

Protection Selectivity Analysis of a Medium-Voltage Network with Battery Energy Storage Systems

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Abstract. The paper investigates the impact of Battery Energy Storage System (BESS) integration on short-circuit (SC) contribution and protection selectivity in an 11 kV medium-voltage (MV) network located in Söderala, Sweden. The SC analysis is performed under weak-grid and strong-grid operating conditions to evaluate the impact of the upstream grid strength on fault contribution at the main busbar and BESS feeder locations. The results show that the upstream grid remains the dominant fault source at the main busbar, while locally connected BESS units become the dominant contributors to faults located electrically closer to the converter-interfaced sources. The Protection selectivity is evaluated using Time-Current Characteristic (TCC) analysis and verified through Short-Circuit Trace (SC Trace) simulations in DIgSILENT PowerFactory. The implemented protection scheme demonstrates a satisfactory selectivity, where faults are isolated by the protection device associated with the faulted section without unnecessary disconnection of healthy feeders. The findings indicate that a properly coordinated conventional overcurrent protection can maintain a reliable operation in inverter-dominated MV systems.

Keywords: Battery Energy Storage System, protection selectivity, short-circuit analysis, overcurrent protection, medium-voltage network

Analiza selektivnosti zaštite sredjenapetostnega omrežja z baterijskimi hranilniki energije

V prispevku obravnavamo vpliv vključevanja baterijskih hranilnikov energije (BESS) na prispevke k kratkostičnim tokovom in selektivnost zaštite v 11-kV sredjenapetostnem omrežju v kraju Söderala na Švedskem. Analiza kratkostičnih razmer pri šibkem in močnem napajalnem omrežju pokaže, da je glavni vir okvarnih tokov na zbiralkah nadrejeno omrežje, medtem ko imajo lokalni baterijski hranilniki prevladujoč vpliv na okvare v njihovi neposredni električni bližini. Selektivnost zaštite smo ovrednotili z analizo časovno-tokovnih karakteristik in simulacijami kratkostičnih dogodkov v programu DIgSILENT PowerFactory. Rezultati potrjujejo ustrezno delovanje zaščitne sheme, ki omogoča odklop okvarjenega dela omrežja brez nepotrebne izklapljanja nepoškodovanih odcefov. Ugotovitve kažejo, da lahko ustrezno usklajena klasična nadtokovna zaščita zagotavlja zanesljivo delovanje tudi v sredjenapetostnih omrežjih z velikim deležem pretvorniško priključenih virov.

1 INTRODUCTION

The increasing penetration of the Battery Energy Storage Systems (BESS) and inverter-based renewable energy resources has significantly changed the operating characteristics of modern power systems [1-4]. Unlike the conventional synchronous generators, the inverter-based resources contribute a limited short-circuit current

due to the converter current limitation during fault conditions [5-9]. As a result, the fault-current distribution and the behaviour of the conventional protection systems may significantly differ from the traditional power-system configurations.

In the medium-voltage (MV) networks with a high penetration of converter-interfaced resources, protection coordination becomes increasingly important in order to ensure selective fault clearing while maintaining the network reliability [1], [2], [4], [8-10]. The Improper coordination between the feeder and upstream protection may result in unnecessary disconnection of healthy feeders or delayed fault isolation [1], [4], [8], [9], [11]. Therefore, evaluating the protection performance under different grid operating conditions, including variations in the grid strength, has become increasingly important in modern MV protection studies [1], [3], [4], [7], [10].

Several studies have investigated the impact of the inverter-based resources on the fault current contribution and protection coordination. Reiz and Leite [1] propose a protection coordination methodology for the distribution networks with distributed energy resources and microgrids, highlighting the increasing complexity of the protection systems in the converter-dominated networks. Turcotte and Katiraei [6] analyse the fault contribution characteristics of the grid-connected inverters and show that the inverter-based sources contribute significantly lower short-circuit currents compared to the synchronous

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generators. Yazdanpanahi et al. [8] investigate the impact of the inverter-based distributed generation on the fuse–recloser coordination and demonstrate that a high penetration of the inverter-based resources may lead to protection miscoordination under certain fault conditions. Pan et al. [9] examine the fault behaviour of the inverter-interfaced distributed generators and show that their fault current contribution is highly dependent on the converter control strategies, which can significantly affect the overcurrent protection performance and coordination. Pola and Azzouz [10] propose an optimal protection coordination approach for the active distribution networks with inverter-based resources, emphasizing the challenges in maintaining a reliable operation of the directional overcurrent relays and the need for advanced coordination strategies in converter-dominated systems.

