Assessing the Impact of VSC-HVDC on the Interdependence of Power System Dynamic Performance in Uncertain Mixed AC/DC Systems

Rian Fatah Mochamad, Student Member, IEEE, and Robin Preece, Senior Member, IEEE

Abstract—In recent years, voltage source converter (VSC) HVdc has emerged as an excellent solution for transmitting offshore renewable energy sources and strengthening transmission corridors. It is also reported in the literature that VSC-HVdc is able to enhance specific types of stability. With growing capacity of VSC-HVdc and increasing uncertainty in the current power system, it is essential to perform a rigorous analysis of its impact on the interdependence of power system dynamics. This paper presents a methodology for the thorough assessment of the impact of VSC-HVdc on interdependence among four types of stability: small-disturbance rotor angle, large-disturbance rotor angle, frequency, and voltage. This analysis is performed assuming uncertain conditions for various VSC-HVdc topologies and system loading and generation conditions. The impact of the VSC-HVdc on the interdependence of dynamic performance is assessed using the Spearman correlation coefficient as a quantification tool. The results obtained show that a significant alteration over the interdependence between power system dynamics occurs with the addition of VSC-HVdc.

Index Terms—VSC-HVDC, small-disturbance, large-disturbance, frequency, voltage, interdependency.

I. INTRODUCTION

The renewable energy sector has grown tremendously in recent years due to increasing awareness and incentives from governments and the advancement of power electronics [1], [2]. Renewable energy sources (RES) can often be located far from load centers and HVDC can be an attractive transmission solution. Voltage Source Converter (VSC) based HVDC transmission enables independent control over active and reactive power, making the technology well suited to support the fluctuating demands of the grids to which they are connected [3]. Due to this capability, VSC-HVDC has seen rapid development in recent years and established itself as the preferred transmission solution for distant offshore wind farms [4].

It has been shown in previous research that VSC-HVDC lines are able to enhance specific types of power system stability [5]–[10]. VSC-HVDC is reported to improve the small-signal stability of an offshore network feeding into power grid compared to equivalent HVAC lines [5]. The improvement is reported due to the installation of power oscillation damping which utilizes the quick response feature of the VSC-HVDC. Transient stability enhancement has been exploited in [7], [8] by utilizing the VSC-HVDC’s capability in controlling active and reactive power independently. In [7], it is proposed that during fault conditions, active power is injected into the grid in proportion with the weighted-average frequency at each VSC terminal. This control is not only able to enhance the transient stability of the system but also maintains the DC voltage. Scanning of weighted-average frequency is also explored by [8] with the aim to give coordinated reactive power injection during the fault. The proposed method is able to improve the critical clearing time of the modified Nordic 32 A system compared to the case when the injection is solely based on local frequency measurement. The use of VSC-HVDC for increasing the long-term voltage stability of a modified Nordic 32 test system is reported in [6]. The proposed control strategy exploits VSC-HVDC’s ability in controlling active and reactive power independently by introducing ramp up-down rates for active and reactive power every 30 minutes. The proposed method is able to avoid voltage collapse in the system subjected to tripping transmission line and generator. An approach to enhance frequency stability by providing fast support from the simultaneous utilization of energy stored in HVDC capacitors and wind turbines is proposed by [10]. The method is shown to stabilize the system frequency while maintaining better voltage and captured wind power during disturbances compared to the system without the control.

Despite there being evident enhancement in specific facets of power system stability, research encompassing the impact of VSC-HVDC on multiple power system dynamic phenomena and specifically the interdependency of different dynamic behavior is not available to the best of the authors’ knowledge. All of the aforementioned literature (and many others not mentioned for brevity) display the improvement in specific aspects of stability due to the inclusion or control of VSC-HVDC. It is not well reported if the improvement in the specific type of stability is at the expense of other types of stability, or whether the addition
of VSC-HVDC affects all system dynamics. Therefore, this research proposes a thorough assessment methodology to identify the impact caused by the introduction of VSC-HVDC into power systems by considering multiple stability phenomena. This is of increasing importance given the growing utilization of VSC-HVDC and increasing uncertainty within mixed AC/DC systems.

It should be noted that although the study of interdependency is rarely employed in the field of power system, it is widely used in health and social areas. A method in correlating the interdependency between color images with abnormalities in the retina is proposed in [11]. The effectiveness of the method presented in [11] is determined using Spearman correlation coefficient and claimed to have a high correlation with expert judgment in mitigating the risk of cardiovascular disease. An interdependency study is also introduced in [12] where it is used in quantifying the influence of different breathing patterns on the neural respiratory drive. Furthermore, an interesting investigation on the correlation between poverty, low education and psychotic-like experiences is conducted within [13] where it highlights the Spearman correlation coefficient as the quantification tool for all subscale parameters used.

