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Analysis of the Effects of HVDC Technology on Regional Power System Security: Impact of the MONITA HVDC Interconnection

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Abstract—**This paper provides an overview of High Voltage Direct Current (HVDC) technology, including its development, current status, key characteristics, limitations, and applications. It also presents power system security criteria, highlighting their importance for maintaining stability and reliable operation under all conditions. Special focus is given to the MONITA HVDC interconnection, examining its technical and operational features and evaluating its reliability under varying scenarios. The practical part of the study involves security analyses of the interconnection to assess its impact on the regional power system. Multiple operating conditions were considered, including normal operation, overload situations, and scenarios involving electricity import and export in the region. The objective of the research was to evaluate the behaviour of the MONITA HVDC interconnection under realistic operational conditions and its contribution to system stability and reliability. Detailed simulations were performed to assess its ability to maintain grid stability during sudden load variations, changes in power flows, and in cases of disconnections or failures of other network elements. The results demonstrate how the interconnection influences the regional power system's operational security, identifying strengths and potential vulnerabilities. These findings provide valuable insights into the role of HVDC technology in enhancing the reliability and stability of modern power systems, and offer guidance for future planning, operation, and expansion of cross-border HVDC interconnections.**

Keywords - HVDC technology, power system security, MONITA HVDC interconnection, security analysis

I. INTRODUCTION

Ensuring the security of the power system is a key task at all stages of system development – from planning to operation. Power system security implies the system's ability to remain stable and functional despite disturbances, faults, and changes in operating conditions. In the context of the energy transition and the expected increase in the share of renewable energy sources (RES) to 55% by 2030, system stability is becoming increasingly challenging due to the inherent variability of RES. Consequently, modernisation of grid infrastructure, increased system resilience, and the adoption of advanced technical solutions have been essential. HVDC technology plays a crucial role in this transition by enabling accurate power flow control, isolation of disturbances, and enhanced system stability. However, the N-1 criterion continues to represent the fundamental principle of system security, with N-2 contingency analysis gaining increasing relevance in contemporary power system operation.

This paper examines the MONITA HVDC link (Montenegro – Italy) from the perspective of operational planning, with the aim of analysing its behaviour under various operating conditions. The analyses were performed using the eTNA (Enterprise Transmission Network Analyzer) tool and were based on available pre-real-time datasets (D-1/D-2). While real-time flows may differ from planned values due to a variety of system-wide factors, the planned datasets proved sufficiently accurate to support meaningful analyses and to enable reliable conclusions.

The purpose of this paper is to provide, through simulations of representative scenarios across the Balkan region, a detailed assessment of the influence of the MONITA HVDC interconnection on power system stability and security, while emphasising the importance of timely planning and security analyses for ensuring efficient and reliable electricity transmission between Montenegro and Italy. Rather than investigating the root causes of the analysed system states, the study focuses on their implications for system security. The obtained results provide a basis for improving operational control and protection strategies in a regional context.

II. OPERATING PRINCIPLES OF HVDC SYSTEMS

Technological advancements in the early 20th century revitalised interest in HVDC as an efficient means for long-distance electricity transmission, especially in submarine cable applications. HVDC technology enables the interconnection of power systems operating at different voltage levels and characteristics. Converter stations are central to this process, providing voltage transformation and system adaptation to ensure stable and reliable network integration. Every HVDC transmission system includes two converters, one at each end.

At the sending terminal, a source station operates as a rectifier, converting AC (alternating current) from the grid into DC (direct current). At the receiving terminal, a station operates as an inverter, converting DC back into AC for distribution within the target network.

HVDC converters are implemented using thyristor-based technology or IGBT-based (Insulated Gate Bipolar Transistor) solutions, with devices connected in series to achieve high voltage ratings or in parallel for higher current capability. Converters are structured as multiphase bridges containing multiple valves, the number of which depends on the system's power and voltage requirements. These high-voltage semiconductor valves enable precise control of power flow. HVDC systems are generally designed so that each converter can operate in both rectifier and inverter modes, depending on the direction of power transfer. The converter provides the interface between the AC network and the valves by transforming voltage and current to levels suitable for valve operation. Stable and reliable HVDC operation requires additional equipment, including filtering reactors, measurement and protection devices, and cooling and control systems [1].

HVDC systems can be configured in various topologies to meet specific operational requirements (Figure 1). The basic configuration is a monopolar connection with a single conductor and current return through the ground or sea, reducing costs by requiring only one cable. The conductor typically operates with negative polarity to minimise losses and radio interference. Ground return in monopolar HVDC systems is implemented through dedicated electrodes designed to withstand both continuous operation and overload conditions. Although monopolar configurations are economically more attractive than bipolar ones, ground return use has become increasingly limited due to environmental and operational concerns. To prevent corrosion and stray currents in transformers and other metallic structures, grounding electrodes must be located at a sufficient distance from converter stations and transmission cables. Regions with high soil and water conductivity provide more favourable conditions for implementing such electrode systems.

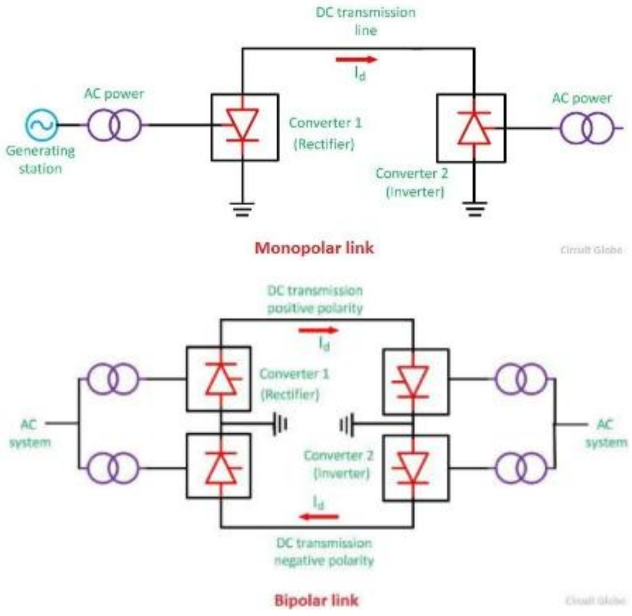

Figure 1. Monopolar configuration and bipolar configuration HVDC [2]

To meet the requirements of higher power transfer, the monopolar configuration is expanded into a bipolar one, which provides double the transmission capacity. A bipolar link has two DC lines, one operated with a positive polarity and the other with a negative polarity. If a fault occurs on one of the lines, the system automatically switches to monopolar operation.

