Impact of Voltage Source Converter (VSC) based HVDC interconnection on AC power system energy transmission wide-area disturbances

***Emily Maggioli***, Helder Leite***, Jun Liang*†*, Adriano Carvalho****

**University of Porto, Portugal,* †*Cardiff University, United Kingdom*

Abstract

The future of Power systems include high penetration of renewable energy and interconnectivity between different networks through VSC-HVDC. However, this has increased the stress on transmission systems. WAMS and WAP aim at providing an awareness of the system state and increase the robustness when faced with disturbances, thus increasing security of operation. In this context, the present work provides an overview of the key concepts and challenges of wide-area in Power System energy transmission, as well as highlighting possible impact of VSC-HVDC towards disturbances. In order to be able to assess these disturbances, this paper proposes a methodology to study of VSC-HVDC contribution towards wide-area disturbances and impact on protection systems.

Keywords: Wide-area protection, SIPS, HVDC, VSC-HVDC, Power System Protection, Transmission, AC-DC networks, CAPE

1 Introduction

Following legislative and government pressures for emissions reduction [1], in the energy sector it is widely accepted the proliferation of renewables in power systems, becoming a prominent source of energy [2]. For example, in 2018 wind energy represented 15% of European Union's electricity (2% increase from previous year) [3]. In parallel HVDC (High Voltage Direct Current) connections are being implemented, given their economic benefit in energy transmission over long distances, increasing the access to renewable energy. This way countries which are rich in renewable energy can fulfil high consumption countries, with less renewable sources, as well as allowing to explore offshore wind [2].

There has been a gradual increase of the stress on transmission systems due to growing electricity transfers, particularly during high wind intensity. It is also expected that power systems will be operated closer to the limits, with tighter operating margins, less redundancy [4–6]. All the above mentioned factors have increased the risk for large-scale power system blackouts and the vulnerability of interconnected power systems to operate outside their originally intended design limits [7, 8]. Protective relays prevent the propagation of wide-area disturbances, but can also sometimes contribute to its propagation (e.g. cascaded failures, load shedding) [8]. To ensure transfer capacity and enhance the security of operation and robustness of power systems, System Integrity Protection Schemes (SIPS) and Wide-Area Monitoring Protection and Control Systems (WAMPAC) offer a solution to deal with a more variable system operation and enhance conventional operational security [4, 9]. Wide-area monitoring capability is based on the use of PMU (Phase Measurement Units) to get a vision of the system and provide a response in unforeseen disturbances ensuring security of supply and preventing blackouts [5, 9].

The aim of this paper is to provide an overview of the key concepts and challenges of wide-area in power system energy transmission, listing possible contributions of VSC-HVDC towards disturbances and impact on protection systems. A methodology for assessing the disturbances is proposed, with some initial trials using CAPE TS-Link with PSS/E.

The paper is organised as follows: Section II provides an overview of the key concepts in wide-area; Section III lists the main challenges for WAMPAC and SIPS/WAPS; Section IV provides a list of possible disturbances caused by VSC-HVDC and some mitigation options using SIPS; Section V provides details of the proposed methodology for studying disturbances of VSC-HVDC on AC network and protections; Section VI provides final remarks of the paper.

2 Overview of main concepts in wide-area

2.1 Wide-Area key phenomena

When analysing wide-area phenomena they can be organised into: i) Disturbances or Stressed conditions, ii) Triggering events, iii) Cascaded failures and blackouts.

A wide area disturbance occurs by the propagation of stressed conditions, which can be on the following [8, 10, 11]:

- Voltage instability/collapse;
- Voltage excursions;
- Angular instability (possibly leading to loss of synchronism);

- Small signal excursions;
- Oscillatory instability causing self-sustaining inter-area-oscillations;
- High equipment loading and high power transfer or system bottlenecks;
- Frequency excursions (under and over frequency), due to imbalance between in active power between generation and load;
- High system phase unbalance;
- Cascading failures/tripping, such as line tripping by dynamic line loading (often lends to unsuccessful line restoration attempts), or equipment tripping by over-excitation;

The definition of these phenomenas has been covered in detail in [5, 8, 12].

The triggering events for disturbances can be varied, such as external threats, earthquakes, weather-related events, hidden failures, operator errors and event sabotage events [13]. Hidden failures are different from faults, as they are the failure of the protective device itself [6, 8]. They are called hidden because they remain this way until the case of a fault and thus fail to operate. This also includes incorrect settings or application of a protective device. These types of failures have been reported to be significant contributors to blackouts. [6].