This broader research has highlighted the value that can be gained from interdependency studies and has highlighted suitable analysis techniques. If the impact of the addition of VSC-HVDC on the interdependency between different stability performance metrics can be identified and quantified, this could result in better utilization of VSC-HVDC for further stability enhancement or ancillary services. In summary, this paper provides the following novel contributions:

i) a methodology for quantifying the impact of VSC-HVDC on the interdependency of power system dynamics;
ii) thorough probabilistic evaluation of the impact of VSC-HVDC on multiple system dynamic phenomena;
iii) a technique to establish the required number of Monte Carlo simulations for stability interdependency assessment;
iv) rigorous quantification regarding the changes in interdependency of power system dynamics after the addition of VSC-HVDC under varying loading conditions.

II. QUANTIFICATION OF INTERDEPENDENCY

A. Interdependency Assessment

Interdependency expresses the extent to which two or more quantitative variables relate to each other. There are several correlation quantification techniques available to quantify the interdependency with each having their own usability. Based on knowledge of the data, a statistical test can be classified into two categories: parametric and non-parametric.

Parametric tests are employed when the parameter of the population distribution is known, while non-parametric tests can be loosely defined as “distribution-free”. The Pearson correlation coefficient is a well-known parametric tool which quantifies the strength of the linear relationship between variables. On the other hand, as shown in Fig. 1, the Spearman correlation coefficient is non-parametric and can better capture monotonic non-linear relationships when compared to the Pearson correlation coefficient.

![Fig. 1. Pearson vs. Spearman correlation coefficient for different trial distributions.](image)

**TABLE I**

| Size of Correlation (absolute value) | Interpretation          |
|------------------------------------|-------------------------|
| 0.90 to 1.00                       | Very high correlation   |
| 0.70 to 0.90                       | High correlation        |
| 0.50 to 0.70                       | Moderate correlation    |
| 0.30 to 0.50                       | Low correlation         |
| 0.00 to 0.30                       | Negligible correlation  |

Fig. 1(a) shows that, unlike the Pearson correlation coefficient, the Spearman correlation coefficient is able to perfectly capture two gradients of increase (shown by correlation value of 1), while in Fig. 1(b) displays the Spearman correlation coefficient’s ability in quantifying “broadly” non-linear relationship. These advantages of Spearman correlation coefficient are due to the fact that it employs rank of variables instead of the numerical values of variables themselves. It measures the degree to which two variables rise (or fall) together regardless whether the relationship is linear or nonlinear. Power systems are highly non-linear systems; hence in this research, the Spearman correlation coefficient will be utilized instead of the (typically better known) Pearson correlation coefficient when quantifying the interdependency of different power system dynamic phenomena. The Spearman correlation coefficient ρ is defined mathematically as (1).

$$\rho = 1 - \left( 6 \sum \frac{d_i^2}{N} (N^2 - 1) \right)$$

In (1), N is the sample size and $d_i = X_i - Y_i$ represents the difference between the ith ranks of the observations of the variables X and Y. The Spearman correlation coefficient has a range of −1 to +1. The Spearman correlation coefficient is employed to quantitatively assess the interdependency while qualitative assessment will be carried out using Table I which presents general rules of thumb for interpreting the size of correlation coefficients [14].

B. Proposed Methodology

As previously discussed, the study of interdependency is rarely explored in power system analysis. In this section, the methodology developed to assess the impact that VSC-HVDC has on the interdependency of stability phenomena is outlined. The proposed methodology is shown in Fig. 2. The first part details the uncertainty modelling which comprises load forecast...
uncertainty and wind generation variability. This is elaborated on in Section III.A. Power systems exhibit various uncertainties including parameter and operational uncertainties, as well as uncertain disturbances. In this research, operational uncertainties (load forecast values and renewable energy generation) will be considered as they have previously been identified as the most critical uncertainties affecting power system stability [15]. The VSC-HVDC control is thoroughly explained in Section III.B with indices used to assess power system stability phenomena are provided afterwards. The procedure to create operational scenarios for the numerical Monte Carlo simulation (MCS) is described in Section III.D and is directly related to the uncertainty modeling. The impact of VSC-HVDC on the individual system dynamic stability phenomena is assessed in a modified New England Test System (NETS) under four test cases relating with the VSC-HVDC topology which are detailed in Section IV. Section V analyzes the interdependency between various power system stability indices. The methodology can of course be extended to include further uncertainties should they be a priority.