A. Advantages and Limitations of HVDC in Comparison with HVAC

The stability and reliability of the power system largely depend on the choice of transmission technology. The two main approaches to electric power transmission are HVAC (High Voltage Alternating Current) and HVDC, each offering specific advantages and limitations, with the choice between them determined by both technical and economic factors. HVAC systems have long been the standard solution in power systems, primarily due to their inherent capability for straightforward voltage transformation and seamless integration into existing network infrastructures. However, when applied over long transmission distances, HVAC systems experience substantial efficiency limitations. These arise from reactance-related losses, skin effect, and capacitive charging currents, which collectively increase transmission losses and impose strict constraints on the maximum technically and economically feasible transmission distance.

In contrast, HVDC systems operate using direct current, which maintains a constant polarity and eliminates several loss mechanisms inherent to AC transmission. This enables more stable and efficient power transfer over long distances, enhanced controllability of power flows, and a reduced number of required conductors. Owing to these advantages, HVDC technology is particularly well suited for submarine cable applications, the integration of remote and offshore energy resources, and the interconnection of power systems operating at different frequencies.

HVDC systems offer several technical benefits over AC transmission. The absence of skin effect allows more efficient utilisation of conductors, while the lack of reactance enables stable power transfer over long distances without reactive power limitations. Moreover, HVDC transmission is free from induced and zero-sequence currents, resulting in reduced electromagnetic interference, although specialised DC circuit breakers are required for effective current interruption. Another key advantage is the absence of capacitive charging currents, which allows reliable and efficient power transmission through long cable links.

The main disadvantages of HVDC systems are the high initial costs resulting from the complexity of converter stations, filters, protection systems, and grounding installations. Specialised equipment is required for current interruption, which further complicates operation. HVDC systems also generate harmonics and electromagnetic disturbances, and their control and maintenance require advanced technical support. For these reasons, they are less suitable for shorter distances, where HVAC remains the more cost-effective solution. HVDC becomes economically viable beyond approximately 50 km in cable applications and enables the interconnection of AC networks operating at different frequencies without increasing system short-circuit levels. Although HVDC systems require fewer conductors and allow simpler cable designs, the initial investment-primarily for converter stations—remains substantial. Nevertheless, for transmission distances of approximately 500-1000 km, HVDC solutions become increasingly cost-effective due to lower transmission losses and reduced maintenance requirements. Consequently, HVAC is generally preferred for shorter distances, while HVDC is the optimal choice for long-distance and submarine interconnections [3].

III. MONITA HVDC INTERCONNECTION

The MONITA project represents an HVDC interconnection between Italy (Villanova) and Montenegro (Lastva), commissioned in 2019. The primary objective of the project was to integrate the Montenegrin power system and, by extension, the broader Balkan region, into the Adriatic transmission corridor of central Italy, thereby strengthening cross-border connectivity and enhancing regional power system integration.

MONITA is characterised by a nominal power of 600 MW and a nominal direct current voltage of 500 kV. The interconnection has a total length of 445 km, of which 16 km is a land cable on the Italian coast, 423 km is a submarine cable at a depth of 1,200 metres to the Montenegrin coast, and 6 km is a land cable in Montenegro. This submarine cable connects the Italian 400 kV converter station in Ceppagatti with the Montenegrin 400 kV station in Kotor.

MONITA is based on a monopolar configuration with the possibility of upgrading to a bipolar configuration and expanding to 1,200 MW. It has a power transmission capacity of 600 MW in both directions (from Montenegro to Italy and vice versa).

The interconnection was developed, is owned, and is operated by Terna, the Italian transmission system operator (TSO), while the Montenegrin TSO CGES, was responsible for the construction of the Lastva 400 kV AC substation and its integration into the national 400 kV transmission network. Figure 2 shows the electrical connection between Italy and Montenegro, highlighting the ownership and management of the infrastructure.

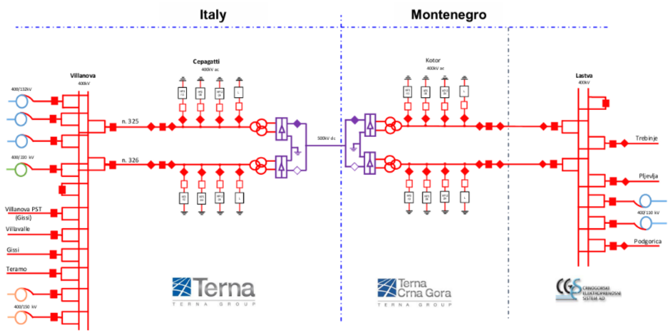

Figure 2. Electrical connection between Italy and Montenegro: ownership and management [4]

The aim of the project is to ensure N-1 security for the transfer of 500-1000 MW via the submarine HVDC cable, thereby enhancing the reliability of electricity supply along the Montenegrin coast and enabling a direct interconnection with Italy. The project contributes to reduced network loading, lower transmission losses, improved voltage profiles, and an increase in overall transmission capacity of approximately 500 MW. Furthermore, by interconnecting the electricity markets of Italy and Southeast Europe, the project enhances market competitiveness and supports the reduction of CO_2 emissions. The operation of the MONITA link is jointly managed by Terna and CGES under the 2019 agreement, which includes shared operational protocols, real-time coordination, mutual support during critical events, automatic control of active and reactive power, emergency assistance when required, and the management of reactive power exchange with a maximum limit of 50 MVAr [4].

