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Keywords

«Reliability», «FMECA», «Wind Farm», «Power Converter», «HVDC», «Criticality», «Failure Mode».

Abstract

Power electronics is becoming an underpinning technology for modern power systems. Power converters are increasingly used in various applications implying different levels of importance in power systems. Hence, optimal decision-making for manufacturing, control, operation and maintenance of them requires understanding of their importance in the power systems. Furthermore, identifying the converters importance may be beneficial for simplifying the system-level reliability modeling in a large Power Electronic based Power Systems (PEPSs). Thereby, a Failure Mode, Effects and Criticality Analysis (FMECA) approach is proposed in this paper in order to figure out the importance of converters in PEPSs. The failure modes are classified by contingency analysis and their effects are predicted by a power system risk measure. Afterwards, the critical modes and critical components are identified. The FMECA is exemplified by a wind farm connected to the grid through an HVDC transmission system. The obtained results imply the criticality of the HVDC control system, its DC filters followed by its converters.

I. Introduction

Power electronics plays an underpinning role in modernization and decarbonization of the modern electric systems [1]. Power converters are increasingly used in a wide range of applications such as renewable energies, battery storages, electric vehicles and their charging stations, HVDC and MVDC systems [2]. However, power converters are one of the weaker links in this conversion process and may cause failures due to the possible huge system downtime and also costly maintenance. Thereby, in recent years with the high penetration of power electronics-based applications, reliability-oriented design and control of power electronic systems have gained the highest interest.

Physics of failure analysis and accelerated tests are the approaches employed to model the lifetime of converter components (mostly power semiconductor switches and capacitors). The corresponding lifetime models are, hence, used in order to design a converter for a specific level of reliability. Moreover, control and protection schemes are used to enhance the lifetime and reliability of a converter during operation [3].

These efforts have been carried out in the component, converter and operation levels for a single or multiple converter [4] from a wear-out failure point of view, which is suitable for the design and manufacturing of converters.

Besides design and control of converters, reliability-oriented operation, planning and maintenance of power electronic systems are of high importance. It requires system level reliability assessment approaches in order to model the system availability [5–7]. The system availability depends on its components failure rate and downtime or repair rate. For instance, the gear-box, control and electric system have a major contribution to the failure rate and downtime of wind turbines [8–11]. Furthermore, inverters have the dominant failure rate and downtime costs in photovoltaic systems [12, 13]. Following [8–13], the impacts of different components on the availability of single unit, i.e., Wind Turbine (WT) system or photovoltaic system, are illustrated based on historical reliability data. However, the contribution of the components at the power system level needs to be known as an important factor from the economical operation, planning and maintenance level points of view.

The aforementioned issues are intensifying the significance of reliability modeling in a modern PEPS, specially its main and failure prone components such as power converters. The converter reliability modeling can be carried out at three hierarchal levels including device, converter and system levels [4]. Device level modeling requires to consider the very fast dynamics of operation such as semiconductor switching effects [14]. This may introduce more complexity for the system level analysis in the large PEPSs [15]. Therefore, understanding the importance of different converters in the overall system performances is important for time-efficient and simplified system-level analysis.

This paper proposes a Failure Mode, Effects and Criticality Analysis (FMECA) approach in PEPSs in order to identify the weakest links of the system and its critical components. The main contribution of this paper is to analyze the reliability of a power electronic based power system with detailed reliability model of its sub-systems to show the importance of power electronics in the overall system performance. The obtained results would be useful for power system engineers to have an optimal planning and maintenance in modern power electronic based power systems. Also power electronic manufacturers could identify the critical components of the converters from a power system reliability point of view, and consequently have an optimal, reliable and economical design and control based on converter application and its importance in the system. Furthermore, it may facilitate system level reliability modeling of large PEPSs for design, planning and operation purposes.

