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DEFINING FAULT RIDE-THROUGH CURVES FOR BESS INTEGRATION IN TURKISH TRANSMISSION GRID

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Abstract: As renewable energy integration grows, managing its intermittent nature has become a key challenge for system operators. Energy storage, especially Battery Energy Storage Systems (BESS), helps address this but adds complexity—particularly in hybrid facilities. Clear grid codes are essential to ensure stability and smooth integration. While Türkiye's Transmission System Operator (TEİAŞ) had established Low Voltage Ride Through (LVRT) requirements for wind and solar, BESS-specific criteria were only introduced in late 2024. Since introduced criteria demanded real-time testing to validate BESS performance during faults, this study explores new LVRT and fault response requirements for standalone and hybrid BESS in Türkiye's transmission grid. Through the simulations regions were selected based on short-circuit power variability, and using DigSILENT PowerFactory software, BESS responses under different fault scenarios are analyzed. The results inform a nationwide framework for BESS fault ride-through capabilities.

Keywords: Low Voltage Ride Through, BESSs, hybrid BESSs, grid code requirements for BESS, Energy storage regulations

INTRODUCTION

As the share of renewable energy in power grids increasing, stabilizing their intermittent output has become a significant challenge for system operators. Energy storage provides an effective solution to mitigate instability and reduce curtailments; however, it also introduces unavoidable complexities in system management, especially in hybrid facilities. To ensure the seamless integration of hybrid assets while maintaining grid stability, well-defined grid codes are essential. Battery Energy Storage Systems (BESS) require a thorough evaluation of their post-fault support capabilities, as these are crucial factors in pre-connection assessments. While the Turkish Transmission System Operator (TEIAS) had established Low Voltage Ride Through (LVRT) requirements for wind and solar power plants, specific criteria for BESS remained an entirely new subject for both the transmission system operator (TSO) and market players until the end of 2024. Following the introduction of these criteria, real-time testing procedures were implemented to verify their effectiveness in grid-connected storage systems.

The development of LVRT criteria for BESS is a crucial step toward ensuring the reliability of Türkiye's transmission grid as energy storage becomes more widespread. Unlike traditional renewable generators, BESS units operate with different control strategies, making it necessary to define fault response behaviors that align with grid stability needs. Additionally, the implementation of LVRT standards for BESS provides valuable insights into the broader role of storage in future power grids. As hybrid systems combining renewable generation and storage become more common, understanding their dynamic response to faults is essential for long-term grid planning. The lessons learned from Türkiye's experience can contribute to international best practices, helping other countries develop similar regulations to manage the evolving energy landscape. Establishing clear operational requirements for BESS not only supports grid stability but also enhances investor confidence, encouraging further deployment of energy storage solutions in modern power networks.

This study offers new insights into the requirements for zero and low-voltage ride-through, as well as active and reactive current support during and after faults. It also explores the potential for fast fault support schemes for standalone and hybrid BESSs in Türkiye's transmission grid. Regions were selected based on variations in short-circuit power under both minimum and maximum strength conditions. Simulations, conducted using DigSILENT PowerFactory, analyzed the response of a BESS facility with constant installed power to predefined fault scenarios influenced by this variability. The findings provide a framework for developing low-voltage support schemes tailored to different connection types, enabling nationwide application. Additionally, the study introduces a novel perspective on the LVRT curve for both individual and hybrid BESS facilities.

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The primary objective of this paper is to propose effective assessment strategies for conducting fault ride-through (FRT) simulations, rather than outlining the complete procedure for a standard low voltage ride-through (LVRT) analysis. Battery Energy Storage Systems (BESSs) are relatively new to the Turkish transmission grid, creating a need for detailed modeling of their fault response behaviors. Currently, there is no in-use methodology for pre-connection analysis of standalone BESSs—an issue that becomes even more complex in hybrid installations.
In the literature, numerous studies have explored the ability of renewable energy facilities to provide voltage ride-through support [1], [2], [3], [4], [5]. While a well-defined foundation has been established for the voltage ride-through capabilities of renewable sources, BESS-specific criteria remain largely limited to grid codes, as seen in [6], [7], [8] and [9].