IV. POWER SYSTEM SECURITY AND THE IMPACT OF HVDC TECHNOLOGY

Secure power system operation requires maintaining the system within the limits of stable operation, even in the event of an outage of an individual system component, a requirement most commonly assessed using the **N-1 security criterion**. According to this criterion, the power system must be capable of withstanding the loss of any single element without causing violation of voltage or thermal limits in remaining components, and without interrupting electricity supply [5, 6]. Within this framework, HVDC systems represent a key mechanism for enhancing system security, as they enable precise control of power flows and efficient decoupling of interconnected network areas. Their ability to provide rapid regulation and disturbance isolation significantly limits the propagation of system disturbances and enhances overall network resilience.

Nevertheless, the impact of HVDC technology on power system security is highly dependent on overall system conditions at the regional level and may not always be uniformly beneficial. Under certain circumstances, the specific characteristics of HVDC links can introduce operational challenges or produce unforeseen effects. The following sections present a series of scenarios that illustrate how HVDC technology may behave differently with respect to maintaining operational security during the pre-real-time operational period.

A. *Operational Planning and Coordinated Security Analyses*

Operational planning is a fundamental element of power system management, as effective planning ensures efficient and reliable real-time system operation. The model applied today has evolved through technical, legal, organisational, and market-related developments within the electricity sector. In order to coordinate and centralise specific tasks, specialised companies known as RSCs/RCCs (Regional Security Coordinators / Regional Coordination Centres) have been established, owned by the TSOs. Leveraging the data provided by TSOs, RSCs/RCCs perform detailed analyses, identify potential risks, and issue recommendations, while ultimate decision-making authority remains with the TSOs. All European RSCs/RCCs provide their clients with five core services: validation and merging of individual grid models and the creation of a common grid model, coordinated capacity calculation, coordinated security analyses, coordination of outage planning, and short-term adequacy [7].

Once transmission capacities have been allocated and cross-border exchanges are known, a security analysis is performed on the interconnected network model of Continental Europe (the CGM - Common Grid Model), assessing compliance with the N-1 security criterion and forecasting congestion. The assessment is carried out using predefined outage lists and monitored-element lists. The most reliable results are provided by the intraday Congestion Forecast (IDCF) analysis, which is based on data close to real time, while in the absence of such data, day-ahead Congestion Forecast (DACF) results are used.

B. *Case Study on the MONITA HVDC Interconnection*

In the UCTE format, HVDC systems are most commonly modelled as fixed active power injections on both sides of the cable, within the appropriate TSOs' network models. The MONITA cable represents a specific case because it is not a cross-border asset in terms of ownership; instead, it is fully owned by a single TSO (Terna), as shown in Figure 3.

In the CGES model, the MONITA HVDC cable is represented as two short 400 kV transmission lines connecting the Lastva substation (SS Lastva) to so-called X-nodes, which represent a notational system boundary. The remaining portion of the interconnection, including the second half of the HVDC cable, is modelled within Terna's transmission system. The interconnection points (X-nodes) between Montenegro and Italy are located at the electrical midpoint of the 400 kV line linking the CS Kotor and SS Lastva substations.

In Terna's models, MONITA is represented through injections, modelled as generation and matching consumption at the nodes ICEPR121 and IKOTR121, depending on the operating mode. The converter stations at CS Kotor and CS Ceppagatti are connected to the network via two 400 kV transmission lines: one used for active power transfer, and the other providing limited reactive power control.

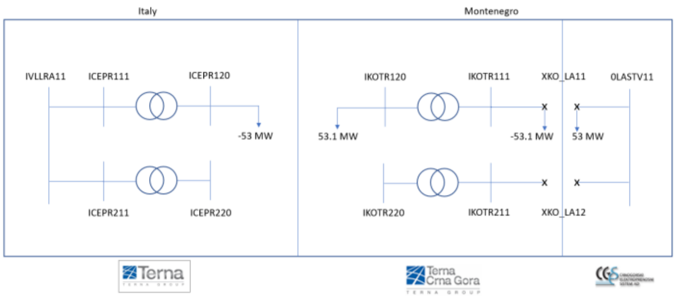

Figure 3. The modelled representation of the MONITA HVDC interconnection

C. *Security Analysis Tool and Model Validation*

Enterprise Transmission Network Analyzer (eTNA) is a professional software tool designed for the calculation, validation, and analysis of transmission power systems. The software enables comprehensive processing of network models, including validation, correction, merging, and conversion of transmission network models in various data formats, as well as power flow calculations and security analyses [8]. In this study, eTNA.2.4 was used as the primary tool for performing regional security analyses based on merged IGMs (Individual Grid Models) provided by TSO. The IGMs contain detailed information on network topology, generation, load, and interconnections between systems.

Prior to merging the IGMs into a CGM for analysis purposes, each IGM was subjected to a set of validation rules defined within the ETNA framework and prescribed by ENTSO-E. These rules were applied to ensure data consistency, model validity, and compliance with power system modelling standards. Models that did not meet all validation criteria were excluded from the CGM and replaced with appropriate validated models. This process ensures reliable input data for further analysis and enables accurate and comparable simulation results across different analysed scenarios.

V. COORDINATED SECURITY ANALYSES

The security assessment in this study is not limited solely to the conventional N-1 criterion, but also includes N-X security analyses in accordance with ENTSO-E recommendations. These analyses encompass comprehensive monitoring of thermal constraints of transmission elements, verification of voltage limit compliance, and monitoring of voltage angle differences.