II. Proposed Failure Mode, Effects and Criticality Analysis (FMECA)

In this section, the general concept of FMEA/FMECA and the proposed FMECA approach for a PEPS are explained. The main concept is adopted from IEC 60812:2018 [16] and MIL-STD-1629A [17] and modified for power system applications as discussed in the following.

A. General Concept of FMECA

The FMEA/FMECA is a technique to brake an item or a system down into its elements to explore the failure modes and corresponding effects. The criticality analysis can also be performed in order to prioritize the failure modes for potential treatment. The main purposes of FMEA/FMECA may include the following [16]:

(a) to identify the failures which have unwanted impacts on the system operation,

(b) to identify the techniques to improve the system reliability (such as design modifications and development of an item),

(c) to satisfy the customer’s contractual requirements,

(d) to develop a reliability test program,

(e) to provide a maintenance planning and support such as through the reliability centered maintenance,

(f) to identify the system risks for risk management.

The general concept of FMECA has been explained by IEC 60812:2018 [16] and MIL-STD-1629A [17]. According to the system, the failure modes should be identified and the impact of different modes on the system performance should be predicted. A failure mode criticality can be measured by a risk index of system, R, where it is defined as the product of severity, S, and probability of the failure mode, P, as:

$$R = S \cdot P \tag{1}$$

in which the severity is the impacts or consequences of the failure mode on the system performance. The term criticality can also be affected by the failure detectability, D, which is defined as the chance of identifying and mitigating the failure before the system is affected. Hence, the Risk Priority Number (RPN) can be defined by using (2) as another criticality index.

$$RPN = S \cdot P \cdot D \tag{2}$$

The criticality of different failure modes can be estimated by using (1) or (2). The criticality of an item, hence, can be obtained by cumulating the criticality of failure modes involving the corresponding component. The highest criticality number identifies the most critical components. Moreover, the other quantitative or qualitative measures can also be used for criticality assessment based on the type of system [16, 17]. Then, the qualitative criticality matrix and qualitative/qualitative criticality plots can be used to rank the system components criticality based on the corresponding impact on the system risk. A criticality plot enables identification of the criticality rank by defining suitable criticality boundaries.

B. Proposed FMECA for PEPSs

The proposed FMECA for PEPSs is based on the contingency analysis in reliability assessment of conventional power systems [18]. In this approach, a single and multiple outage events are considered and the reliability of the system associated with the corresponding outage is evaluated. This approach is adopted here for FMECA as shown in Fig. 1. The system states, including outage of one or multiple components, can be identified by the state enumeration technique. Then, the contingency analysis is performed in order to figure out the consequences of each outage events. To do so, the security assessment [19] can be performed to figure out the contingency effects on the steady state and dynamic performance of the system. After any contingency, the system might be subjected to steady state or dynamic performance violations. Steady state overloading of transmission lines and bus voltages together with transient and dynamic instability of voltage, frequency, and rotor angle may cause severe issues to the overall system operation. If the system security associated with the selected contingency is ensured, then it is not a failure mode in the system. Otherwise, a suitable remedial action should be carried out to keep the system as secure as possible. The remedial actions could be load curtailment, generation re-scheduling, network splitting, network re-configuring, and so on. After applying a remedial action, the system security should be assured by security re-assessment. The next step is analyzing the socioeconomic consequences of the contingency by performance measures such as loss of load or energy, loss of generation, fine of generation re-scheduling, social impacts, and so on. In power systems, the effects of an outage event on the generation, transmission and distribution level, can be measured by various risk indices. For instance, indices such as Expected Energy Not Supplied (EENS) or Loss Of Load Expectations (LOLE) can be used to measure the impacts of component outages on the customer supply [18]. Moreover, the generation power affected by an outage can be determined by the Power Not Produced (PNP) and Expected Energy Not Produced (EENP) [20].