1. RECENT DEVELOPMENTS ON BESS INTEGRATION TO TRANSMISSION GRID IN TÜRKİYE

Türkiye started the BESS integration journey by mentioning the term “electricity storage” in Electric Market Rule [10] in 2018 laying the groundwork for regulatory developments. This initiative took shape with the implementation of the Storage Activities Code in 2021 [11]. The process continued with the document of Technical Criteria of Grid Connection and Ancillary Service Utilization for Electric Storage Facilities which defines main frequency services and reactive support schemes for standalone BESSs. This frame of only-standalone batteries is updated with another revision in Electric Market Rule which defines certain incentives to BESS+RES facilities. No sooner than this Storage Activities Code revised to include Hybrid (Renewable Integrated) BESSs, BESSs Integrated to Production (conventional production facilities) and BESSs Integrated to Consumption facilities.

At the end of 2024 three guideline documents to cover newly introduced hybrid facility types, defining monitoring and data requirements of BESSs and declaring grid compatibility requirements usable for BESS facilities implemented by Transmission System Operator of Türkiye, TEIAS.

- At the document of Procedures and Principles on Monitoring and Control of Electric Storage Facilities [12], all data that need be kept available throughout the lifetime of BESSs, commands that is to be sent by TSO and all feedback signal list of BESSs control systems are given.
- In revised version of existing Technical Criteria of Grid Connection and Ancillary Service Utilization for Electric Storage Facilities document [13], hybrid facilities added to the scope and new service definitions like FFR and asynchronous reactive support services are defined for BESSs. Existing criteria is extended to also include test procedures on ancillary service procurement for BESSs.
- Grid connection requirements, statement of before commissioning data and procedure of approval of grid compatibility process is defined in Grid Connection and Compatibility Criteria of BESSs document [14].

1.1. LVRT Requirements From Grid Connection and Compatibility Criteria of BESSs Document

In Türkiye’s grid code, there is currently no specific definition of Low Voltage Ride Through (LVRT) curves for synchronous generators. In contrast, solar and wind power plants are subject to well-defined fault ride-through (FRT) requirements. During the development of grid code provisions for Battery Energy Storage Systems (BESSs), no significant modifications were made to the existing FRT curves, as they were already considered suitable for fault conditions specific to Türkiye. These existing curves and reactive current support schemes are applied uniformly across different types of generation, including synchronous, renewable, and hybrid installations.

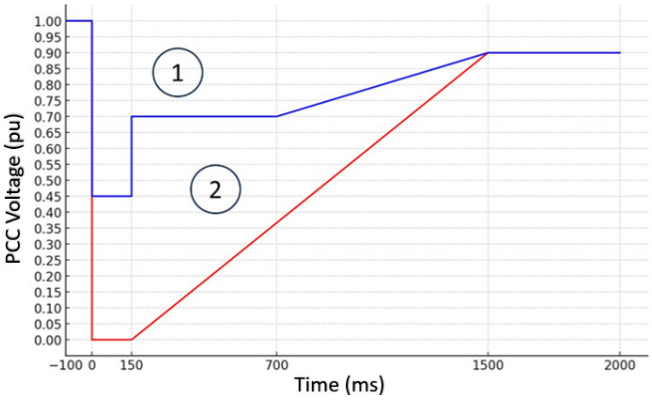

Figure 1: LVRT Curve for BESSs Integrations from Grid Connection and Compatibility Criteria of BESSs document

<u>*According to previously announced regulations:*</u>

(1) During the time the network phase-to-phase voltage at the transmission or distribution system connection point remains in regions 1 and 2, as shown in Figure 1, voltage drops that occur in any phase or across all phases must keep the BESSs and storage units connected to the grid.
(2) In the event of a fault, if the voltage drop remains in region 1, the EDTs and storage units must increase their active power by at least 20% of their nominal active power per second immediately after the fault is cleared, in order to reach the active power value prior to the fault.

(3) In the event of a fault, if the voltage drop remains in region 2, the EDTs and storage units must increase their active power by at least 5% of their nominal active power per second immediately after the fault is cleared, in order to reach the active power value prior to the fault.

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(4) In the event of faults at the grid connection point that cause voltage fluctuations outside the limits defined in Grid Code, each BESS and storage unit inverter must provide maximum reactive current support, either inductively or capacitively, at levels up to 100% of the nominal current, if necessary, without exceeding the designed temporary regime nominal values. This temporary regime must reach the maximum reactive current support value within 60 ms, with a 10% tolerance, and must be sustained for 1.5 seconds.