III. SYSTEM UNCERTAINTIES AND STABILITY INDICES

A. Uncertainty Modelling

The probabilistic load model is designed in two stages: hourly selection from the load curve and then the addition of uncertainty around this hourly load value. First, a random integer number from 1–24 (representing the hour) is generated to obtain specific load value within the daily load profile as shown in Fig. 3(a). Following this, uncertainty in the precise load value is added by randomly sampling a normal distribution with the mean taken from previously selected load value and three standard deviations equal to 5% of this mean. This means that the sampled value has 99.7% confidence of being within ±5% of the mean value. The normally distributed uncertainty is independently sampled for each load. Meanwhile, the wind speed is modeled independently of the load using Monte Carlo simulations of a Weibull distribution which follow scale parameter, \( \alpha = 2.2 \) and shape parameter, \( \beta = 11.1 \) [15]. The wind speed output is subsequently converted to a power output by considering the wind speed – power curve from [16]. Since the wind is modeled for a 2 MW output (single turbine), the number of RES generators will be multiplied to meet specific 10% penetration levels for each test case. The probability density function (pdf) of a typical 2 MW wind turbine is shown in Fig. 3(b).

B. VSC-HVDC Control

The HVDC controllers are selected based on common operational practice. The VSC-HVDC operated in parallel with AC line is utilized as an embedded transmission; hence it uses \( V_{DC} − Q \) and \( P − Q \) controls to ensure constant power support. Whilst, the infeed VSC-HVDC employs \( V_{DC} − Q \) (grid-side) and \( V_{AC} − f \) (offshore) control combination in order to facilitate the wind power generation. Since the aim of the research is to showcase the inherent impact of VSC-HVDC in the interdependency of various power system stabilities, standard VSC-HVDC controls without additional ancillary control loops, shown in Fig. 4, Fig. 5 and Fig. 6 are utilized. The K constant in \( V_{AC} − f \) control is based on the DIgSILENT PowerFactory model where the relationship between \( V_{AC}, V_{DC} \) and pulse-width modulation index (\( Pm_{in} \)) are shown in (2). Whereas, the \( P − Q \) control

Fig. 2. Proposed methodology to assess VSC-HVDC impact on stability interdependency.

Fig. 3. (a) Daily load curve, (b) pdf of wind output.

Fig. 4. \( V_{AC} − f \) control in infeed HVDC configuration.

Fig. 5. \( P − Q \) control in parallel HVDC configuration.
I \zeta - \pm 360 I = \omega = \text{The TSI based on power angle is selected as the index for symbolize the then I} + Given the oscillatory complex eigenvalue, I are modified from [3] to suit the simulation software.

\[ P_{m\_in} = 1.633 \frac{V_{ac\_pu} * V_{ac\_base}}{V_{dc\_pu} * V_{dc\_base}} \quad (2) \]

In Fig. 5 and Fig. 6, I_d and I_q are used to represent the d-axis and q-axis stator currents. The proportional integral (PI) control block is employed to transform specific control value unit into its equivalent I_d and I_q. The value of I_d and I_q then forwarded into the built-in inner loop block from DIgSILENT PowerFactory where the pulse -width modulation index for d-axis and q-axis (P_mdc and P_mmq) are obtained and processed as the input of the VSC-HVDC converter. The asterisk sign (*) used throughout the control modes (V_{AC}, f*, P*, Q*) symbolize the reference value of AC voltage, offshore frequency, active power and reactive power respectively and other variables without the asterisk sign are the observed values. Aside from frequency (f) which is measured in Hz, all variables are measured in pu unit.

C. Power System Stability Indices

In order to analyze the interdependency of various power system dynamics, specific indices are required to capture and quantify the phenomena in specific power system stability. This section elaborates the indices recommended and used in this work to quantify various stability phenomena. Four stability analyses are carried out in this research: small-signal rotor angle stability, large-signal rotor angle stability, voltage stability and frequency stability. For more information regarding power system stability indices, refer to [17], [18].