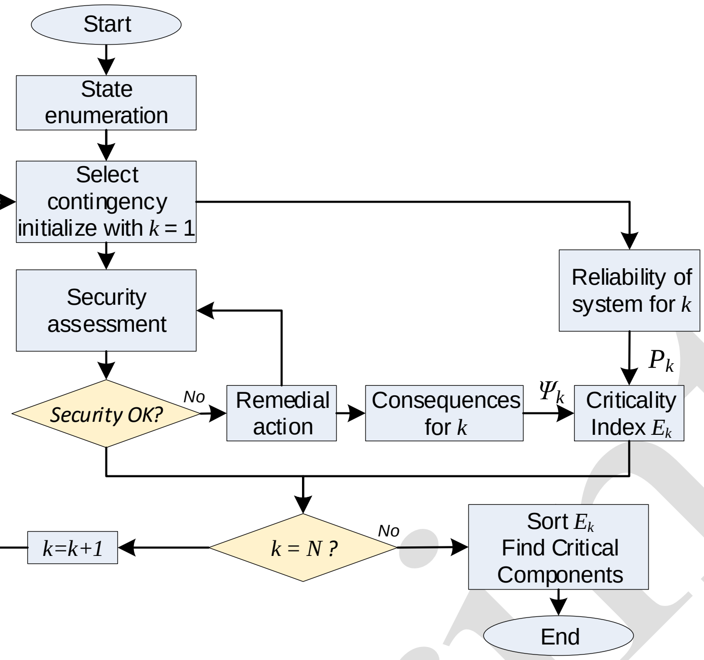

Fig. 1. Flow of proposed FMECA for power electronic based power systems.

If the contingency is appeared as a failure mode, the mode criticality, E_k, can be defined by using (3).

$$E_k = P_k \cdot \Psi_k \tag{3}$$

where, Ψ_k denotes as the failure mode consequences and P_k is its probability. Furthermore, the failure mode probability P_k is defined by using (4).

$$P_k = \prod_{j=1}^{N_f} \left(U_{k|j}\right) \cdot \prod_{j=1}^{N-N_f} \left(1 - U_{k|j}\right) \tag{4}$$

where, $U_{k|j}$ is the unavailability of component j's outage in the state k with failure rate of λ_j and repair time of r_j as given in (5).

$$U_{k|j} = \lambda_j \cdot \frac{r_j}{8760} \tag{5}$$

N is the number of total events and N_f is the order of outage events including any multiple components outage. The criticality of a component can also be defined by cumulating the criticality index of the modes involving that component [17]. Hence, the component criticality can be obtained by using (6):

$$C_j = \sum_{k \in \Phi_j} E_k \tag{6}$$

in which, C_j denotes the criticality index of component j, and Φ_j denotes the set of outage events caused by component j. This procedure will be repeated for all system states to identify the criticality of any outages.

III. Case Study

The proposed FMECA is exemplified by a wind farm as a PEPS in this section. The structure of the wind farm and numerical studies are presented in the following.

A. *Power Electronic based Power System Structure*

In this study, a 60-MW wind farm consisting of 20×3-MW DFIG-based Wind Turbine (WT) is considered as shown in Fig. 2. The wind farm is connected to the grid through an HVDC transmission system. The system includes four main sub-systems comprising WT, wind side Voltage Source Converter (VSC Wind), DC Transmission Line (DCTL), and grid side converter (VSC Grid). The reliability of WTs is modeled by 12 components, and VSCs are modeled by 8 components as shown in Fig. 3 [7]. Therefore, the total number of components in the reliability diagram is 265 as shown in Fig. 3 which can be considered for FMECA to find out the critical components. The reliability data of components are summarized in Table I [7]. The FMECA analysis and results are presented in the following section.