2. WHY POWER SYSTEMS NEED LVRT CURVES?

Voltage sags and swells are common occurrences throughout the year, typically caused by short circuits or sudden fluctuations in power sources and loads. These events can last anywhere from half a cycle to several seconds. If the magnitude of the voltage sag exceeds a critical threshold, it is classified as a fault event, which may lead to the disconnection of Distributed Generation (DG) inverters from the electrical power system, in accordance with the IEEE 1547-2018 standard. [15]. Low Voltage Ride-Through (LVRT) refers to the capability of power systems equipment to withstand significant voltage dips at the PCC and remain connected to the grid for a specified duration until the fault is cleared [1].

Generally, voltage ride through (VRT) includes three types of requirements: low-voltage ride through (LVRT), zero-voltage ride through (ZVRT), and high voltage ride through (HVRT). As a main definition VRT the power system equipment's durability to fault conditions and ability to react for its mitigation [2].

According to EU NC RfG 613/2016 [16], definition of LVRT curves are advised for TSOs. In this document, it is stated that defined voltage profile must express a lower limit to the phase-to-phase voltages in case of a symmetrical fault, as a function of time before, during and after the fault. In order to assess the power grids' actual reaction to the faults each TSO should make publicly available the following data on the faults;

- Calculation of the minimum short circuit capacity at the connection point prior to the fault.
- Determination of the pre-fault active and reactive power operating points and the voltage at the connection point.
- Calculation of the minimum short circuit capacity at the connection point following the fault.

Since BESSs are considered inverter-based resources, similar to other renewable energy sources, they are connected to the grid through an inverter. The capability of the grid-connected inverter is critical in defining the BESS's voltage ride-through ability. Grid-following (GFL) inverters, commonly used in Wind Power Plants (WPPs) and Photovoltaic Plants (PVPs), are likely to be utilized in most hybrid BESS installations.

A GFL inverter operates as a current source, responding to grid faults by injecting both real and reactive power into the main power grid, helping to maintain stability during disturbances [1]. However, the current injection capability of GFL inverters alone is not sufficient for ensuring grid resiliency, as both grid frequency and voltage support are also essential. Unlike GFL inverters, Grid-Forming (GFM) inverters have the ability to act as a voltage during faults. While the use of GFM inverters has a significant positive impact on voltage stability following faults, they are still not widely adopted in power grids due to factors such as complexity, cost, and integration challenges.

3. EUROPE APPLICATIONS ON LVRT REQUIREMENTS

Since voltage ride through capability is a critical property of power systems, it is stated and well defined in many grid codes throughout the Europe and the World. Although the term voltage ride through is in the scope of many grid codes, for BESSs focused voltage ride through requirements a mature criteria have not been defined yet. Among these few examples on BESS focused LVRT criteria; Finland (Fingrid), UK(Eirgrid & Soni) and Denmark (Energinet) applications on LVRT requirements are discussed at this study. A detailed comparison of these countries is implemented at Figure 2 and a deeper analysis is shown in Table I.

For Fingrid's case in suppression of introduced fault, a fault current injection criteria is defined. According to this [8],

- Fault current injection must be focused on reactive current.
- k-factor of fault current injection must be 2.5, in asymmetrical faults positive and negative sequence component must be supplied in the ratio defined by the k-factor. Maximum level of fault current must be limited with rated current level of normal operation (between 1.1-1.2 pu).
- Injection must rise to desired level in 30-50 ms and settle to there in 60-80 ms.
- Fault current injection must be triggered when any of the three phase voltages falls to 0,85pu level. And must be deactivated when the disturbed voltage turns back to 0,90 pu level.

For UK aplications details on the LVRT support are given in the devoted grid codes under the titles of power park modules (PPM) [7], [9]. According to these grid codes, a PPM must provide active power in proportion to retained voltage and provide reactive current to the Transmission System and additional reactive current providers (STATCOMS, SVCs etc.) are accepted. For active power support in case of a fault;

- For fault disturbances cleared in 140 ms, 90% of available active power must be provided in within 500ms after the fault occurs and recover the voltage to 90% of its nominal value and
- For longer faults 90% of available active power must be provided in within 1 seconds after the fault occurs and recover the voltage to 90% of its nominal value