Although the previous studies addressed the protection challenges associated with the distributed generation and inverter-based resources, detailed investigations of the practical MV networks with integrated BESS under different grid strength conditions remain limited.

Therefore, the paper investigates the impact of the BESS integration on the short-circuit current contribution and protection selectivity in an 11 kV MV network located in Söderalä, Sweden. The study includes short-circuit calculations under weak-grid and strong-grid operating conditions, protection selectivity analysis using the TCC curves, and SC Trace verification in the DIgSILENT PowerFactory [12].

The main contribution of the work is the evaluation of the protection selectivity and the short-circuit behaviour of a practical MV distribution network with integrated BESS under varying grid strength conditions using an IEC 60909-based analysis.

The remainder of the paper is organized as follows. Section II presents the analysed MV network model and system configuration, Section III presents the simulation results and selectivity analysis, Section IV presents the discussion, and Section V summarizes the main conclusions of the study.

2 METHODOLOGY

2.1 Network Description

The investigated network which is located in Söderalä, Sweden is an 11 kV MV system designed for the integration of BESS. The network is supplied from a 220 kV external grid through two upstream transformers, T1 and T2, connected to the 130 kV level. However, since transformer T2 was out of operation during the investigated system condition, only transformer T1 is considered in our simulations. From the 130 kV system, transformer T3 supplies the 11 kV network through the cable H01-T3 connection to the main MV busbar A10.

The A10 busbar represents the main 11 kV busbar of the investigated system and supplies nine outgoing

feeders. Eight feeders are dedicated to the BESS units, while one feeder supplies the auxiliary load LT1. The H01 bay represents the incomer connection to the A10 busbar. Feeders H04–H11 are connected to the BESS units, whereas H12 supplies the auxiliary load.

Each BESS feeder is connected through an 11/0.69 kV transformer to the inverter and battery system. The auxiliary load feeder is supplied through an 11/0.4 kV transformer. The investigated network topology is shown in Fig. 1.

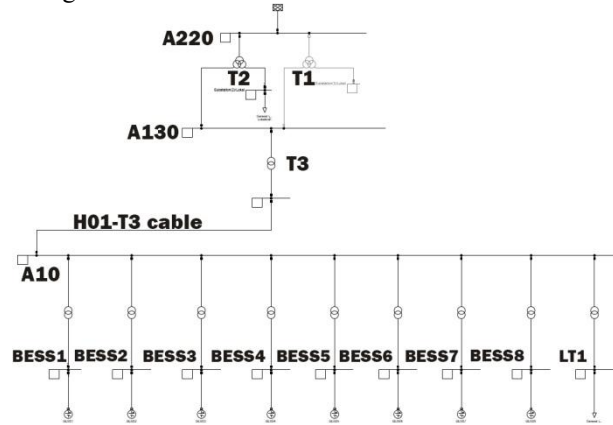


Figure 1. Single-Line Diagram

To evaluate the short-circuit (SC) behaviour and protection selectivity, two representative fault locations are considered: the main MV busbar A10 and the BESS2 feeder busbar. The corresponding fault locations are highlighted in Fig. 2.