1) Small-Disturbance Stability. Critical Modal Damping Factor (MDF): Given the oscillatory complex eigenvalue, \( \lambda = \sigma \pm j \omega \), the mathematical definition of modal damping factor \( \zeta \) is shown in (3). In (3), the real and the imaginary part of the most critical eigenvalue are selected for calculating the critical MDF. Moreover, it is preferred for the MDF to possess value \( \geq 5\% \) [18]

\[ \zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (3) \]

2) Large-Disturbance Stability. Transient Stability Index (TSI): The TSI based on power angle is selected as the index for large-disturbance stability and is given in (4). In (4), \( \delta_{\text{max}} \) is the maximum angle separation of any two generators at the same time in the post-fault response. The TSI has a range of 0–100 with values closer to 100 denoting a more stable system [19].

\[ \text{TSI} = \frac{360 - \delta_{\text{max}}}{360 + \delta_{\text{max}}} \times 100 \quad (4) \]

The TSI is calculated by subjecting the system into a 100 ms three phase fault self-cleared at bus 29. Bus 29 is selected as the fault location as it provides the most severe transient response (of all non-generator bus fault locations) and the 100 ms fault duration is typically used. Studies of different fault locations will yield differences in precise transient stability metrics obtained, but not differences in the relationships between stability metrics as main underlying phenomena that bind together the various stability types will remain the same.

3) Frequency Stability. Rate of Change of Frequency (RoCoF): Frequency stability can be described by the rate of change of frequency (RoCoF). In this research RoCoF is calculated by determining the empirical RoCoF for the first 0.5 s following the disturbance. The desired value for RoCoF is different for various networks and operators depending on the system conditions experienced and control methodologies used. For example, in the GB system, it is desirable to maintain RoCoF below 1 Hz/s with a definite time delay of 500 ms as above this threshold the loss of mains of protection for generators greater than 5 MW is triggered [20]. Some networks are able to operate with higher values of RoCoF whilst some require much lower values. It is common to utilize the loss of the largest infeed as the way to determine the maximum RoCoF likely to be experienced in a system. However, the highest infeed generation in NETS is G10 (1000 MW) which is approximately equivalent to 20% of the total system generation. This infeed loss would be unreasonably large compared to practical systems. Instead, a load disturbance is used to test the system’s frequency stability. A 5% load increase is considered in this research. This is approximately equivalent to a GB system maximum infeed loss (1320 MW) during minimum system loading (approximately 25 GW).

4) Voltage Stability. System Loadability Index (SLI): Voltage stability can be measured by using the system loadability index (SLI). The SLI is defined as the percentage of additional load compared to the base load which can be supported by the system before voltage collapse [19]. This can be determined by calculating the nose point in the P-V curve using continuation power flow. In this work, an approximation is made by iteratively increasing loading until power flow fails to converge. It is acknowledged that this does not represent the true nose point as ill-conditioning occurs before the nose but provides a reasonable approximation using standard power system simulation software. To the best of authors’ knowledge the preferred SLI margin cannot be generalised as it is subject to local phenomena and significantly varies for different networks and operators.

Each of the power system stability indices is then tabulated and put into ranked order, then the Spearman correlation coefficient between various stability types is determined based on these ranks. This means that the correlation coefficient calculation is not based on the actual index values but on the index value ranks. For example, from 10000 voltage stability simulations the lowest and the highest SLI values obtained are 27.4% and 43.1% respectively. These values are then converted to ranks in which
the highest 43.1% value is ranked 1 and the lowest 27.4% value is ranked 10000. For frequency stability, as the most negative value of RoCoF is the worst-case, this receives the ranking value 10000 and the best response (i.e., least negative RoCoF) is ranked 1.

D. Generation of Dataset

This section elaborates how the dataset for each test case is generated. First, each of the test cases is modeled in the steady state condition to calculate the initial operating points using an OPF solution. This step is intended to remove the synchronous generator uncertainty and ensure feasible operating conditions [21]. Since the NETS is a benchmark system for stability assessment, its default cost function for each generator is set to be uniform, hence the study is focused on power system dynamics. Furthermore, the RES’s cost function for this research is displayed to be zero; hence all of renewable generation is absorbed by the system. The integration of RES is modeled as causing continuous derating of the remaining synchronous generators according to their dispatched power as formulated in (5).

\[ S_{SG,i} = \frac{P_{SG,i}}{\cos \phi_{SG,i} \cdot SC_{SG,i}} \quad (5) \]