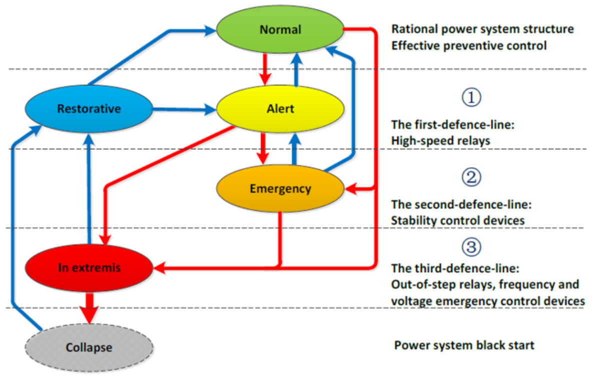

Fig. 1: Power system operating states [5]

A blackout or cascading blackout is, according to NERC (North American Electric Reliability Corporation), *"the uncontrolled successive loss of system elements triggered by an incident at any location"* [13]. In this scenario, the operator and control actions are not able to return the network or section of it to a normal operating condition, failing all the alert and emergency states (see Fig. 1). However, not all cascading outages will result in a blackout, but they are typically triggered by or more disturbance events [13].

2.2 Wide-Area Monitoring System (WAMS) and Wide Area Monitoring, Protection and Control (WAMPAC)

The concepts of Wide Area Monitoring System (WAMS) and Wide Area Monitoring Protection and Control (WAMPAC) are closely related. The first, consists of an advanced measurement system, data and information tool that provides the operator with full visibility of the power system's behaviour in real time. This is achieved through Synchronized Measurement Technology (SMT) and Global Positioning System (GPS) [10]. PMUs are the main form of achieving this information, as they are able to include GPS data and a high sampling rate for dynamic power system data, considering the adequate communication network and data processing are in place [10]. This provides a more accurate information, as many of the current systems rely on RMS measurements for system status calculations. The second, refered to as WAMPC by some authors, is the term used for the wide-area system which combines all the WAMS functionalities with the additional protection and control functionalities [5, 10, 14]. Fig. 2 demonstrates the intervention of WAMPAC in the Power system state change.

Currently WAMS may be used as a complementary system to the operator's Supervisory Control And Data Acquisition (SCADA) system [10]. SCADA contains three main functions: data acquisition, supervisory control and alarm display and control [10]. However the time frame of operation is slower than WAMS (See Fig. 3). Some authors suggest that WAMPAC could replace SCADA in the future [14].

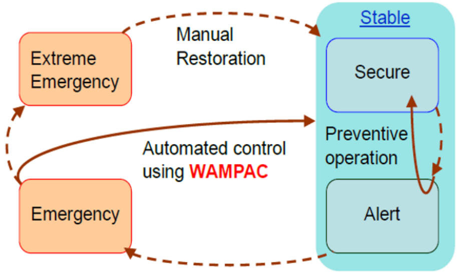

Fig. 2: State change for WAMPAC [5]

2.3 Wide-Area Coordination (WAC)

Wide-area coordination (WAC) or Protection Coordination is a system study to analyse the coordination between relays, to reduce the risk of interruptions during service .This concept is used when referring to unit prelection coordination, but is not the focus of the current work.

2.4 Wide-Area Protection (WAP) and System Integrity Protection Schemes (SIPS)

System Integrity Protection Schemes (SIPS) consist in a set controls/actions defined to protect the integrity of the power system or a part of it, as opposed to fault protection or relays which are dedicated to protect a specific power system element [10, 12]. Authors also consider SIPS to encompass Remedial Action Schemes (RAS), Emergency control Schemes (ECS) [6, 15].

In the case of SIPS used in WAMS/WAMPAC, they are also referred to as Wide-Area Protection (WAP) or Wide-Area Protection Schemes (WAPS) or system wide SIPS. In this scenario, SIPS require the measurement obtained through WAMS as they provide the global vision of the system (as explained in sections above) [10].

The time-frame for WAP or SIPS is demonstrated in Fig. 3. Conventional or ”unit” protection schemes respond immediately upon fault, however, system issues only occur a few seconds after, as currents and voltages change [12].