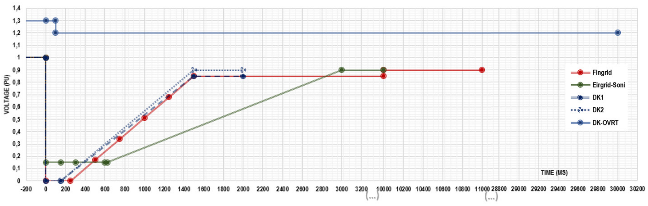

Figure 2: Comparison of Voltage Ride Through curves

In Denmark, BESSs focused voltage ride through criteria is given under to title of "Non-synchronous energy storage facilities connected to the transmission system" in [6]. Different from the UK and Finland, in Denmark over voltage ride through (OVRT) requirements are also defined. For low voltage ride through case the country's two devoted market regions have two different criteria. Apart from the conventional voltage ride through requirements, a scheme Fast Fault Current (FFC) is defined, according to this energy storage unit must begin giving current support 100ms after the voltage dip, the support must be continue from 0.85 (DK2) pu (0.90 for DK1 application) to 0.5 pu with a tolerance of ±20% of In.

4. CASE STUDIES FOR TÜRKİYE

For Türkiye four main connection types are considered according to existing regulations; (1) Standalone BESSs, (2) Hybrid (Renewable Integrated) BESSs, (3) BESSs Integrated to Production (conventional production facilities) and (4) BESSs Integrated to Consumption. With existing approach no pre-connection requirement is considered for consumption integrated facilities so they are kept out of the scope of this study. Therefore, a fault ride through analysis is conducted for the three other integration types given above.

For each of the scenarios an additional minimum short circuit power grid assumption is made to see how the grid strength affects the overall grid resilience following a fault. The cases examined are summarized below;

1. Standalone BESS
2. Standalone BESS with weak grid condition
3. Hybrid (Renewable Integrated) BESS
4. Hybrid (Renewable Integrated) BESS with weak grid condition
5. BESS Integrated to Production (conventional production facilities)
6. BESS Integrated to Production (conventional production facilities) with weak grid condition

For the given scenarios above, same power level BESS is connected to the two different short circuit power levels and results are assessed.

4.1. Selected Regions for Study

In today's transmission grid planning procedures one of the most critical factors to be decided is the location availability meaning the asset suitability and the required environmental effect assessment procedures etc. Although whole design and implementation, planning and construction than building and commissioning process is

Table I: Comparison of Voltage Ride Through Requirements of Denmark, UK and Finland

Countries	Denmark	UK	Finland
Reactive Current Injection	Energy storage unit must begin current support 100ms after the voltage dip, the support must be continue from 0.85 pu to 0.5 pu with a tolerance of ±20% of nominal current.	The current support provided by the PPM must be continue until the voltage recovers to normal operating range of Transmission System or at least for 500 ms. The reactive current supplied must have a rise time no greater than 100 ms and a settling time no greater than 300ms.	Fault current injection must be triggered when any of the three phase voltages falls to 0,85pu level. And must be deactivated when the disturbed voltage turns back to 0,90 pu level.
Balanced / unbalanced faults	-	-	+
Duration of Voltage Dips	150ms@0 pu voltage 1,5 seconds total duration (duration to retain the voltage to 0.85 pu for DK2 and 0.90 for DK1)	625ms@0,15pu voltage 3 seconds total duration (duration to retain the voltage to 0.90 pu)	200ms@0 pu voltage 10 seconds total duration (duration to retain the voltage to 0.90 pu)
HVRT	+	-	-
ZVRT	+	-	+
LVRT	+	+	+

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depended to numerous factors. Solely possibility of grid connection regions for each of the above three type of facilities are concern of this paper. With this manner for the cases concentrated on Standalone BESS, Thrace region of Turkey is taken as the basis to define the lowest short circuit power level (approximately 320 MVA according to one year of statistical data taken from a selected representative busbar) as standalone type BESSs which have smaller physical size could be a more appropriate solution for high demand but narrower available plant area problem of this region. For the hybrid BESS cases a wind power plant (WPP) + BESS scenario is considered so west anatolia region is selected for the connection and the minimum short circuit power (approximately 713 MVA according to one year of statistical data taken from a selected representative busbar) is defined by the values taken from this region. Since conventional-plant-based production rates are higher in south-east and eastern sides of Türkiye again the same approach is applied to decide on the short circuit power (approximately 560 MVA for eastern side and 660 MVA for south-eastern side according to one year of statistical data taken from selected representative busbars-a short circuit power of 560 MVA is taken for the minimum SK case) by taking the values from this regions.

