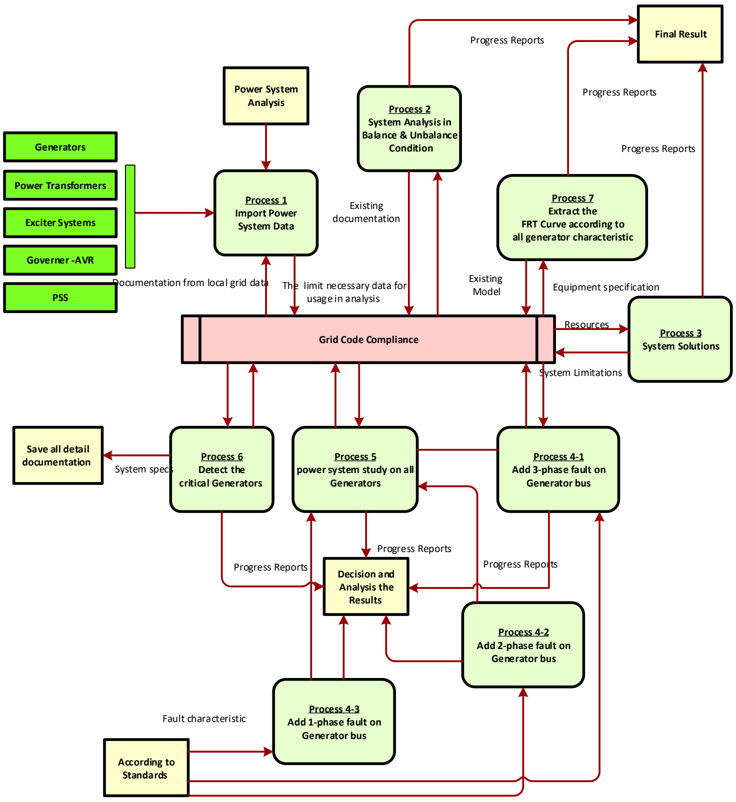


Fig 9. Grid code compliance in unbalance conditions

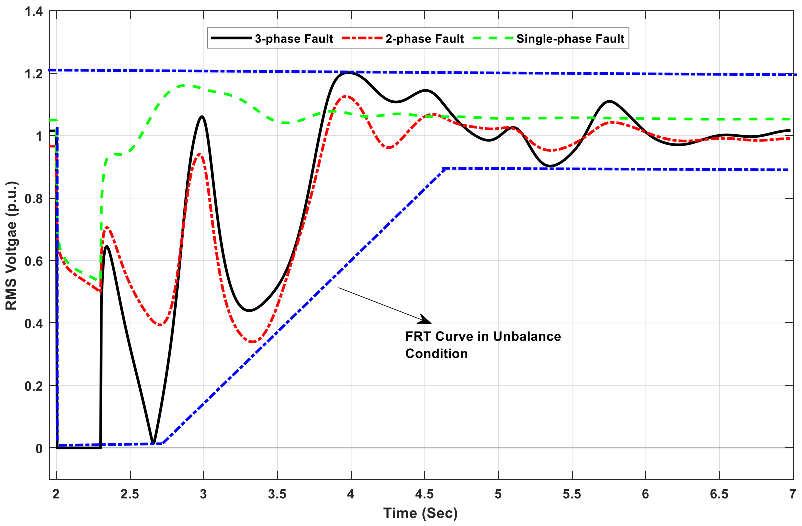


Fig 10. Extracted grid code requirement curve in generator 26 in unbalance condition

V. CONCLUTION

Considering the demand and expansion of renewable energy, it is necessary to constantly modify and revise the grid codes and the requirements curves of the grid code. Therefore, power system planners and operators must propose a grid code development approach in each study. Then, the IEEE test grid was selected to implement the method in a real grid. Assuming a balanced fault, the results under different scenarios were derived by applying faults in the generator busses and led to the development of a balanced grid code. The results are re-evaluated by developing the mentioned curve by connecting the renewables with different capacities. Finally, considering the importance of developing the grid code under unbalanced conditions due to the inclusion of critical grid faults of the unbalanced type, all the steps of developing the grid code under single-phase faults in the generator busses are replicated, and the results and fault ride-through requirement curve under single-phase faults for the IEEE 118-bus grid are presented.

In this article, the following results were obtained according to the approach of extracting and determining the grid code.

- According to symmetric and asymmetric faults, grid codes were categorized in this respect.
- The approach of determining the grid code in a large power system was presented.
- According to the dynamics of the generators, the inertia factor was determined as the most essential characteristic in determining the FRT curve.
- According to the study of asymmetric faults, a two-phase fault was identified as the dominant condition in determining the characteristics of the FRT curve in this system.

Therefore, checking all symmetric and asymmetric faults in determining grid codes is necessary, and without the need to study the characteristics of all generators, only generators with high capacity and low inertia can be considered to determine the characteristics of the FRT curve.

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