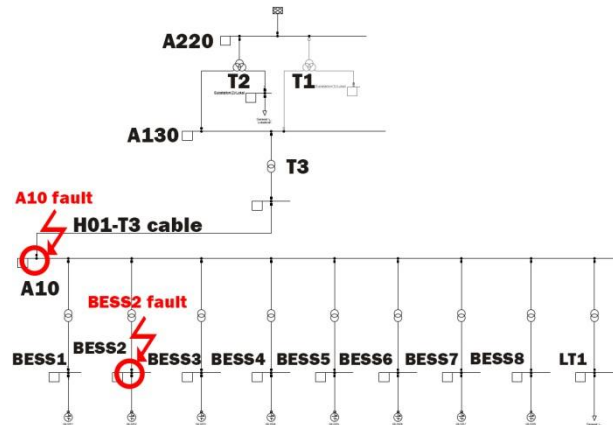


Figure 2. Observed Two Individual Fault Locations

2.2 Battery Modelling

BESS is modelled as inverter-based resources in DIgSILENT PowerFactory 2026 SP1 [12]. The investigated system consists of eight BESS units, each rated at 5 MVA, resulting in a total installed BESS capacity of 40 MVA. Each unit is connected to the MV network through a dedicated feeder. The three-phase

short-circuit current contribution of each BESS unit is limited by the inverter to $1.01 \times I_n$ (4.24 kA) [13].

Unlike the conventional synchronous generators, the inverter-based BESS units are characterized by a limited SC current contribution due to the converter current limitation during fault conditions. In a practical operation, the inverter controllers limit the output current in order to protect the semiconductor components and maintain the converter stability. Consequently, the fault current contribution of the BESS units is considerably lower compared to the conventional synchronous generation [5-7], [8], [9].

Each BESS feeder is equipped with a dedicated protection and circuit breaker control. A consistent protection philosophy is applied to all BESS feeders in order to enable a uniform selectivity analysis.

2.3 Short-Circuit (SC) Analysis

SC calculations are performed in DigSILENT PowerFactory according to the VDE 0102 Part 0 / DIN EN 60909-0 methodology, based on the IEC 60909 standard implemented in the PowerFactory [12].

The SC study focuses on evaluating the fault current contribution and protection behaviour under different operating conditions of the investigated MV network. The analysis includes:

- Three-phase SC faults
- Fault at the main MV busbar A10
- Fault at the BESS2 feeder busbar
- Weak-grid operating condition
- Strong-grid operating condition

To evaluate the impact of the upstream grid strength on the SC current contribution and protection selectivity, two operating conditions are considered: a weak-grid scenario with a SC power of 5000 MVA and a strong-grid scenario with 20000 MVA.

For each investigated fault location, the contribution of the incomer source from the upstream network and individual BESS units to the total short-circuit current is evaluated. A Particular attention is given to the impact of the grid strength on the fault current distribution and on protection selectivity.

2.4 Protection

The original substation configuration utilizes the ABB REF615 feeder protection relays [14]. However, due to the modelling limitations encountered within the available DigSILENT PowerFactory relay library, the ABB REF620 relay models are partially used for the simulation purposes while preserving the original protection philosophy and coordination principles of the investigated system [15].

Due to the relay library limitations, an additional relay element is implemented to represent the instantaneous overcurrent protection stage ($I>>$) required for the protection coordination analysis. The implemented protection scheme includes:

- Overcurrent protection
- Earth-fault protection
- Voltage protection functions
- Frequency protection functions

The Current transformer (CT) and voltage transformer (VT) data are modelled for each protection device to ensure a realistic relay operating behaviour. The applied parameters correspond to the actual substation configuration.

Fig. 3 presents the protection configuration of the investigated MV network, including the feeder relays, circuit breakers, CT/VT measurements, and BESS transformer connections implemented in DigSILENT PowerFactory.

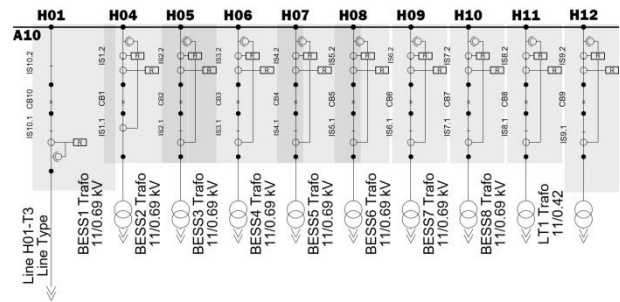


Figure 3. Protection Configuration

The Protection coordination is performed using the overcurrent protection functions based on the ABB relay functionality [14], [15]. The study focuses primarily on the feeder and incoming feeder overcurrent protection in order to verify the selective fault clearing and grading margins between the protection stages [11], [16], [17].