In (5), \( S_{SG,i} \) and \( P_{SG,i} \) are the rating and the dispatched active power of the \( i \)th synchronous generator, \( \cos \phi_{SG,i} \) and \( SC_{SG,i} \) represent the power factor and the spare (i.e., reserve) capacity of the \( i \)th generator. In this research, \( \cos \phi_{SG,i} \) and \( SC_{SG,i} \) are both set as 0.85. This derating process is continuous as loading varies and captures variations in the system synchronous kinetic energy as RES and loading varies. The modeled RES unit has 10% installed capacity – and not 10% instantaneous injection where its probabilistic variation is independently modelled of other variations. Therefore the cumulative inertia of the synchronous generators in the system will vary, even under the same loading conditions. In a practical system, an increase in RES would lead to the disconnection of synchronous machines, resulting in the loss of their synchronous kinetic energy from the system. In this test system with larger equivalent machines, disconnection of machines or reduction in rating in discrete steps is arbitrary. Instead a continuous derating process is used where the rating of the synchronous generators are determined according to (5). The synchronous kinetic energy is therefore reduced in a continuous (and not discrete, or stepped) manner as the RES increases. In order to understand the consequence of different derating mechanisms, the impact of discrete derating on the interdependency will be explored later in Section V.D.

Various software is employed to perform these analyses. A combination of MATLAB and MATPOWER are used for calculating the initial operating point, whilst the dynamic analysis is performed in DigSILENT PowerFactory. The quantification of Spearman correlation coefficient is then assessed in MATLAB.

IV. Test System Description

The modified NETS shown in Fig. 7 has 39 buses and 10 generators, one of which is a representation of the USA/Canada interconnection. Aside from being the IEEE benchmark test case for the small-signal stability, NETS possesses enough complexity where the impact of VSC-HVDC and wind generation can be easily showcased. The modifications over the NETS network are in the form of parallel and VSC-HVDC addition. Each VSC-HVDC converter is modelled as a modular multilevel converter (MMC). The parallel VSC-HVDC is installed between bus 16–19 as it is identified as one of the lines with highest loading from the nominal power flow solution. In order to more accurately reflect the practical implementation of parallel HVDC, data from HVDC Directlink of Australia is used in order to create a basic operational regime, where it will transmit approximately 75% of the power flowing between bus 16 and bus 19 (to act as an embedded transmission asset).

Bus 7 is selected as the connection point of the infeed VSC-HVDC and wind generation due to it being identified as the critical bus from PV curve calculation and the point in most need for local load support. The wind turbines employ type 4 model from DigSILENT PowerFactory. All of the dynamic data of synchronous generator from the initial NETS are still retained. The one line diagram of the modified New England test system is shown in Fig. 7 with data available in [22].

In the interest of showcasing the impact of VSC-HVDC on the interdependency of various power system dynamics, four test cases are developed based on the modified NETS.

- Initial Case: The first test case is the initial system.
- Parallel Case: The second test case is the initial system with the integration of one parallel VSC-HVDC line between bus 16 and 19.
- Infeed Case: The third case is the initial system with the inclusion of one VSC-HVDC link connected RES infeed at bus 7.
- Complete Case: The combination of parallel (one HVDC link at bus 16–19) and infeed VSC-HVDC (one HVDC link at bus 7) represents the fourth test case.
Both the infeed and the complete test cases include 10% RES penetration (with respect to total load). The impact of the topological change is additionally analyzed across four loading conditions. In total, with four stability types and six interdependencies being investigated, this leads to 384 test cases.

V. RESULT AND DISCUSSION

The result and discussion section is divided into three subsections. The first subsection is focused on the investigation of the stopping criterion for a number of MCS required for stability interdependence studies. The second section is an assessment of VSC-HVDC’s impact on the interdependency between power system dynamics. The final subsection highlights the impact of loading conditions on this dependency.

A. Stopping Criterion for Correlation Coefficient

One deciding factor in the accuracy of MCS is the number of the simulations used. Typically MCS can range from thousands to hundreds of thousands of samples depending on the purpose of simulation. Therefore, Monte Carlo is often considered as a computationally expensive method. Stopping rules exist to assess when a single output distribution is adequately captured. Unfortunately, no work defining the minimum number of MCS as a convergence criterion when assessing the interdependency between two output distributions could be identified. Therefore, a novel and pragmatic approach in defining the stopping criterion for correlation between two stability types is proposed and used in this research.