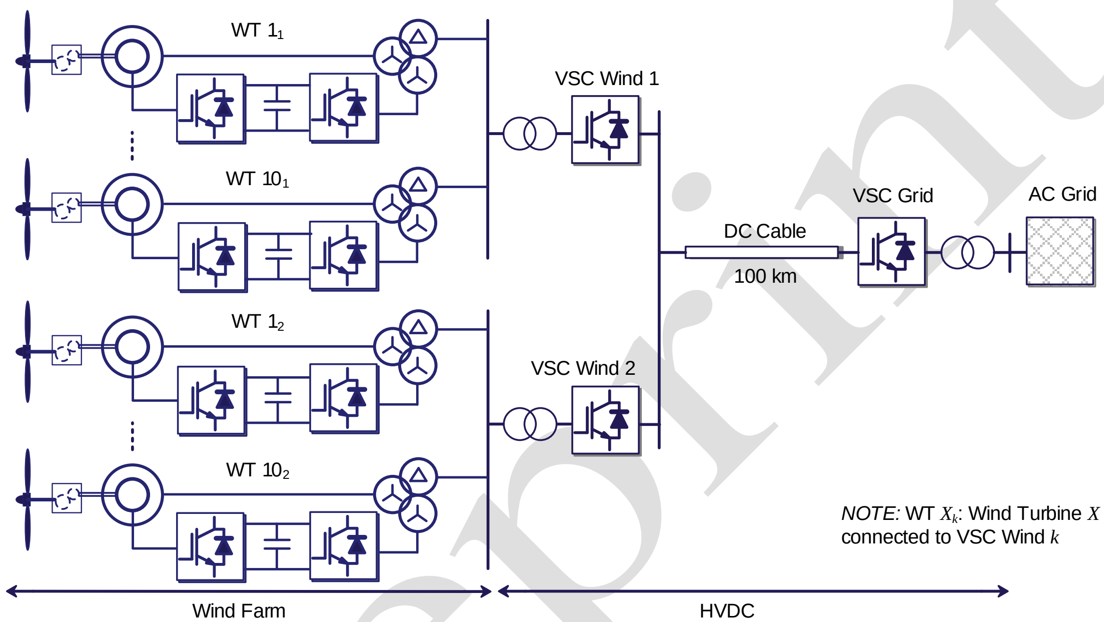

Fig. 2. Power System Structure with a Wind farm and HVDC system.

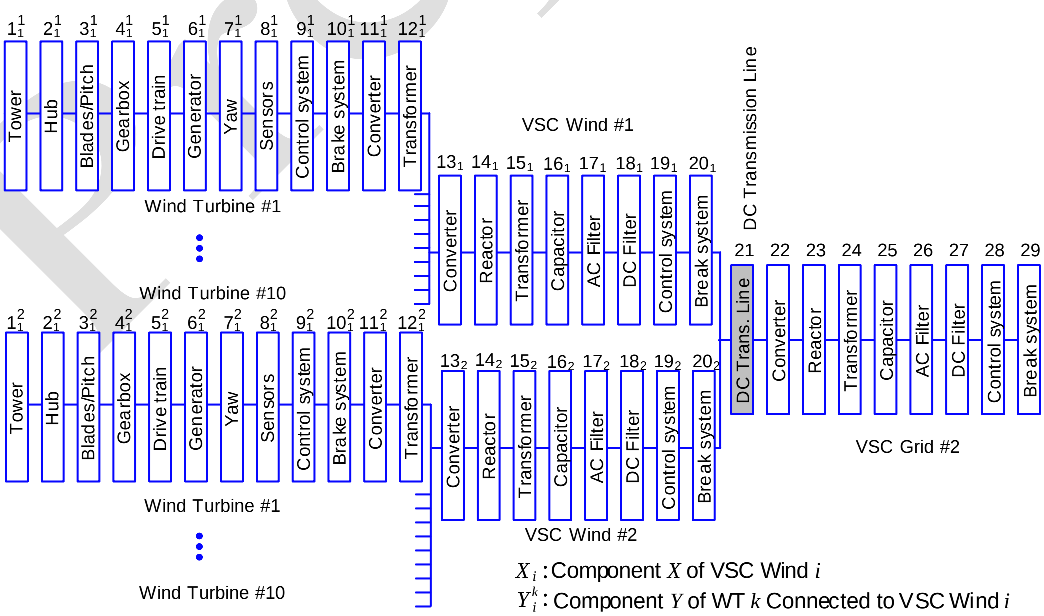

Fig. 3. Reliability model of the wind farm shown in Fig. 2.