4.2. BESS System Properties

Since the installed power limit for BESSs to be monitored and directly sent the measurement (SCADA) data to TSO is 10 MW (also the limit for a standalone BESS to be connected from transmission level) and a limit of 30 MW is also applied for a BESS to participate in ancillary services and be in the charge of compulsory reactive power support service, a 30 MW BESS is designed for the simulation. One line diagram of the model is shown in the Figure 3.

4.3. Simulation and Results

Through the simulations; a zero volt, 150 ms fault with zero ohm fault impedance is applied to the grid connection point and the active power change in the BESS transformer low voltage side is observed. For further analysis WPP and Thermic Power Plant (TPP) turbine and generator focused reactions to the fault are also implemented.

4.4. Standalone BESS Cases

For only BESS simulations minimum short circuit power level of the grid is decided by using the selected Thrace region measurement data as stated above. For these cases the results are implemented below (Figure 4). Different from the low short circuit power scenario for strong grid case a sudden voltage increase seen in the PCC as a result of cleared 3 phase-earth fault resulting the BESS to move on the charging mode to balance the extra voltage. Other than the different responses to voltage sudden voltage increase there not seen any

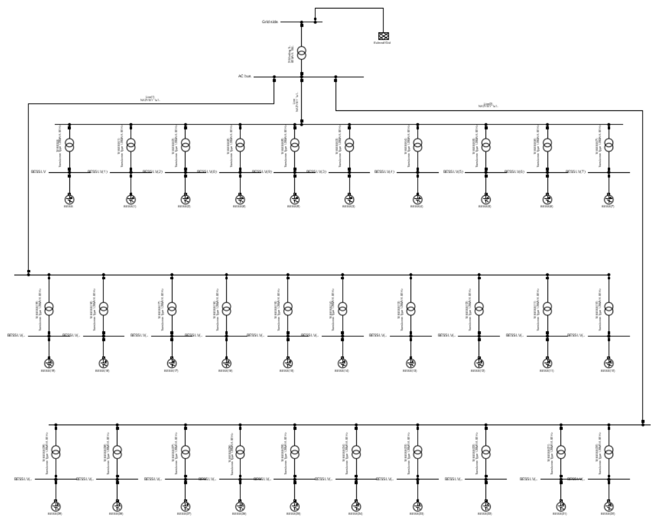

Figure 3: One line diagram of the 30 MW BESS system

further oscillation resulting from weaker grid assumption. According to announced regulations for a 150 ms duration 0 V level fault the BESS unit must increase it's output power at least in a percentage of %5 for each second which is convenient according to conducted simulation.

According to regulations the facility must give reactive current support up to %100 of its nominal current and must reach this current support value within 60 ms, with a 10% tolerance, and must be sustained there for 1.5 seconds. According to results the facility was able to give reactive current support within 60 ms but the level of the provided reactive current was not limited to %100 of nominal current.

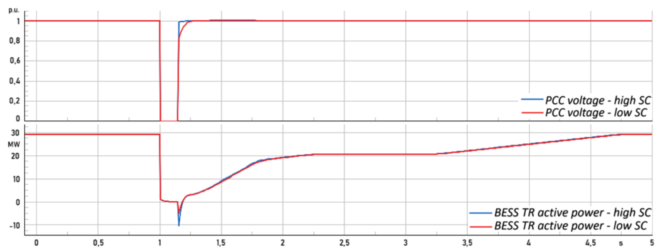

Figure 4: BESS reaction to sudden grid voltage change both for strong (blue) and weak (red) grid options

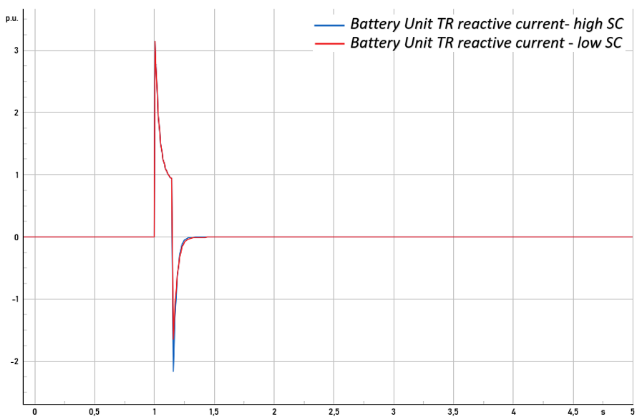

Figure 5: One battery unit reaction to sudden grid voltage change both for strong (blue) and weak (red) grid options