The classification of SIPS can be made in 3 forms. The first, described in [6, 10, 12], organizes based on the the proportion of the system it impacts. This classification is widely accepted. The second, similar to the first, is accepted by the WECC and focuses on the size of the SIPS as well as the impact. In this context, the safety net refers to backup protection limiting the spread of the disturbance. The third, refers to a more detailed classification first based on size and impact, and secondly on the control principle [9,15]. Additionally, [15] have considered the event and parameter based as similar, thus calling them ”Pre-calculated” SIPS, as they are based on offline studies and parameters.

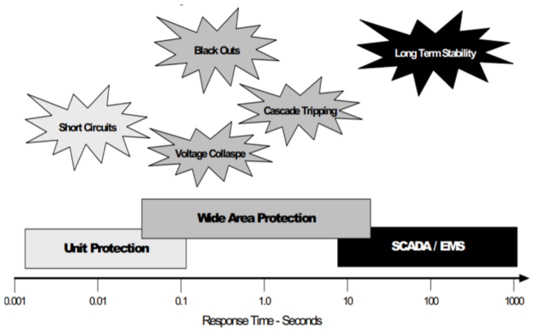

Fig. 3: Response time to Power System events [14]

3 Challenges with Wide-Area Monitoring, Protection and Control

Based on the available literature, the authors have listed some of the challenges faced with integrating WAMPAC/WAMS and WAP/SIPS. It possible to identify, but not limited to, the following challenges: 1. Data management in WAMS/WAMPAC [10]; 2. System observability through optimal PMU location [10, 14]; 3. Co-existence with legacy technology [10, 16]; 4. Reliability and risk of SIPS [4]; 5. Standardization & Regulation [7, 16].

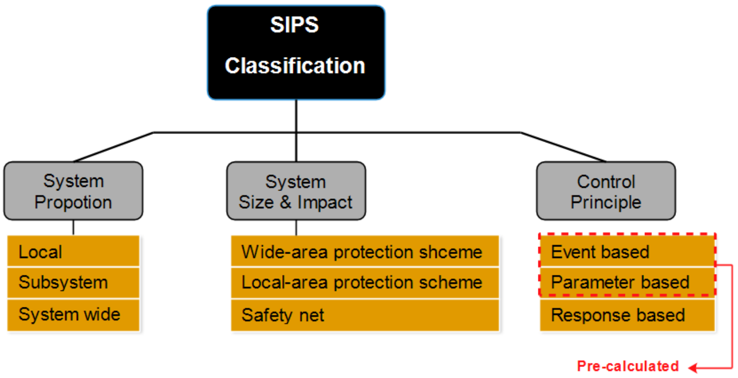

Fig. 4: SIPS classification overview

4 Power system disturbances and increase in VSC-HVDC technology application

4.1 VSC-HVDC links & power system disturbances

Historical disturbances and blackouts have been listed by authors in [13], as well as considerations for test case design based on these events.

The types of wide-area disturbances likely to occur depend on the network configuration. The authors in [6] provide an overview, comparing two grids, one lightly meshed and one densely meshed, both with disperse generation and comparing large or small interconnections. As an overview, the densely meshed system is more susceptible to overloads, regardless of the interconnections, while the lightly meshed is more likely to have frequency and angle instability. The fact of having interconnections means the network is less likely to have frequency instability, overloads or small signal instability, in both meshed scenarios. This assessment could provide useful insight when designing or selecting network configuration for studies. These assumptions could be made considering the interconnection through HVDC, thus still providing valuable insight.

Analysing the list of disturbances provided in Section 2.1 and considering how VSC-HVDC operate, it could be suggested to add another disturbance for ”Off-nominal frequencies” caused by converter operation (e.g. PLL, Switching). Considering some of the categorised interactions between AC and VSC-HVDC presented in [16], an analysis based on assumptions and literature [8, 11, 17–19, 19, 20] was made on the possible stressed conditions originated. The results are summarized in Table 1.

Table 1: Possible disturbances from VSC-HVDC and AC interactions

AC network and VSC-HVDC interaction category	Impact/interaction details	Possible stressed conditions
VSC-HVDC AC fault response	- Increased response time for distance relays - Non-conventional short-circuit characteristics	- Angular instability - Voltage excursion
Protection settings and stability	- Longer response time could mean exceeding critical clearing time	- Voltage instability - Voltage excursion - Angular instability - Small signal excursions - Oscillatory instability
	- Stability studies on interactions	
Short-circuit ratio (SCR) with HVDC links	SCR level reduction with increased VSC-HVDC links, replacing synchronous generators, leads to faster and undamped variations of network parameters	- Voltage excursion - Frequency excursion - Small signal excursions
Harmonics and resonance	- Harmonics in measured signals for relays, will impact the protection function performance - Harmonics caused by converter operation	- Cascaded failure / tripping - Off-normal frequencies

4.2 Mitigation of disturbances using SIPS

As an overview, the authors in [15] provide a diagram (see Fig.5) demonstrating the typical targets and actions based on practical applications for SIPS, considering different disturbances.