Table I. Wind Farm-HVDC outage data [7] (occ: occurrence DCTL: DC Transmission Line).

Sub-system	Component	Failure rate (occ/yr)	Average repair time (hrs)	U_k
Wind Turbine System	Tower	0.006	104.1	7.13E-05
	Hub	0.001	12.5	1.43E-06
	Blades/Pitch	0.052	91.6	5.44E-04
	Gearbox	0.045	256.7	1.32E-03
	Drive train	0.004	291.4	1.33E-04
	Generator	0.021	210.7	5.05E-04
	Yaw	0.026	259.4	7.70E-04
	Sensors	0.054	49.4	3.05E-04
	Control system	0.05	184.6	1.05E-03
	Break system	0.005	125.4	7.16E-05
	Converter	0.067	106.6	8.15E-04
	Transformer	0.02	200	4.57E-04
HVDC VSC	Converter	0.5	4	2.28E-04
	Converter Reactor	0.006585	25	1.88E-05
	Transformer	0.0309	24	8.47E-05
	Capacitor	0.05	11.55	6.59E-05
	AC Filter	0.0833	10.5	9.98E-05
	DC Filter	0.4	12	5.48E-04
	Control System	1.3095	8	1.20E-03
	Break System	0.001	40	4.57E-06
DCTL	DCTL	0.003	500	1.71E-04

B. Numerical Analysis

In this paper, the first and second order outage events are considered since the higher order outages probability is negligible. The probability of outage events is calculated using (4). Afterwards, the effect of outages on the PNP is determined. In this paper, the wind regime for all WTs is considered to be the same, and the system is operating at an average power of 3 MW per WT.

Using the reliability data given in Table I, the probability of single/double outages and the corresponding PNP and EENP are calculated and reported in Table II for the first 30 important events in a descending order of EENP. The likelihood of failure modes against the corresponding consequence, which is loss of generation power, is illustrated in the criticality plot shown in Fig. 4. Obviously, the component 28 (control of grid side VSC) introduces the highest risk to the system, where its probability is 0.001056 according to Table II and 60 MW power will be disconnected. Components 19 (control of wind side VSC) and 27 (DC filter of grid side VSC) are the next critical components.

Table II. FMECA results.

Component outage	P_k	PNP (MW)	EENP (MWhr/yr)
28	0.001056	60	555.0336
19	0.001056	30	277.5168
27	0.000482	60	253.4653
18	0.000482	30	126.7326
22	0.000200	600	105.4563
21	0.000150	60	79.0922
13	0.000200	30	52.7281
26	0.000087	60	46.1602
24	0.000074	60	39.1761
4	0.001161	3	30.5268
25	0.000057	60	30.4805
9	0.000924	3	24.2827
17	0.000087	30	23.0801
15	0.000074	30	19.5880
11	0.000717	3	18.8480
7	0.000677	3	17.8073
16	0.000057	30	15.2402
3	0.000478	3	12.5807
6	0.000444	3	11.6788
4-19	1.3904E-06	33	0.4011
19_1-19_2	1.2584E-06	33	0.3307

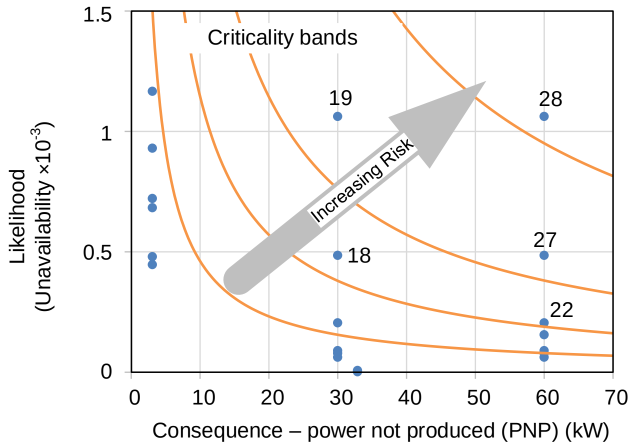

Fig. 4. Criticality plot illustrating the critical components of the system – 28:VSC grid control, 27: VSC grid DC Filter, 19: VSC wind control.