4.5. Hybrid (Renewable Integrated) BESS Cases

For hybrid BESS simulations (120 MW addition to the 30 MW BESS facility) minimum short circuit power level of the grid is decided by using the selected West Anatolia region measurement data as stated above. For these cases the results are implemented below (Figure 6). Like the only BESS scenario a sudden voltage increase seen in the PCC (with cleared 3 phase-earth fault) resulting the BESS to move on the charging mode to balance the extra voltage. For lower short circuit grid there occurred a slight increase in voltage level at the PCC, which is again higher for WPP on case. Similar to the standalone BESS scenario, weaker grid assumption did not resulted a remarkable effect on the output of fault response of the system. According to the announced regulations, during a 150 ms 0 V fault event, the BESS unit must increase its output power by at least 5% per second, a requirement deemed appropriate based on conducted simulations both for strong and weak grid conditions.

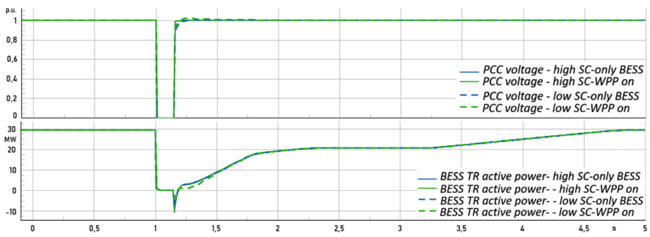

Figure 6: Hybrid BESS reaction to sudden grid voltage change both for strong (solid blue and green lines) and weak (dashed blue and green for lines) grid options

The overall results showed a similar reaction to the voltage change in the PCC both for the high and low short circuit power scenarios as also shown in Figure 7. For the WPP side fault response results, a detailed implementation of one turbine fault reaction is shown in the Figure 9, including both active and reactive power responses.

In proposed regulations the facility must give reactive current support up to %100 of its nominal current and must reach this current support value within 60 ms, with a 10% tolerance, and must be sustained there for 1.5 seconds. According to simulations the facility was able to give reactive current support within 60 ms but the level of the provided reactive current was not limited to %100 of nominal current for the battery side of the facility even the criteria is met for WTG case.

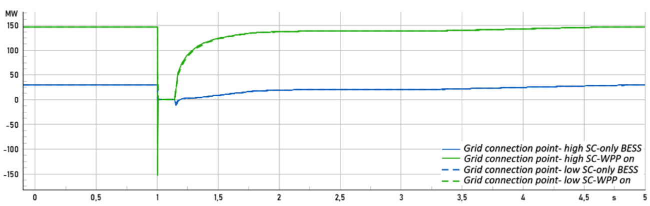

Figure 7: Active power response seen from the grid connection point (at the point WPP+BESS facility connects to the grid)- straight blue representing the reaction for only BESS scenario, straight green representing the reaction for WPP+BESS scenario, dashed blue representing the reaction for only BESS scenario, dashed green representing the reaction for WPP+BESS scenario

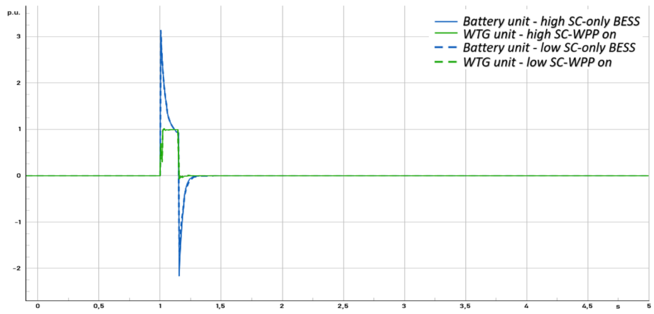

Figure 8: One battery and one WTG unit reactive current response to sudden grid voltage change both for strong (solid lines) and weak (dashed lines) grid options