All results and analyses presented were conducted for day-ahead scenarios using the CGM of the Continental European power system in UCTE format. The findings are reported exclusively for the most critical hour (time stamp) within each considered scenario. The percentage of (over)loading was calculated based on the maximum allowable current (I/Imax*100) or apparent power (S/Smax*100) as provided by the model. In addition to thermal loading, reactive power exchanges were taken into account, and voltage levels were maintained within permissible operational limits across all analyzed scenarios, in line with ENTSO-E operational security requirements.

A. *First Scenario – Hour 13 (06.05.2024)*

In the first scenario, for hour 13 on May 6, 2024, the base case with a flow of 600 MW [9] through the MONITA, in the direction ME → IT, was considered, while the new base case assumes a reduced flow of 300 MW.

In the analysed scenario, power flows were southeast–northwest, with Albania and Montenegro as key transit countries (Figure 4). Montenegro imports around 1,400 MW via three 400 kV eastern interconnections, while exports occur at other borders. The interconnection with Italy reaches a maximum export of 600 MW, corresponding to the technical capacity of the MONITA submarine cable. Exports to Bosnia and Herzegovina and Serbia are significantly lower, approximately 400 MW and 80 MW, respectively.

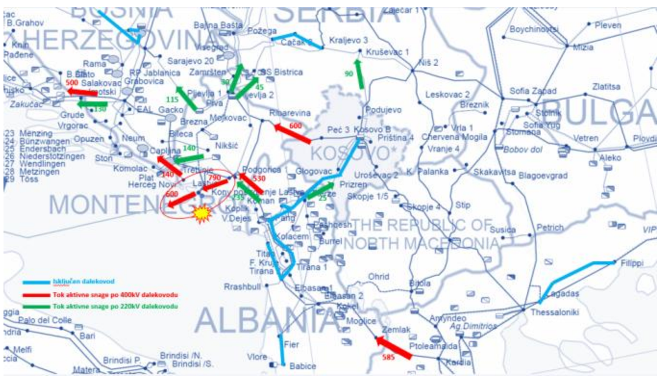

Figure 4. Power flows for the 06/05/2024 scenario, ME→IT=600 MW

The security analysis, shown in Table I, for May 6, 2024 (Monday) at hour 13 indicated overloading of two 220 kV lines. The highest level of overload was detected on the internal Albanian 220 kV line Vau Dejes – Koplik, as well as on the 220 kV interconnection line Podgorica 1 – Koplik, resulting from the outage of the 400 kV interconnection line Tirana 2 – Podgorica 2.

TABLE I. SECURITY ANALYSIS RESULTS FOR HOUR 13 ON 06.05.2024 – MONITA FLOW 600 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
400kV Tirana 2 - Podgorica 2	220kV Vau Dejes - Koplik	157.66	94.9
400kV Tirana 2 - Podgorica 2	220kV Podgorica 1 - Koplik (AL)	153.83	92.06
400kV Tirana 2 - Podgorica 2	220kV Koplik - Podgorica 1 (ME)	153.55	91.62
400kV Peć 3 - Ribarevine	220kV Vau Dejes - Koplik	118.12	94.9
400kV Peć 3 - Ribarevine	220kV Podgorica 1 - Koplik (AL)	114.91	92.06
400kV Peć 3 - Ribarevine	220kV Koplik - Podgorica 1 (ME)	114.53	91.62
400kV Kosovo B - Peć 3	220kV Vau Dejes - Koplik	109.94	94.9
400kV Kosovo B - Peć 3	220kV Podgorica 1 - Koplik (AL)	106.85	92.06
400kV Kosovo B - Peć 3	220kV Koplik - Podgorica 1 (ME)	106.45	91.62
400kV Tirana 2 - Elbasan 2	220kV Vau Dejes - Koplik	103.17	94.9
400kV Tirana 2 - Elbasan 2	220kV Podgorica 1 - Koplik (AL)	100.17	92.06
400kV Tirana 2 - Elbasan 2	220kV Koplik - Podgorica 1 (ME)	99.78	91.62

The results of the security analysis clearly indicate that the 220 kV lines Vau Dejes – Koplik and Podgorica 1 – Koplik are loaded to approximately 150% of their nominal capacity following the outage of the 400 kV line Tirana 2 – Podgorica 2. Such a level of loading implies that, in the event of a failure, these lines would very quickly reach the second stage of overload protection, significantly reducing the time available for remedial action. Practically, this scenario can be treated as a double contingency (N-2 condition).

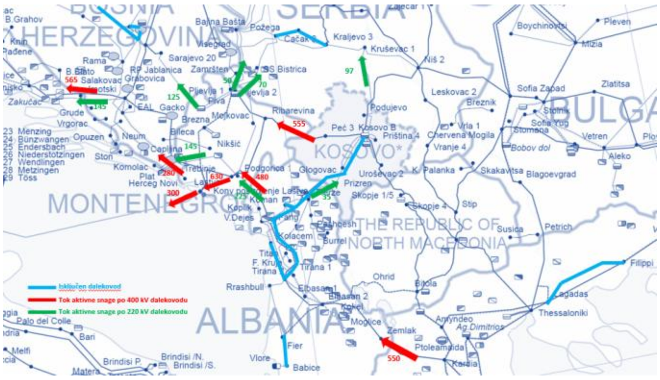

Figure 5. Power flows for the 06/05/2024 scenario, ME→IT=300 MW

Following the implementation of the remedial action, which reduced the MONITA power flow to 300 MW, several notable changes in regional power flows were observed. The flow from Greece to Albania decreased by 35 MW, while the flow from Albania to Montenegro decreased by 60 MW (Figure 5). Concurrently, the 400 kV Trebinje–Lastva interconnection experienced an increase in flow from Montenegro to Bosnia and Herzegovina of 140 MW, resulting in a total export increase of 155 MW from Montenegro to Bosnia and Herzegovina. Additionally, the flow from Montenegro to Serbia rose by 45 MW, whereas the flow from Kosovo* decreased by the same amount, 45 MW.