According to (6) the component criticality can be found by accumulating the EENP of outage events involving the corresponding component. The criticality of individual components is shown in Fig. 5. Following this figure, the control system of the grid side VSC is the most critical component. The second critical component is the control system of wind side VSC followed by DC filter of grid side and wind side VSCs. Afterwards, grid side converter, DC transmission line, and wind side converter are the next critical components respectively.

The obtained results show the criticality of the grid side VSC (converter + control) and then the wind side VSC (converter + control). The WT converter (converter + control) has a low criticality compared to the HVDC converters even though they have almost the same unavailability as given in Table I. This is due to the effect of the corresponding converters on the system level reliability, where the PNP is 3 MW for WT converter outage and 60 MW for the HVDC converter outage. In the exemplified wind farm, this fact could be visually deduced because of the symmetry in the grid topology. However, in a general power electronic

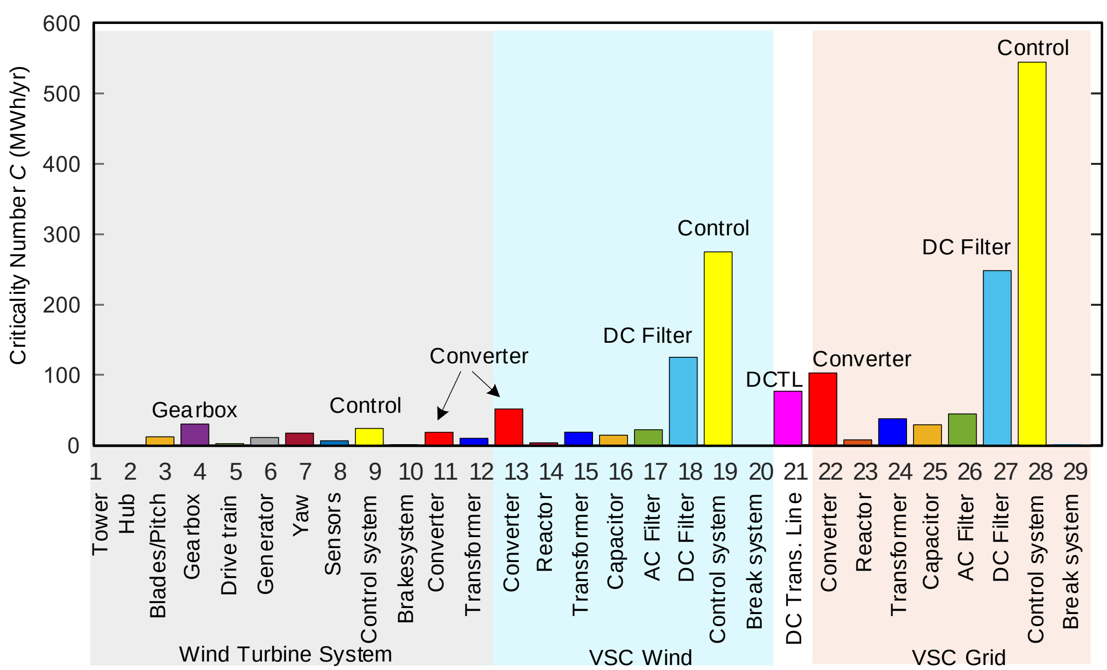

Fig. 5. Criticality analysis results based on FMECA.