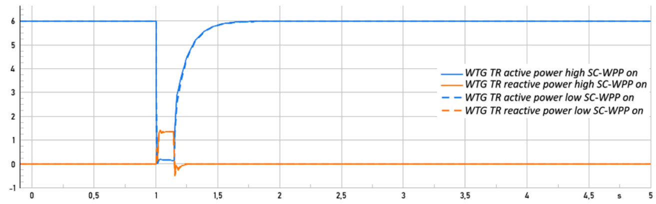

Figure 9: Fault reaction of the one selected WTG turbine

4.6. BESS Integrated to Production (conventional production facilities)

For a facility including BESS and synchronous generation at the same site, same analysis procedure is applied to the PCC with the same fault resistance and duration. For weak grid scenario the highest synchronous production regions (south-eastern and eastern Anatolia region) are considered to define the short circuit level. Reaction to the fault is different from the above cases resulting synchronous generator sourced oscillations in the grid which can be seen for the low short circuit power scenario both for PCC voltage and for active power response monitored at low voltage side of the BESS transformer connecting to the PCC (Figure 10). It can be deduced from here that for a facility including synchronous generation, weaker grid could result in worse after fault performance. Same reaction to the weaker grid assumption is seen at the Figure 11, the 250 MW TPP reacts to the sudden voltage change with oscillations and this result in oscillations even can be seen at the grid connection point of the site implementing a pole slip at synchronous generations part of the side. For the stronger grid scenario, the oscillations can be damped approximately in 5 second after the fault is cleared. According to the announced regulations, during a 150 ms 0 V fault event, the BESS unit must increase its output power by at least 5% per second, a requirement met based on conducted simulations only for strong grid condition.

For reactive current support the facility must give reactive current support up to %100 of its nominal current and must reach this current support value within 60 ms, with a 10% tolerance, and must be sustained for 1.5 seconds. According to simulations the facility was able to give reactive current support within 60 ms but the level of the provided reactive current was not limited to %100 of nominal current. Although the introduced reactive current is neutralized at approximately in 1.5 seconds at most for strong grid assumption, the same stabilizations is not seen for the weak grid conditions.

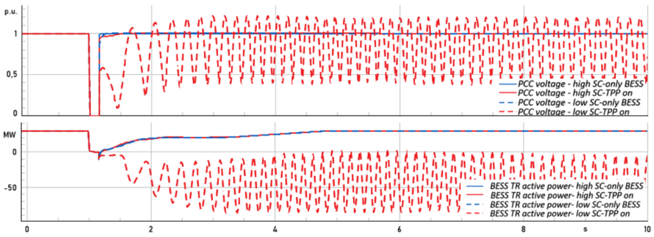

Figure 10: BESS Integrated to Production reaction to sudden grid voltage change both for strong grid (straight blue and red lines) and weak grid (dashed blue and red lines) options

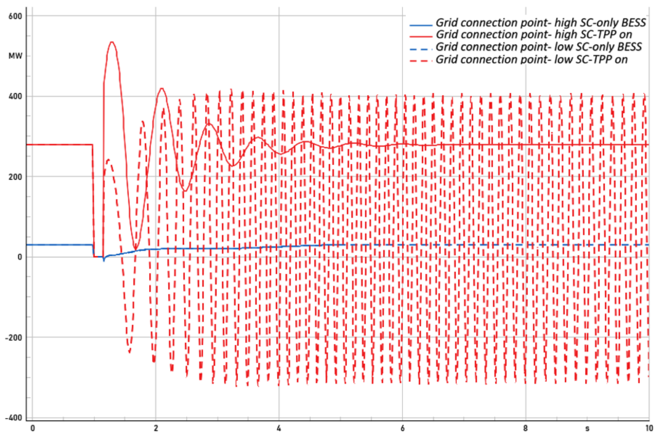

Figure 11: Active power response seen from the grid connection point (at the point TPP+BESS facility connects to the grid)-straight blue representing the reaction for only BESS scenario, straight red representing the reaction for TPP+BESS scenario, dashed blue representing the reaction for only BESS scenario, dashed red representing the reaction for TPP+BESS scenario

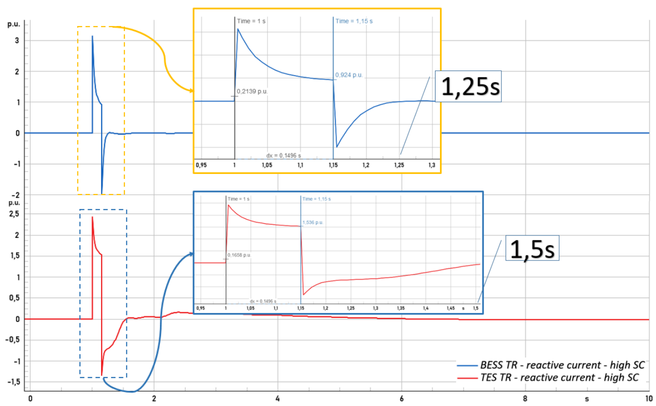

Figure 12: Battery and synchronous generator units' reactive current response to the fault in strong grid conditions