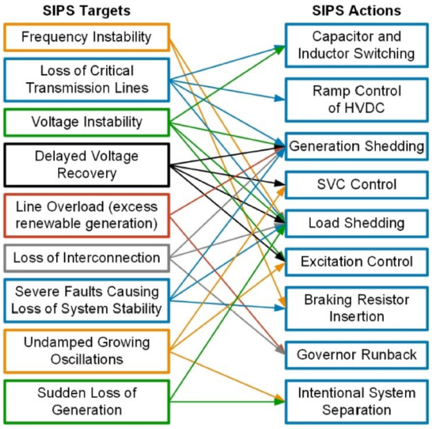

Fig. 5: Typical SIPS targets and actions [15]

5 Methodology for studying disturbances caused by VSC-HVDC on AC network

A methodology is proposed to study the contribution of VSC-HVDC towards power system disturbances, or their propagation, and determine the impact on the AC system or specifically on AC power system protection system. From a high level overview the procedure is divided into 3 parts: 1. Interactions and disturbances, 2. Assessment of interactions and disturbances, 3. Mitigation requirements and procedure(s). The details of each phase are explained in the following sections.

5.1 Disturbances and interactions

The first phase of the methodology consists in identifying the contribution of VSC-HVDC towards AC network disturbances. This is achieved firstly by defining interactions and impact of VSC-HVDC on AC protections (achieved in [16]), secondly to understand the possible stressed conditions originated from the interactions, as shown in Table 1.

In [18] is presented some of the common points found among disturbances. It is worth mentioning high loading of equipment, occurrence of a fault and possible equipment or sections of the network being under maintenance during this period.

In sum, the outcome from this stage is an expectation of the behaviour of the system, the disturbances originated and some of the system conditions which can aggravate the occurrence or propagation of disturbances

5.2 Assessment of interactions and disturbances

Based on the understanding of the previous step it is possible to identify what the expected interactions and disturbances are, this narrows the focus when analysing the system. Once the disturbance has been achieved it is possible to add protection systems or compare the results with the standardized parameters of protection functions (as reference [21]) .

Starting with a smaller network to re-create the disturbance and then increasing the complexity once it is understood. However, this assessment requires a dynamic analysis capability of the tool being used. In this work, the simulation of the behaviour was assessed using CAPE-PSS/E TS-Link, according to the setup described in Fig. 6.

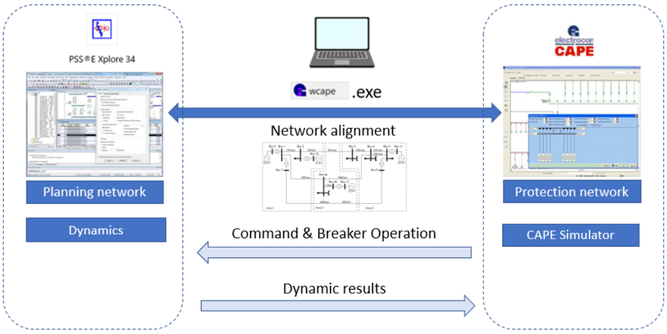

Fig. 6: Simulation setup between CAPE and PSS/E

The outcome from this phase is, after being able to generate a disturbances from the interaction with VSC-HVDC, assess the impact on the protection system. It requires the correct behaviour modelling of the components, which are not be covered in this paper.

5.3 Mitigation requirements and procedure(s)

From the behaviour identified in the previous section, it is possible then to analyse if this behaviour is expected or not and if it can be improved. This can be achieved through requirements, thresholds or recommendations. New assessment with mitigation procedures are carried out using the previous scenario, to confirm effectiveness of the proposed changes.

5.4 Example case: VSC-HVDC fault response

This section provides a case used to exemplify the methodology descripted in sections 5.1 to 5.3. Considering the analysis and assumptions in Table 1. This example, focuses on the VSC-HVDC response to AC faults, specifically voltage stability/excursions.