Shown in Fig. 8 are the boxplots of Spearman correlation coefficients for interdependency between large-signal stability and voltage stability. A hundred thousand MCS are simulated for each stability type and the Spearman correlation coefficient quantification is calculated by randomly selecting batches from this population. Each boxplot represents the distribution of a thousand sets of MCS for the respective batch size. Each data point within each box is the Spearman correlation coefficient calculated for this batch. For example, the first boxplot in the figure represents the distribution of 1000 values of Spearman correlation coefficient, each of which is calculated from batches of 2500 samples of system stability studies. The whiskers of each boxplot are scaled to three standard deviations, such that they capture 99.7% of the data.

There is a clear variation in the values of Spearman correlation coefficient obtained. It is evident that as the higher numbers of MCS batch size are used, the variation in Spearman correlation coefficient reduces. A tradeoff between result confidence and the computational burden needs to be assessed to reduce the computational time without sacrificing much of the fidelity. Therefore, the rate of change of mean and standard deviation of each of these boxplots is studied. The mean is almost constant as the number of MCS increases. However, it is observed that at 10000 MCS, a 17% reduction of the standard deviation is seen compared to 7500 MCS alongside a significant decrease in the number of outliers occurring (N.B. outliers are not shown in Fig. 8 for clarity). Therefore, 10000 MCS is selected for the correlation assessment in each of the test cases.

B. Impact of VSC-HVDC on Interdependency of Power System Stabilities Considering Topological Changes

The impact of VSC-HVDC on the interdependency of power system stabilities for various topologies is investigated first at a nominal 1 pu loading factor condition. Due to a multitude of test cases and complexities surrounding the test cases, this subsection will center on the quantification between large-signal stability and voltage stability. Other correlations between stability types can have been examined by using the same procedure but these cannot be shown due to space limitations.

1) Assessing Interdependency in the Initial Case: The first step in quantifying the interdependency is assessing each stability result. Fig. 9 shows the histograms and pdfs as generated from the large signal stability and voltage stability indicators obtained from repeated 10,000 MC simulations of operational conditions for the initial case including system uncertainty. Both the TSI and SLI can be seen to have multi-modal distributions. However, despite the fact that these distributions stem from the same input uncertainty distributions in loading, the shapes of the
pdfs for each stability indicator are different; further highlighting the complexity of each stability type. TSI is concerned with the global system differences in generator rotor angles whilst SLI is related with loading capabilities determined locally by network conditions [23].

Each value of SLI and TSI is subsequently ranked with respect to its entire set of data to get the rank value which is used in the calculation of the Spearman correlation coefficient that describes the TSI–SLI dependency. The ranked SLI and TSI are plotted in Fig. 10 which has a Spearman correlation coefficient value of 0.89. Despite the high value of Spearman correlation coefficient, the plot displays some unusual behavior with three clusters of behavior (marked on the figure). The first cluster occurs until the TSI rank of approximately 6200 when both of TSI and SLI are having moderate positive correlation. The second and the third cluster arise afterwards possess very high positive and very high negative correlation.

In order to understand the three clusters phenomena better, Fig. 11 and Fig. 12 are provided. Since the only source of uncertainty in the initial case is the load uncertainty, in order to understand these phenomena; each of the rank-based SLI and TSI is plotted against the total load, shown in Fig. 11. Based on the figure, the cause of the three cluster profile can be identified as the TSI response against the load. The SLI consistently maintains a high negative correlation for the entire load range, whilst the TSI rank is more variable with respect to the load ranks. The TSI is having very high positive correlation at lower load ranks followed by very high negative correlation and maintain a broadly moderate negative correlation for higher load ranks.

Further investigation reveals that since the TSI is calculated with respect to the largest relative displacement of any two generators, in any given load profile there is a clear possibility of obtaining the same TSI for different loading scenarios. This phenomenon is clearly showcased in Fig. 12 where different values of total system generation yield the same TSI value. Therefore, it is concluded that the three clusters profile of TSI-SLI shown in Fig. 10 is caused by the variations of the large-signal response (indicated by TSI) against the load as shown in Fig. 11 and the possibility of different loading conditions (and subsequently varying generation profiles) yielding the same TSI value, as explained in Fig. 12.