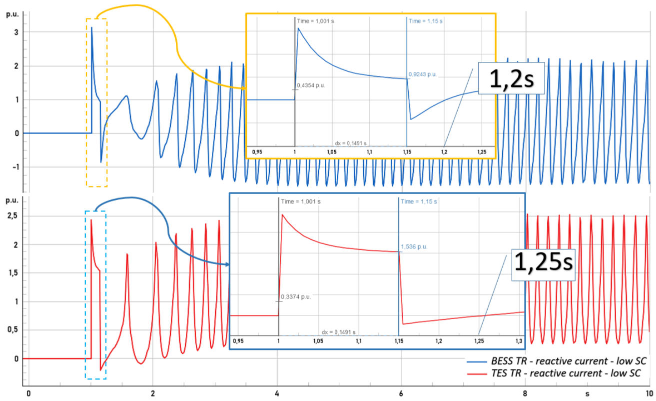

Figure 13: Battery and synchronous generator units' reactive current response to the fault in weak grid conditions

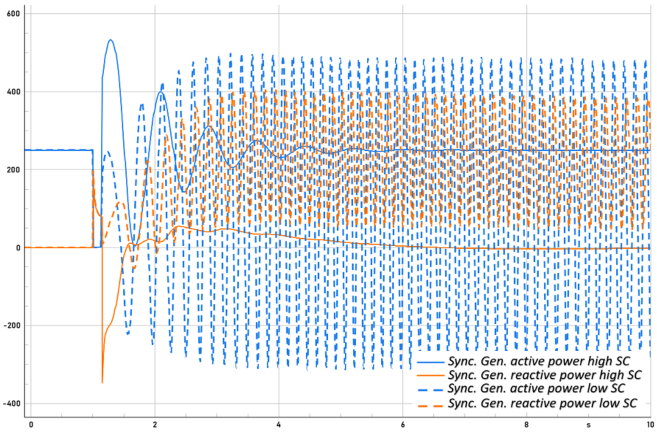

Figure 14: Fault reaction of the synchronous generator

5. CONCLUSION

At this paper a low voltage ride through assessment simulation is conducted for all three types of BESSs stated in existing and recently announced regulations in Türkiye; Standalone BESS, Hybrid (Renewable Integrated) BESS and BESS Integrated to Production (conventional production facilities). Through the study, region-focused short circuit levels are introduced to the model to see a more realistic behaviour of BESSs. As a result of the study, it is observed that the fault reaction of BESS systems is similar to existing fault reaction of WPPS and PVPPs. Reaction of them could be improved with definition of GFM inverters as this study solely depended to GFL inverter technology. Different from the standalone and hybrid BESSs, for BESS integrated to conventional scenarios, the output power of synchronous generator oscillates to high levels. Although this oscillations are supressed in approximately in 5.5 seconds for high short circuit power, this oscillations seems continuous for weaker grid conditions. It is obviously advisable that consideration of synchronous generation sourced oscillations is crucial while defining the low voltage ride through curves for BESS+conventional production facilities.

All in all, according to simulations the generic model based analyses seem to be in line with existing definitions for LVRT except from the level of reactive currents after the fault-reaching 3 times the nominal current-, however the situation is different for synchronous combinations as we need to consider additional oscillations for this case sourced from pole slips in generators (only seen in weaker grid conditions).

FUTURE WORK

The current definition of grid code requirements for BESS is still at the declaration stage, leaving the provisions open to discussion and refinement. TSO-stakeholder meetings are ongoing at the time of this paper's preparation. As there are no large-scale BESS installations yet connected to Türkiye's transmission grid, the ongoing assessment process relies primarily on simulations, stakeholder feedback, and inter-TSO evaluations. Based on the experience gained during this review process, no significant objections have been raised so far.

For further simulations implementation of GFM must also be evaluated to see a more realistic grid behaviour assessment. Since only generic models are used through this study, definition of real models of wind turbines, synchronous generators and a real BESS control implementation should be evaluated for future research with addition of more various grid side fault scenarios.

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