The security analysis was repeated for the modified model, in which the MONITA flow was limited to 300 MW. The results in Table II show that reducing the MONITA flow does not significantly improve overall system relief. However, the remedial action has some positive effects: the critical 220 kV lines that previously reached the second stage of overload protection now remain within the first stage limits. This provides dispatchers with approximately 20 extra minutes to respond, which is crucial for implementing further operational and remedial action to stabilize the system and prevent escalation of disturbances.

TABLE II. SECURITY ANALYSIS RESULTS FOR HOUR 13 ON 06.05.2024 – MONITA FLOW 300 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
400kV Peć 3 - Ribarevine	220kV Vau Dejes - Koplik	114.85	93.34
400kV Peć 3 - Ribarevine	220kV Podgorica 1 - Koplik (AL)	111.72	90.54
400kV Lastva - Podgorica 2	220kV Podgorica 1 - HE Perućica	111.52	62.78
400kV Peć 3 - Ribarevine	220kV Koplik - Podgorica 1 (ME)	111.3	90.07
400kV Lastva - Podgorica 2	220kV Vau Dejes - Koplik	109.65	93.34
400kV Kosovo B - Peć 3	220kV Vau Dejes - Koplik	107.27	93.34
400kV Lastva - Podgorica 2	220kV Trebinje - HE Perućica (ME)	106.68	49.35
400kV Lastva - Podgorica 2	220kV Podgorica 1 - Koplik (AL)	106.57	90.54
400kV Lastva - Podgorica 2	220kV Koplik - Podgorica 1 (ME)	106.17	90.07
400kV Kosovo B - Peć 3	220kV Podgorica 1 - Koplik (AL)	104.26	90.54
400kV Kosovo B - Peć 3	220kV Koplik - Podgorica 1 (ME)	103.82	90.07
400kV Lastva - Podgorica 2	220kV Trebinje - HE Perućica (BA)	99.95	45.86
400kV Tirana 2 - Elbasan (1)	220kV Podgorica 1 - Koplik (AL)	98.38	90.54
400kV Tirana 2 - Elbasan (1)	220kV Koplik - Podgorica 1 (ME)	97.95	90.07

B. *Second Scenario – Hour 02 (24.06.2024)*

In the second analysed scenario, for hour 02 on June 24, 2024, the base operational state with a power flow of 600 MW [9] through the MONITA interconnection, in the direction ME → IT, was considered. The new base case assumed a reduction of this flow to 300 MW.

The scenario is characterized by substantial power flows across the Montenegro–Bosnia and Herzegovina border, with Montenegro exhibiting a high net electricity import. These flows are subsequently directed towards Italy via the MONITA interconnection, as well as through Montenegro's eastern interconnections. Across the three 400 kV interconnections on the eastern border, Montenegro achieves a net export of approximately 550 MW, while the interconnection with Italy reaches a maximum transfer of 600 MW (Figure 6).

The flow configuration at the Montenegro–Bosnia and Herzegovina border is particularly noteworthy, with substantial imports into Montenegro of around 1,100 MW, mostly via the 400 kV network. This configuration indicates that, under this regime, MONITA carries a dominant share of the system power, significantly influencing power flow redistribution and the overall operational topology of the regional transmission network. The security results are presented in Table III.

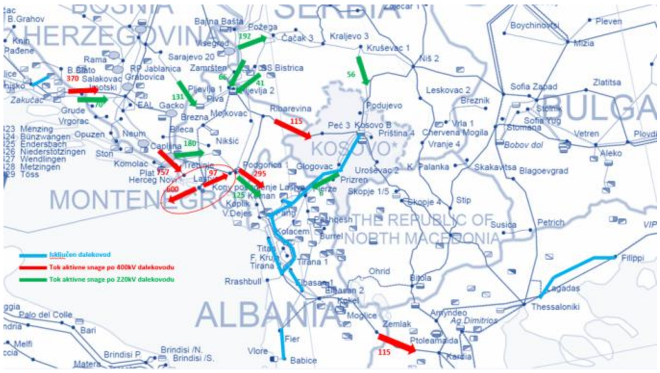

Figure 6. Power flows for the 24/06/2024 scenario, ME→IT=600 MW

TABLE III. SECURITY ANALYSIS RESULTS FOR HOUR 02 ON 24.06.2024 – MONITA FLOW 600 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
400kV Trebinje - Lastva	220kV Podgorica 1 - HE Perućica	140.91	60.24
400kV Trebinje - Lastva	220kV Trebinje - HE Perućica (BA)	140.81	60.01
400kV TE Gacko - Trebinje	TR 400/220kV Trebinje (1)	128.88	43.95
400kV Trebinje - Lastva	220kV Trebinje - HE Perućica (ME)	128.42	54.8
400kV Trebinje - Lastva	110kV Bileća - Čvor Vilusi (BA)	126.97	56.1
400kV Trebinje - Lastva	110kV Bileća - Čvor Vilusi (ME)	120.68	53.12
400kV Trebinje - Lastva	110kV Čvor Vilusi - Nikšić 1	119.88	52.34
400kV TE Gacko - Mostar 4	TR 400/220kV Trebinje (1)	105.37	43.95

The security analyses indicate that, in the event of an outage of the 400 kV interconnection line Trebinje–Lastva, two 220 kV lines become overloaded: the internal 220 kV line Podgorica 1–HE Perućica and the 220 kV interconnection line Trebinje–Perućica. Furthermore, substantial overloading of the 400/220 kV transformer at SS Trebinje was observed during outages of the internal 400 kV lines Gacko–Trebinje and Gacko–Mostar 4. This behaviour is expected, as the loss of certain 400 kV lines forces power flows to be rerouted through the 220 kV network, resulting in additional loading on these system components.