2) Assessing Interdependency With VSC-HVDC: The next step is the assessment of the impact of VSC-HVDC on the interdependency. The three VSC-HVDC cases outlined will be examined. Utilizing the simulation principle outlined, the Spearman correlation coefficient becomes 0.98 for the parallel case. The inherent impacts of VSC-HVDC are the reduction of the reactive power requirement from the generators and a lower aggregate of active and reactive power transmission losses compared to its HVAC counterpart. The lower losses lead to slightly lower generation output and slight reductions in steady state rotor angles. Hence the margin between initial and maximum rotor angles is increasing which leads to an improvement in large-signal stability. The voltage stability is also enhanced due to reduced reactive power losses. Subsequently, as shown in Fig. 13, parallel VSC-HVDC is altering the non-linear relationship between the transient stability index with the lower load (identified in Fig. 11) in the initial case while keeping a very high correlation between loads and the SLI. These leads to a Spearman correlation coefficient of 0.98.
The addition of infeed VSC-HVDC in the infeed case decreases the Spearman correlation coefficient to 0.76. The wind generation and VSC-HVDC are connected at the lowest voltage profile bus (bus 7), and the impacts on both stability indicators are evident in Fig. 14. Compared with the initial system where there is no wind generation, the infeed VSC-HVDC along with the wind generation has a large impact on the system power flows. The response of the large signal stability displays very high negative correlation with respect to the total synchronous generation (selected as a single quantity which is representative of the uncertainty in both loading and wind generation). Whereas, the voltage stability response is shaped into similar to three clusters where it caused by the bimodal distribution function of the wind generation (shown previously in Fig. 3(b)) with regions of no power production, peak power production and the range between these extremes.

It should be noted here that the ‘total synchronous generation’ is used as a single variable which can incorporate both the variability and uncertainty in system loading and in RES generation. With the continuous derating process used in this work, the total synchronous generation will vary along with both of these parameters. Therefore it is important to realise that the inference that increasing synchronous generation leads to lower TSI (from Fig. 11) is not for a fixed value of load or RES. It would be more accurate to interpret these results as high load and low RES leads to low TSI. This finding is consistent with Fig. 11, where, in the initial condition (no wind generation and VSC-HVDC), the increase in load (and subsequently the synchronous generation) is also worsening the large-signal stability response.

The impact the complete case including both parallel and infeed VSC-HVDC is also worth noting. As shown in Fig. 13, the interdependency in the complete case does not show significant difference to that of the infeed case, both in terms of Spearman correlation coefficient value or rank plot. It was discussed how, in the parallel case, the VSC-HVDC enhanced the dynamics of the system. Concurrently, the infeed VSC-HVDC results in a change in the voltage stability behavior due to the addition of a new source of uncertainty in the form of fluctuating wind generation. The aggregated impact of parallel and infeed VSC-HVDC in the complete case is such that the interdependency between SLI and TSI is dominated by the infeed VSC-HVDC affects.

Utilizing the same procedure, the interdependency for all type of stabilities in all topology cases are assessed. However, the level of analysis that is included for TSI-SLI cannot be repeated for other interdependencies due to limited space. Fig. 15 shows the change in the interdependency of power system dynamics for all of these cases.

The impact of the addition of parallel VSC-HVDC is also apparent and consistent in other stability-pair inter-dependencies. Whilst the infeed and the complete case see a varying impact on the Spearman correlation coefficient due to the addition of fluctuating wind generation. Additionally, it is noticeable that when looking at interdependency with RoCoF (relating to frequency stability), the addition of infeed VSC-HVDC reduces the interdependency. Furthermore, the addition of both parallel and infeed VSC-HVDC is essentially removing the interdependency between voltage and frequency stability. The impact of VSC-HVDC on the frequency stability related interdependency will be further highlighted and assessed in the next sub-section as these phenomena are easier to understand when considering varying loading conditions.

C. Impact of Loading Condition Towards Correlation

This section describes the investigation into the impact of loading conditions on the correlation between stability phenomena using the same procedure and framework already outlined. Four varying loading conditions with load factors from 0.7 to 1.0 (in steps of 0.1) are used to replicate the difference between the typical high and low loading conditions in United Kingdom [24]. One key concept in the investigation into the impact of varying loading is the change in total system inertia due to deloading and derating process. It should also be noted that the Spearman correlation coefficient values reported are subject to some uncertainty as previously illustrated in Fig. 8.

In general, as shown in Fig. 16 the interdependency between various types of stability display a consistent trend with respect to the loading condition and the topological changes. For
the initial case, the interdependency can be broadly classified into frequency and non-frequency stability related. The interdependency related to frequency stability is decreasing as the load factor increases with a significant reduction in Spearman correlation coefficient in the region of 0.9 and 1.0 pu loading factors. Whereas, the impact of loading condition in the initial case for interdependencies not related to frequency stability is smaller.