The network considered is a 3 bus system represented in the Fig. 7. The VSC-HVDC was modelled using the generic type-4 wind generator in PSS/E proposed by WECC [22]. As an attempt to provoke a disturbances a fault was a applied and cleared in the network.

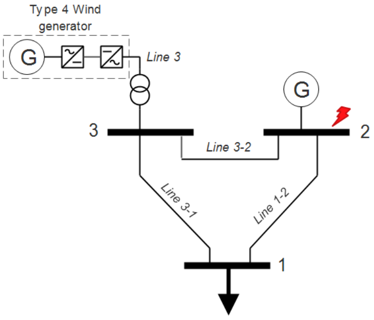

Fig. 7: Case study network

The general expected behaviour for voltage excursion or stability, are low voltage profiles throughout or on specific buses of the system and high reactive power flows. Also, the typical expected behaviour of the converter is a limited fault current between 1.5-2 pu.

Following the above-mentioned steps, it was possible to create an initial disturbance in the network. In Fig. 8 and Fig. 9 below are represented the voltages (in pu) at Bus 1 considering the Generator at Bus 3 as a SG and VSC-HVDC, respectively. This allows to compare the current response and it was observed a cap for VSC-HVDC at about 1.5 pu. At this point a disturbance has been created in the network. The next step is to perform an analysis on the behaviour and impact this will have on typical protection functions such as listed in [16].

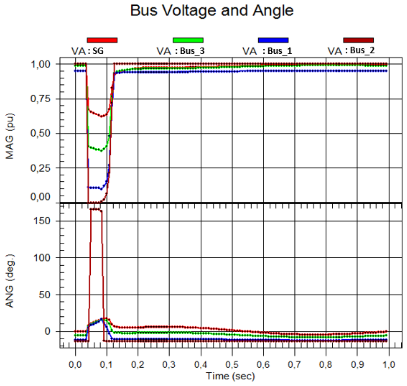

Fig. 8: Example voltage profile for SG on Bus 3

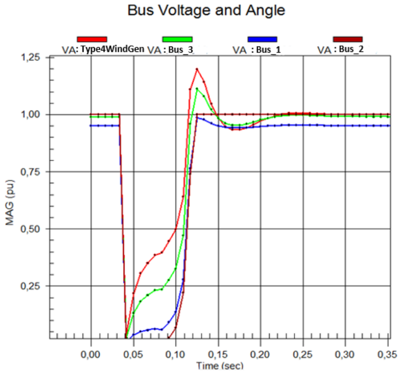

Fig. 9: Example voltage profile for VSC-HVDC on Bus 3

6 Final Remarks

The current paper provided an overview of key concepts used in wide-area and list disturbances and disturbing factors.

This paper proposes an additional consideration for disturbances considering the operation of converters, adding this to the analysis of the some of the contribution of VSC-HVDC towards power system disturbances.

Finally, this paper presents a methodology which can be used for assessing the impact and contribution of VSC-HVDC towards disturbances, focusing on the impact on protection systems. A small example case was performed to demonstrate its application.

Acknowledgements

The current research is done as part of the InnoDC (Innovative Tools for Offshore Wind and DC grids) project. This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 765585.

References

[1] EU, "Paris climate agreement (cop21)." Available online at aec.europa.eu.

[2] H. Nguyen, G. Yang, A. Nielsen, and P. Jensen, "Challenges and research opportunities of frequency control in low inertia systems," *E3S Web of Conferences*, vol. 115, p. 02001, 01 2019.

[3] WindEurope, "Wind europe statistics." Available online at windeurope.org, 2017.

[4] N. Liu and P. Crossley, "Assessing the risk of implementing system integrity protection schemes in a power system with significant wind integration," *IEEE Transactions on Power Delivery*, vol. 33, pp. 810–820, April 2018.

[5] W. G. B5.14, "664 - wide are protection and control technologies," tech. rep., CIGRE, September 2016. Avaialbe at e-cigre.org.

[6] M. Begovic, V. Madani, and D. Novosel, "System integrity protection schemes (sips)," in *2007 iREP Symposium - Bulk Power System Dynamics and Control - VII. Revitalizing Operational Reliability*, pp. 1–6, Aug 2007.

[7] H. Iwaki, Y. Inoue, A. Ishibashi, M. Kimura, K. Omata, and Y. Ishihara, "System integrity protection scheme based on on-line transient stability calculation using protection relay device hardware," in *13th International Conference on Development in Power System Protection 2016 (DPSP)*, pp. 1–6, March 2016.