In such scenarios, remedial actions are essential to prevent overloading and potential cascading outages at lower voltage levels. One such measure involved a set-point adjustment, specifically reducing the power flow through the MONITA HVDC interconnection from 600 MW to 300 MW. While the overall distribution of power flows remained largely unchanged, the primary objective was successfully achieved: the power flow through the 400 kV line Trebinje–Lastva was effectively reduced, with no major deviations observed at other borders (Figure 7).

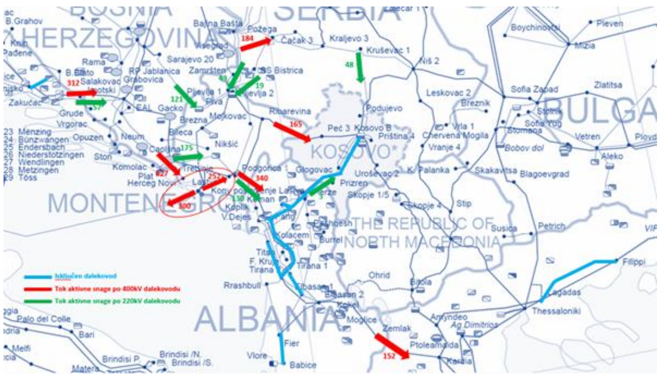

Figure 7. Power flows for the 24/06/2024 scenario, ME→IT=300 MW

TABLE IV. SECURITY ANALYSIS RESULTS FOR HOUR 02ON 24.06.2024 – MONITA FLOW 300 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
400kV Trebinje - Lastva	220kV Podgorica 1 - HE Perućica	124.44	58.02
400kV Trebinje - Lastva	220kV Trebinje - HE Perućica (BA)	124.38	57.8
400kV Trebinje - Lastva	220kV Trebinje - HE Perućica (ME)	113.41	52.78
400kV Trebinje - Lastva	110kV Bileća - Čvor Vilusi (BA)	108.93	50.33
400kV TE Gacko - Trebinje	TR 400/220kV Trebinje (1)	105.91	33.87
400kV Trebinje - Lastva	110kV Bileća - Čvor Vilusi (ME)	103.46	47.62
400kV Trebinje - Lastva	OHL 110kV Čvor Vilusi - Nikšić 1	102.67	46.84

Table IV summarises the security analysis for the updated base case following the implementation of the remedial action. By reducing the MONITA power flow to 300 MW, overloads were alleviated; however, the system remains potentially insecure, necessitating consideration of additional measures. These may include further set-point reductions to 100 MW or 0 MW, or redispatching, although the latter approach is both costly and rarely applied.

C. Third Scenario – Hour 09 (28.06.2024)

The third analysed scenario, corresponding to 28 June 2024 at hour 09, was identified as critical. The base case for the MONITA interconnection is 600 MW [9], while the updated base case reflects a reduced flow of 300 MW in the direction from Montenegro to Italy (ME → IT). In this scenario, substantial power flows persist across the Montenegro - Bosnia and Herzegovina border, with Montenegro exhibiting a net import of approximately 630 MW (Figure 8).

Although this operating regime may initially appear less critical than previous scenarios, detailed analysis reveals otherwise. Due to the specific network topology and the outage of the internal 400 kV line Gacko–Mostar 4, the 400/220 kV transformer at SS Trebinje is already in an overloaded state under the base case conditions.

Figure 8. Power flows for the 28/06/2024 scenario, ME→IT=600 MW

The results of the security analyses for June 28, 2024 (Friday) at hour 09 are presented in Table V. A very similar situation occurs during other hours when the internal 400 kV line Gacko – Mostar 4 is out of service and the MONITA flow is 600 MW in the direction ME → IT.

TABLE V. SECURITY ANALYSIS RESULTS FOR HOUR 09 ON 28.06.2024 – MONITA FLOW 600 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
400kV Lastva - Podgorica 2	TR 400/220kV Trebinje (1)	141.35	101.23
220kV Podgorica 1 - HE Perućica	TR 400/220kV Trebinje (1)	122.64	101.23
400kV Ribarevine - Podgorica 2	TR 400/220kV Trebinje (1)	120.91	101.23
220kV HE Perućica - Trebinje	TR 400/220kV Trebinje (1)	117.65	101.23
400kV Ribarevine - Pljevlja 2	TR 400/220kV Trebinje (1)	111.37	101.23
400kV Obrenovac - Kragujevac 2	TR 400/220kV Trebinje (1)	108.96	101.23
220kV Sarajevo 20 - HE Piva	TR 400/220kV Trebinje (1)	106.94	101.23
TR 400/220kV Sarajevo 20 (1)	TR 400/220kV Trebinje (1)	106.92	101.23
400kV RP Mladost - S. Mitrovica 2	TR 400/220kV Trebinje (1)	106.69	101.23
TR 400/220kV Trebinje (1)	220kV Trebinje - HE Perućica	94.36	36.42
400kV Trebinje - Lastva	220kV Trebinje - HE Perućica	94.22	36.42

Critical outages have been identified in Montenegro, Bosnia and Herzegovina, and Serbia, resulting in overloading of the 400/220 kV transformer at SS Trebinje. Moreover, there is a potential risk of cascading effects in N-2 scenarios, where transformer outages at Trebinje coincide with other critical contingencies highlighted in the security analyses.