The main relay settings relevant to the coordination study are summarized in Table 1.

Table 1. Relay settings

Relay	Protection	Pickup Current (sec.A)	Pickup Current (prim.A)	Time Delay (s)
H01	$I>$	5	2500	1.2
H01	$I>>$	15	7500	0.1
H05	$I>$	0.7	280	0.6
H05	$I>>$	2.8	1120	0.02
H05	$I0>$	0.01	1	1

Time–Current Characteristic (TCC) curves are generated in the DigSILENT PowerFactory to verify the selective operation between the feeder and the incomer protection [12]. The primary objective of the coordination study is to ensure that the feeder protection devices operate before incoming feeder backup protection during the feeder fault conditions, and vice versa.

2.5 Short-Circuit Trace

The Short-Circuit Trace (SC Trace) analysis is performed in the DigSILENT PowerFactory to evaluate the relay operating sequences, breaker tripping, and fault isolation during SC conditions [12].

The analysis is used to verify that only the protection associated with the faulted section disconnects the fault while the remaining network remains energized, thereby confirming the proper protection selectivity [1], [10], [11], [16], [17].

Although, the directional earth-fault protection is implemented and coordinated within the investigated system, its directional operation cannot be fully visualized in the SC Trace environment due to the software limitations. Therefore, the SC Trace analysis in this study focuses primarily on, the overcurrent protection operation and breaker coordination.

3 RESULTS

3.1 Short-Circuit Analysis

3.1.1 Fault A10 Busbar – Weak Grid

Under the weak-grid operating conditions the total three-phase SC current at busbar A10 reaches 23.68 kA, corresponding to the SC power of 451.2MVA. The upstream grid represents a dominant fault current source, contributing 21.553 kA and 410.6 MVA to the total fault level. In contrast, each individual BESS unit (BESS1 - BESS8) contributes 0.266 kA and 5.1 MVA.

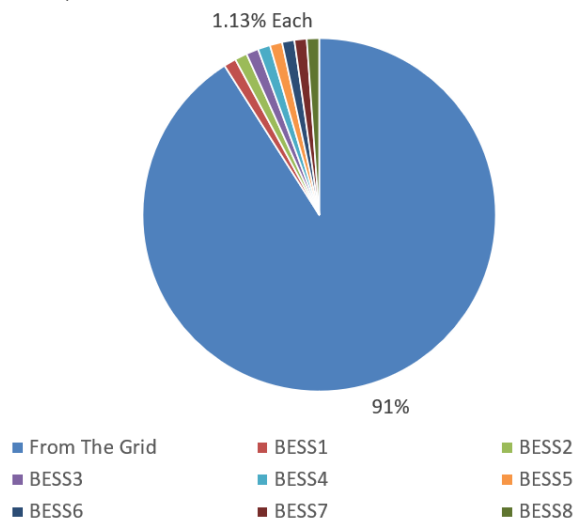


Figure 4. Fault contribution at A10 (Weak Grid)

The results in Fig. 4 indicate that the upstream grid has a dominant contribution to the fault current with 91% of the total SC level. The contribution of each BESS unit is small and evenly distributed, reflecting the current-limited behaviour of the inverter-based energy storage systems.

3.1.2 Fault BESS2 Busbar – Weak Grid

Under the weak-grid operating conditions the total three-phase SC power at the BESS2 busbar reaches 66.6 MVA. Since the fault location is situated on the low-voltage side of the 11/0.69 kV transformer, the contribution of individual elements is evaluated using the SC power rather than the current magnitude. This approach is selected to avoid misleading comparisons caused by

different voltage and current levels across the transformer.

The upstream grid contributes 26.1 MVA to the total fault level, while each individual BESS unit (BESS1–BESS8) contributes 5.1 MVA.