[8] D. Novosel, G. Bartok, G. Henneberg, P. Mysore, D. Tziouvaras, and S. Ward, "Ieee psrc report on performance of relaying during wide-area stressed conditions," Tech. Rep. 1, Jan 2010.

[9] E. hILLBERG, F. Trengereid, O. Breidablik, K. Uhlen, G. Kjolle, S. Lovlund, and J. O. Gjerde, "System integrity protection schemes - increasing opreational security and system capacity," tech. rep., GIGRE, 2012. Avaialbe at e-cigre.org.

[10] A. Vaccaro and A. F.Zobaa, *Wide Area Monitoring, Protection and Control Systems*. IET, iet power and energy series 73 ed., 2016.

[11] D. Tziouvaras, "Relay performance during major system disturbances," in *2007 60th Annual Conference for Protective Relay Engineers*, pp. 251–270, March 2007.

[12] W. G. C4, "Global industry experinece during wide-area stressed conditions," tech. rep., IEEE Power System Relaying and Controll Committee (PSRC), October 2010. Avaialbe at www.pes-psrc.org.

[13] J. Bialek, E. Ciapessoni, D. Cirio, E. Cotilla-Sanchez, C. Dent, I. Dobson, P. Henneaux, P. Hines, J. Jardim, S. Miller, M. Panteli, M. Papic, A. Pitto, J. Quiros-Tortos, and D. Wu, "Benchmarking and validation of cascading failure analysis tools," *IEEE Transactions on Power Systems*, vol. 31, pp. 4887–4900, Nov 2016.

[14] E. Price, "Practical considerations for implementing wide area monitoring, protection and control," in *59th Annual Conference for Protective Relay Engineers, 2006.*, pp. 12 pp.–, April 2006.

[15] K. G. Ravikumar and A. K. Srivastava, "Designing centralised and distributed system integrity protection schemes for enhanced electric grid resiliency," *IET Generation, Transmission Distribution*, vol. 13, no. 8, pp. 1194–1203, 2019.

[16] E. Maggioli, M. Ayiad, H. Leite, and A. Carvalho, "Overview on the impact, interactions and challenges faced by ac transmission protection systems with hvdc technology," in *IEEE 45TH Annual Conference on the Industrial Electronics Society (IECON)*, October 2019.

[17] W. Winter, K. Elkington, G. Bareux, and J. Kostevc, "Pushing the limits: Europe's new grid: Innovative tools to combat transmission bottlenecks and reduced inertia," *IEEE Power and Energy Magazine*, vol. 13, pp. 60–74, Jan 2015.

[18] D. Tziouvaras, "Relay performance during major system disturbances," in *2007 60th Annual Conference for Protective Relay Engineers*, pp. 251–270, March 2007.

[19] J. Gleadpw, G. Love, and b. . C. y. . . m. . O. et all, title = TF-77-AC fault response options for VSC HVDC converters

[20] R. Shah, J. C. Sánchez, R. Preece, and M. Barnes, "Stability and control of mixed ac–dc systems with vsc-hvdc: a review," *IET Generation, Transmission Distribution*, vol. 12, no. 10, pp. 2207–2219, 2018.

[21] "Ieee guide for protective relay applications to transmission lines," *IEEE Std C37.113-2015 (Revision of IEEE Std C37.113-1999)*, pp. 1–141, June 2016.

[22] W. E. C. C. (WECC), "Type 4 wind generator model phase 2." Available online at https://www.wecc.biz.

[23] C. Lu, T. Bi, M. Ilic, K. Tomsovic, and X. Wang, "Guest editorial: New trends in wide-area monitoring and control of power systems with large scale renewables," *IET Generation, Transmission Distribution*, vol. 11, no. 18, pp. 4403–4405, 2017.

[24] W. G. C15, "Design and testing of selected system integrity protection schemes (sips)," tech. rep., IEEE Power System Relaying and Controll Committee (PSRC), November 2012. Avaialbe at pes-psrc.org.

[25] S. Skok, D. Brnobic, and I. Ivankovic, "Overview of intelligent solution for power transmission system," in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–6, Oct 2018.

[26] F. Yu, C. Booth, A. Dyśko, and Q. Hong, "Wide-area backup protection and protection performance analysis scheme using pmu data," *International Journal of Electrical Power and Energy Systems*, vol. 110, pp. 630–641, 09 2019.

[27] EU, "Guideline on electricity transmission system operation." Available online at https://eur-lex. europa.eu, 2017.