Figure 9. Power flows for the 28/06/2024 scenario, ME→IT=300 MW

The results for the updated base case indicate that overall power flows remained largely unchanged (Figure 9). Notably, the power flow across the Montenegro–Bosnia and Herzegovina border was reduced by approximately 80 MW. While this reduction may appear modest, it represents a critical shift in the distribution of power flows. In particular, a substantial decrease in the loading of key 400 kV lines was observed; for instance, the flow on the 400 kV line Podgorica 2–Lastva decreased from 170 MW to approximately 40 MW, accompanied by a corresponding reduction in the loading of the 400/220 kV transformer at SS Trebinje. The updated security analysis results, presented in Table VI, corroborate these findings.

Following the reduction of the MONITA flow to 300 MW, the overload on the 400/220 kV transformer at SS Trebinje decreased by over 15%, representing a significant improvement under the prevailing conditions. Critical outages on the 400 kV lines were eliminated, with the only potentially critical situation remaining the outage of the internal 220 kV line Podgorica 1–HE Perućica. Nevertheless, the observed overload of approximately 105% is deemed acceptable within operational limits.

TABLE VI. SECURITY ANALYSIS RESULTS FOR HOUR 09 ON 28.06.2024 – MONITA FLOW 300 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
220kV Podgorica 1 - HE Perućica	TR 400/220kV Trebinje (1)	104.9	84.53

D. Fourth Scenario – Hour 22 (12.07.2024)

The fourth scenario, corresponding to 12 July 2024 at the critical hour 22, considers a state in which Montenegro imports 600 MW from Italy (Figure 10) [9].

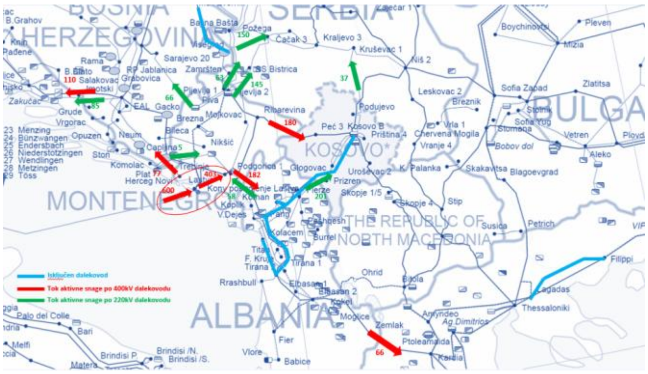

Figure 10. Power flows for the 12/07/2024 scenario, IT→ME=600 MW

Unlike previous scenarios, this case specifically examines imports at the Montenegro–Italy border at 600 MW. While the system is not highly critical, it is observed that Montenegro exports electricity through nearly all other borders, except the one towards Italy. Power flows are predominantly directed eastward, mainly through the 400 kV network, with the highest flow recorded on the internal 400 kV line Podgorica 2–Lastva.

The data in Table VII indicate that no significant overloads were detected within the Montenegro system, with only overloads occurring in the 110 kV network. The majority of overloads were identified in the Albanian system, highlighting the influence of the MONITA interconnection on these lines. As a remedial action, the set-point was once again reduced from 600 MW to 300 MW.

TABLE VII. SECURITY ANALYSIS RESULTS FOR HOUR 22 ON 12.07.2024 – MONITA FLOW 600 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
220kV Koman - Vau Dejes	220kV Tirana 3 - Tirana 2	129.86	91.86
220kV Koman - Tirana 3	220kV Koman - Vau Dejes	122.57	78
220kV Tirana 3 - Tirana 2	220kV Koman - Vau Dejes	122.57	78
110kV Virpazar - Podgorica 2	110kV Budva - Bar	112.51	45.78
220kV Prizren 2 - Fierza	220kV Tirana 3 - Tirana 2	106.58	91.86
220kV Fierza - Peshqesh	220kV Tirana 3 - Tirana 2	101.96	91.86
400kV Tirana 2 - Podgorica 2	220kV Tirana 3 - Tirana 2	101.95	91.86
110kV Budva - Bar	110kV Virpazar - Podgorica 2	101.16	53.88
220kV Vau Dejes - Tirana 1 (1)	220kV Tirana 3 - Tirana 2	99.93	91.86
220kV Vau Dejes - Tirana 1 (2)	220kV Tirana 3 - Tirana 2	91.86	99.93
220kV Prizren 2 - Fierza	220kV Koman - Vau Dejes	78	99.32
220kV Vau Dejes - Koplik	220kV Tirana 3 - Tirana 2	91.86	98.42

The updated base case, assuming a reduction of imports to 300 MW (Figure 11) shows that flows on the 400 kV lines Tirana 2 – Podgorica 2 and Ribarevine – Peć 3 decreased by 50 MW each, resulting in a total reduction of approximately 100 MW at these borders. Furthermore, a change in the flow direction on the 400 kV line Trebinje – Lastva was observed, from 77 MW export to 68 MW import, representing a net change of approximately 130 MW. The updated security analysis results are presented in Table VIII.

The analysis indicates that reducing the MONITA flow to 300 MW does not mitigate the overloads in Montenegro's 110 kV network. Furthermore, overloads in the Albanian system slightly increased compared to the scenario with a 600 MW flow on MONITA. These findings suggest that, under the prevailing conditions, this remedial action has a limited impact on alleviating the situation in the Albanian system, highlighting the need for additional remedial actions.