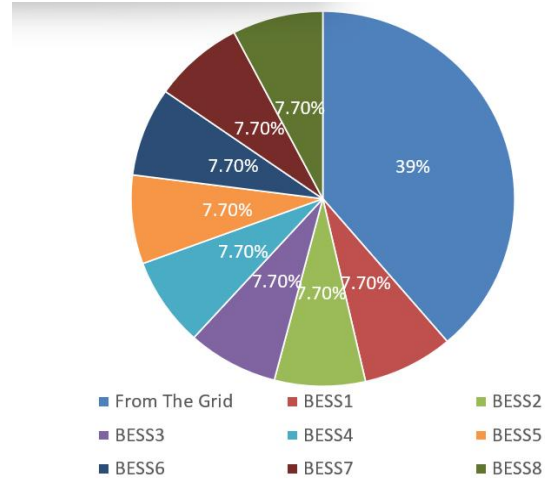


Figure 5. Fault contribution at BESS2 (Weak Grid)

The results in Fig. 5 indicate that the BESS units collectively represent the dominant contribution to the fault level at the BESS2 busbar, accounting for approximately 61% of the total SC level. The upstream grid contributes approximately 39% of the total fault level. Since each BESS unit contributes approximately 7.7%, the results confirm the distributed and current-limited behaviour of the inverter-based energy storage systems under weak-grid conditions.

3.1.3 Fault A10 Busbar – Strong Grid

Under strong-grid operating conditions the total three-phase SC current at busbar A10 reaches 25.011 kA, corresponding to a SC power of 476.5 MVA. The upstream grid represents the dominant fault current source, contributing 22.883 kA and 436 MVA to the total fault level. In contrast each Individual BESS unit (BESS1 - BESS8) contributes 0.266 kA and 5.1 MVA.

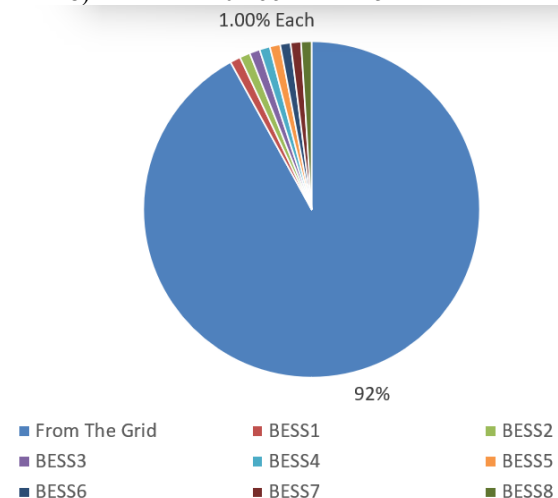


Figure 6. Fault contribution at A10 (Strong Grid)

The results in Fig. 6 indicate that the upstream grid is dominant again but with, a 1% higher contribution to the fault current with 92% of the total SC level. The absolute contribution of each BESS unit remains the same, but their relative contribution decreases due to higher fault contribution of the upstream grid. This again emphasizes the current-limited behaviour of the inverter-based energy storage systems.

3.1.4 Fault BESS2 Busbar – Strong grid

Under strong-grid operating conditions the total three-phase SC power at the BESS2 busbar reaches 66.8 MVA. The upstream grid contributes 26.3 MVA to the total fault level, while each individual BESS unit (BESS1–BESS8) contributes 5.1 MVA.

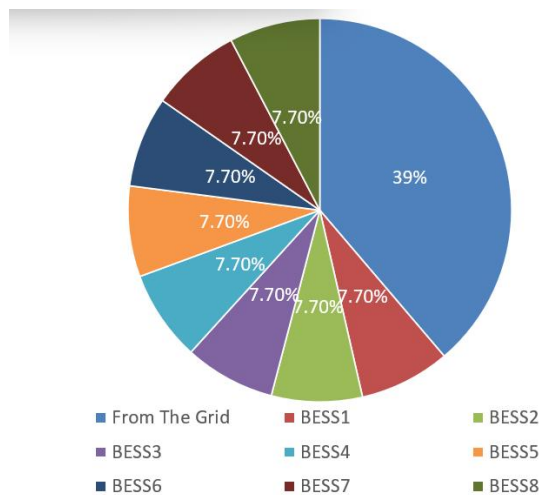


Figure 7. Fault contribution at BESS2 (Strong Grid)

The results in Fig. 7 indicate that the BESS units remain the dominant contributors to the fault level, accounting for approximately 61% of the total SC level, while the upstream grid contributes approximately 39%. Compared to the weak-grid scenario, here is only a marginal increase in the upstream grid contribution observed. The contribution of each BESS unit remains unchanged, confirming that the inverter-based BESS fault contribution is largely independent of the upstream grid strength due to the converter current limitation.