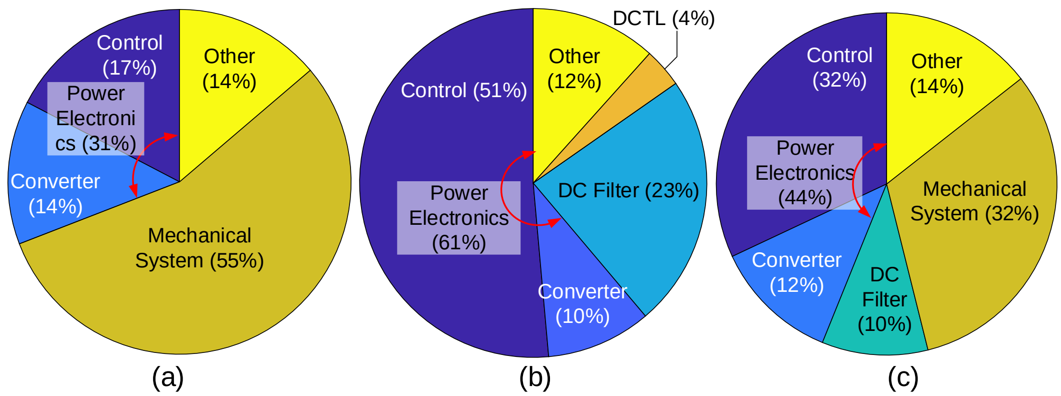

Fig. 6. Contribution of different categories in the risk of (a) wind turbines, (b) HVDC, and (c) wind farm.

based power system with different power converters in generation, transmission and distribution levels, the FMECA approach can properly identify the critical converters of the system. This approach shows the weakest links of the system and its sub-systems. For instance, the gear-box and control system are the two most critical component of the WT sub-system as shown in Fig. 5. However, its importance is quite low in the overall system performance. Therefore, one component may have the highest interest for one sub-system, here the wind generation company, while it has low importance for the overall system.

The contribution of different categories consisting of control systems, power converters, DC Filters, WT mechanical systems, and other parts on the risk of different sub-systems are illustrated in Fig. 6. Fig. 6(a) highlights the 31% contribution of power electronics on the reliability of WTs, and the mechanical system failure has the dominant impact on their performance. However, the impact of power electronics on the HVDC system reliability is quite dominant (61%) as shown in Fig. 6(b). Meanwhile, the control has the same as the converter on the WTs reliability as shown in Fig. 6(a). The impact of control is 5 times of the converter in the HVDC system as shown in Fig. 6(b). The contribution of power electronics, mechanical system and DC filters on the overall system reliability is shown in Fig. 6(c) implying that the power electronics has 44% contribution on the total system risk. The impact of the mechanical system comprising of various components (Tower, Hub, …) is 32%. Following Fig. 6(c), the control system of power electronics is more important that converters. Notably, the obtained results rely on the historical reliability data which are reported in [7].

IV. Conclusions

This paper has explored the criticality of power electronic converters in power systems by Failure Mode, Effects, and Criticality Analysis (FMECA). A 60-MW wind farm has been studied, which is connected to the grid through an HVDC transmission line. The wind turbines and HVDC converters are modeled according to the historical reliability data. The obtained results show that the power electronics has 44% contribution on the overall reliability of the studied wind farm. Power electronics is also the critical component of each sub-system. The analysis shows the criticality of HVDC converter control system and its DC filters. The grid side converter is the next critical component followed by the DC transmission line and wind side converter. Furthermore, the individual wind converter has less impact on the overall system reliability. The gear-box is the most critical component of a wind turbine system, and the next important components of wind turbines are its control system and converter. As a result, the converter control system is a dominant factor affecting the system reliability which should be improved by converter manufacturers. Moreover, identifying the critical modes and components can be beneficial for optimal and economical design, planning, operation, and time-efficient modeling of power electronic based power systems.

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