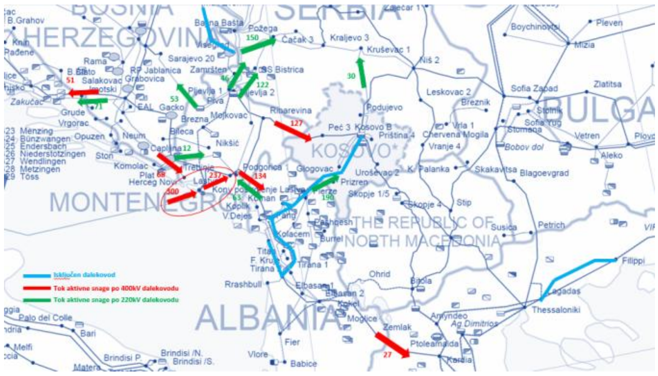

Figure 11. Power flows for the 12/07/2024 scenario, IT→ME=300 MW

TABLE VIII. SECURITY ANALYSIS RESULTS FOR HOUR 22 ON 12.07.2024 – MONITA FLOW 300 MW

Outage	*(Over) Load*	*Overload after outage [%]*	*Base load [%]*
220kV Koman - Vau Dejes	220kV Tirana 3 - Tirana 2	131.35	92.71
220kV Koman - Tirana 3	220kV Koman - Vau Dejes	124.26	79.29
220kV Tirana 3 - Tirana 2	220kV Koman - Vau Dejes	124.26	79.29
110kV Virpazar - Podgorica 2	110kV Budva - Bar	112.14	45.78
220kV Prizren 2 - Fierza	220kV Tirana 3 - Tirana 2	106.71	92.71
220kV Fierza - Peshqesh	220kV Tirana 3 - Tirana 2	102.94	92.71
110kV Budva - Bar	110kV Virpazar - Podgorica 2	100.88	53.86
220kV Vau Dejes - Tirana 1 (1)	220kV Tirana 3 - Tirana 2	100.76	92.71
220kV Vau Dejes - Tirana 1 (2)	220kV Tirana 3 - Tirana 2	100.76	92.71
400kV Tirana 2 - Podgorica 2	220kV Tirana 3 - Tirana 2	100.05	92.71
220kV Vau Dejes - Koplik	220kV Tirana 3 - Tirana 2	99.71	92.71
220kV Prizren 2 - Fierza	220kV Koman - Vau Dejes	99.49	79.29

VI. EXPANDED DISCUSSION OF RESULTS

The results of the security analyses clearly demonstrate that the MONITA HVDC interconnection plays a significant role in shaping power flows and maintaining system stability across the Balkan region. Across all analysed scenarios, several key observations emerge:

– **Impact of flow direction**: The system's response depends on the direction of power transfer. Maximum exports from Montenegro to Italy (600 MW) tend to impose higher stress on regional transmission lines and transformers compared to import scenarios. This finding underlines the importance of considering directional flows.
– **Identification of critical network elements**: Certain network components repeatedly appeared as bottlenecks under N-1 contingencies. Notably, 220 kV and 400 kV lines connecting Montenegro with Bosnia and Herzegovina and Albania, as well as the 400/220 kV transformer at Trebinje, were identified as vulnerable points. These elements require focused monitoring and potential reinforcement to prevent cascading outages.
– **Effectiveness of remedial actions**: Reducing MONITA flows from 600 MW to 300 MW proved effective in alleviating overloads in most scenarios, providing dispatchers with additional time to respond. However, some scenarios illustrate that flow reduction alone may not always resolve all overloads highlighting the need for additional remedial actions and coordinated operational strategies.
– **Regional coordination benefits**: The analyses underscore the importance of coordinated operational planning among TSOs and RCCs. Cooperating and sharing information enables quick actions to prevent overloads and strengthen system security.
– **Implications for HVDC integration**: The findings confirm that HVDC interconnections, while offering significant benefits for precise flow control and system stability, can intensify regional congestion if not properly managed. This dual nature of HVDC technology underscores the importance of continuous security analyses, real-time monitoring, and the development of dynamic operational strategies to fully leverage its advantages while mitigating associated risks.

VII. CONCLUSION

The analysis of the impact of the HVDC MONITA interconnection under various operational scenarios demonstrated that its influence on the security of the power system strongly depends on power exchange direction (export or import), the prevailing network topology, and the regional load level.

Notably, maximum export from Montenegro to Italy (600 MW) exhibits a considerably greater system impact compared to situations in which Montenegro is importing. Multi-scenario assessment indicated that high power flows towards Italy, in correlation with increased transit loading (i.e., the occurrence of loop flows), lead to overloads on critical network elements. Reducing the MONITA set-point (from 600 MW to 300 MW), as a remedial action, alleviates system stress in most of the analysed cases, extending the time available for operator response and enabling the implementation of additional remedial action. However, the effects are not universal - in one scenario (the fourth), the reduction did not produce the expected relief, indicating the need for a detailed and scenario-specific approach when defining remedial actions.

The described action in the analysed scenarios, the set-point change of the MONITA interconnection, was considered within the operational planning process, i.e., during the pre-real-time phase when TSOs make final operational decisions. To provide more comprehensive recommendations, the study should be expanded to include additional scenarios and the consideration of other remedial actions not covered in the current work. Such measures may include:

– **Changes in system topology**, such as adjusting the duration of planned outages, returning transmission system elements to service, transformer tap changes, or busbar separation actions (e.g., energy evacuation from HE Koman to the 400 kV network, or separation of the GR busbar at TS Kardia with the corresponding transfer of transmission lines between busbar systems).
– **Redispatching** measures, such as internal redispatching within the Albanian network in HE Vau Dejes and TE Vlora.
– **Counter-trading** between market zones, for instance cross-border redispatching between Montenegro and Albania (e.g., HE Perućica and HE Vau Dejes).
– **Load reduction**, wherever technically and operationally feasible.

Including these additional scenarios and remedial actions would provide a more robust framework for operational planning and support TSOs in ensuring system security under varying conditions.

Throughout all analysed cases, the MONITA HVDC interconnection has proven to be a powerful tool for managing power flows and maintaining network security, but also as an element that, under unfavourable system configurations, can exacerbate existing overloads. Therefore, precise coordination among TSOs and continuous security analyses are essential for its optimal use.

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