3.2 Protection Selectivity Analysis

Relay H05 operates as a downstream feeder protection and, relay H01 operates as an upstream incomer A10 protection. Both relays include the overcurrent protection with, a lower ($I>$) stage and an instantaneous ($I>>$) stage.

Fig. 8 represents the TCC plot to evaluate the coordination between the protection devices. The upper characteristic corresponds to the time-delayed overcurrent stage ($I>$), while the lower represent the instantaneous high-set overcurrent stage ($I>>$). The characteristic located at the lower current values corresponds to directional earth-fault protection.

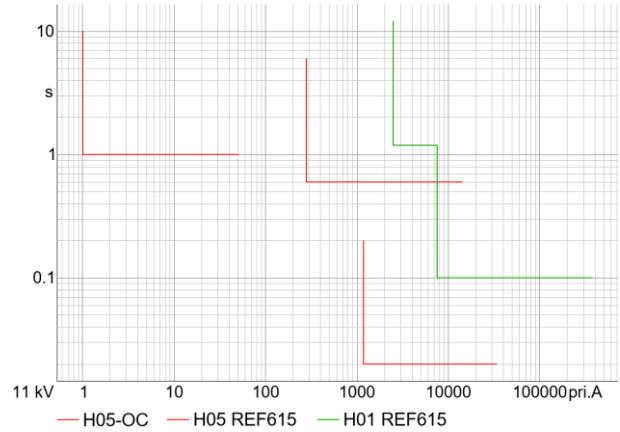


Figure 8. TCC Coordination

The H05 relay operating characteristic remains lower and to the left of the H01 operating characteristic, confirming that the downstream protection operates faster than the upstream protection within the observed fault current range. This coordination ensures selective fault clearing by disconnecting only the faulted feeder while maintaining the power supply to the healthy section of the network. The obtained TCC characteristics confirm adequate grading margins and proper selectivity between the feeder and upstream protection devices.

Relay H05 has, a directional earth-fault protection, is visible at lower current levels on the left side of the TCC graph due to lower earth-fault current magnitudes, typically associated with the earth-fault conditions.

3.3 Short-Circuit Trace

3.3.1 Fault at the BESS2 Busbar

A three-phase fault is applied at the BESS2 busbar, shown in Fig. 9, to verify the protection coordination and selectivity of the implemented protection scheme.

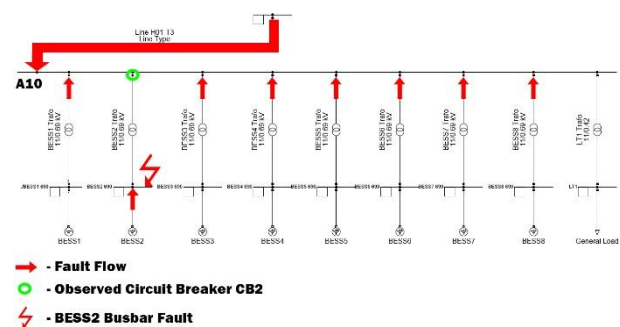


Figure 9. BESS2 Fault

During the fault condition, the neighbouring relays detect the disturbance and enter the started state, indicating the fault detection across the surrounding feeders. However, only the protection associated with the faulted feeder reaches the trip condition. Due to the high fault current magnitude, the high-set overcurrent protection stage ($I>>$) of relay H05 operates after 0.02 s and issues a trip command to circuit breaker CB2. The upstream relay H01 and the adjacent feeder relays detect the fault but

remain in the started state without tripping. This behaviour confirms the proper protection coordination, as only the relay associated with the faulted feeder initiates fault clearing.

Following the breaker operation, only the faulted BESS2 feeder is disconnected while the remaining healthy sections of the MV network remain energized. This confirms a successful protection selectivity, since the fault is isolated locally without an unnecessary interruption of unaffected feeders.

3.3.2 Fault at A10 Busbar

A three-phase fault is applied at the A10 busbar, shown in Fig. 10, to verify the protection response of the upstream feeder and the selectivity of the implemented protection scheme.

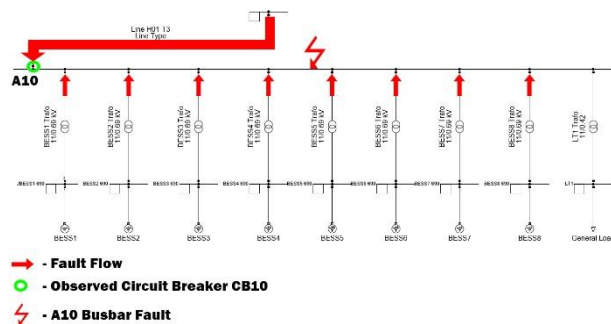


Figure 10. A10 Fault

During the fault condition, multiple feeder relays detect the disturbance and enter the started state. However, due to the fault location at the upstream busbar, protection relay H01 associated with the incomer reaches the trip condition. Since the fault current magnitude is sufficiently high, the high-set overcurrent stage ($I >>$) operates and issues a trip command to circuit breaker CB10 after 0.10 s. The downstream feeder relays detect the fault but remain in the started state without initiating tripping, thereby preventing unnecessary feeder disconnections.

Following the CB10 operation, the faulted section connected to the A10 busbar is isolated, while the unnecessary tripping of the downstream feeders is avoided. This behaviour confirms a proper selectivity of the protection scheme, since the fault is cleared by the relay associated with the fault location.

4 DISCUSSION

The obtained results indicate that the dominant SC source depends on the fault location within the investigated network. For faults at busbar A10, the upstream grid remains the dominant SC source under both the weak-grid and the strong-grid operating conditions. Under the weak-grid conditions, the upstream source contributes approximately 91% of the total fault level, while under the strong-grid conditions this contribution increases slightly to approximately 92%. Although eight BESS units are connected to the investigated MV network, their

individual contribution remains limited due to the inverter-based nature of the BESS systems, where converter control limits the SC current to protect the semiconductor components and maintains a stable operation [3], [5-9].

For faults at the BESS2 busbar, the contribution pattern changes due to the electrical proximity of the fault to the converter-interfaced sources. Since the fault occurs on the low-voltage side of the 11/0.69 kV transformer, the contribution analysis is evaluated using the SC power in order to avoid a misleading comparison of the current magnitudes across the different voltage levels. The results show that the BESS units collectively contribute approximately 61% of the total fault level, while the upstream grid contributes approximately 39%, with only minor differences between the weak-grid and strong-grid conditions. The protection coordination study confirms the satisfactory selectivity between the feeder and the incomer protection devices. The TCC analysis demonstrates adequate grading margins, while the SC Trace simulations confirm that only the protection associated with the faulted section reaches the trip condition. Similar observations are reported in previous studies on the converter-dominated active distribution networks. For the BESS feeder faults, the local feeder protection isolates the fault, whereas the faults at the busbar A10 are selectively cleared by the H01 incomer protection.

Some limitations are encountered during the simulation process. Due to the relay modelling limitations within the available DIgSILENT PowerFactory relay library, the ABB REF620 relay models are partially used instead of the originally installed REF615 relays while maintaining the original protection philosophy. As the directional earth-fault operation cannot be fully visualized in the SC Trace environment due to the software limitations, the selectivity verification primarily focuses on the overcurrent protection functions.

5 CONCLUSION

The study evaluates the impact of the BESS integration on the SC contribution and protection selectivity in an 11 kV MV network located in Söderala, Sweden. The results show that the fault contribution strongly depends on the fault location. At busbar A10, the upstream grid remains the dominant fault source, while for the faults at BESS2, the locally connected BESS units become the dominant contributors.

Our Protection coordination analysis confirms the satisfactory selectivity between the feeder and the incomer protection, where faults are isolated by the protection device associated with the faulted section without unnecessary interruption of the healthy feeders. The findings indicate that a properly coordinated conventional overcurrent protection can maintain a reliable operation in the inverter-dominated MV systems.

Further work may include detailed investigation of the directional earth-fault protection performance and advanced protection approaches for converter-interfaced systems.

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