The enhancing impact of parallel VSC-HVDC which was discovered in the previous section is also valid for varying loading conditions. For any interdependencies, the parallel case results in either higher correlation or at least the maintenance of a very high correlation with respect to the initial case. The inherent impact of parallel VSC-HVDC is lower losses and slightly reduced generation requirement. The assessment of the interdependency is based on the relative change of rank in both stabilities. Therefore, even though a minor improvement in one or both stabilities may be realized due to the inherent impact of the parallel VSC-HVDC, it is possible for the interdependency to remain very high. Furthermore, since the parallel VSC-HVDC does not introduce a new source of uncertainty, the observed trend is very similar to the initial case.

The fact that the infeed VSC-HVDC connecting the wind generation are located at the lowest voltage bus also plays a significant role when assessing the interdependencies related to voltage stability. The injection of active power along with the $V_{DC} - Q$ control mode used in the grid side VSC-HVDC converter supports the voltage for varying loading conditions. This explains the negligible correlation between voltage and frequency stability as loading conditions increase. The increase in loading condition drastically changes the frequency stability response while the infeed VSC-HVDC maintains almost constant voltage stability margin at the critical busbar. The impact of the infeed case – that the VSC-HVDC decreases interdependency due to inertia reduction – is consistently found across varying loading condition and interdependency types. In summary, the impacts of VSC-HVDC with different topologies are listed:

1) As a result of its inherent impact in lowering the losses and subsequently reducing the generated power, parallel VSC-HVDC increases the strength of all types of interdependencies.
2) Infeed VSC-HVDC (due to its $V_{DC} - Q$ control mode used at grid side converter) tends to reduce the strength
of interdependencies for all voltage stability related relationships.

3) The complete case with a combination of parallel and infeed VSC-HVDC tends to result in interdependencies similar to that seen with an infeed case, albeit with reduced strength particularly for frequency stability related interdependencies.

D. Impact of Discrete Inertia Reduction

In the interest of showcasing the impact of discrete inertia reduction, further simulations are conducted. Two discrete derating mechanisms are implemented where it is assumed that units are switched in or out of service depending on the active power generation at each generator bus. This is completed on a per 100 MW and a per 250 MW basis using the general formula shown in (6).

\[
S_{SG,i} = n_{SG} \times \frac{P_{SG\_unit,i}}{\cos \phi_{SG,i} S_{C\_SG,i}}
\]

Equation (6) is similar to the continuous derating formula shown in (5), with the addition of the variable \(n_{SG}\) and \(P_{SG\_unit,i}\). As previously denoted in the continuous derating formula, the \(S_{SG,i}\) is the nominal apparent rating of the \(i^{th}\) synchronous generator which is directly tied with the respective inertia constant. \(P_{SG\_unit,i}\) is the power generation in a single generating unit of the \(i^{th}\) synchronous generator with \(\cos \phi_{SG,i}\) and \(S_{C\_SG,i}\) denote the power factor and the spare (i.e., reserve) capacity of the \(i^{th}\) generator. \(n_{SG}\) is the number of synchronous generator units in operation at a bus and it is calculated in an increment base of \(\leq 100\) MW and \(\leq 250\) MW of the nominal active power generation. For example, consider the generator modelled as G1 with a nominal 1000 MW of active power generation when it is dispatched to provide 550 MW. On a per 100 MW derating basis, this will require six units to be active. On a per 250 MW derating basis, this would require three active generation units. These two different discrete derating mechanisms will result in the MVA capacity of G1 being 830.46 MVA and 1038.1 MVA respectively. An illustrative example of how these different derating mechanisms affect the considered generation capacity (and subsequently total system’s synchronously connected kinetic energy, or inertia) is given in Fig. 17 for G1. The same approach is taken for all generators in the system.

Utilizing these discrete derating mechanisms, the simulation methodology has been conducted and the results of the different power system stability responses obtained for the complete topology are shown in Fig. 18. As can be seen, there is an enhancement in the pdfs of small-signal and frequency stability with respect to the use of higher derating capacities. The impact of higher derating capacity on transient stability is a wider pdf of the TSI. The TSI is captured as the largest displacement between any two generator rotor angles. Due to the altered capacities under this derating process, generators may accelerate at different rates and so the TSI for each case is not necessarily measured between the same two generators under different derating processes. This is especially true given the complex mechanism underlying the transient stability response during the fault. This phenomena results in the pdf of TSI spreading wider with higher derating capacity. This pdf does not follow the same trend as seen with the pdfs of small-signal and frequency stability where both of these responses are enhanced due to the higher levels of system inertia caused by the discrete derating. Meanwhile, the SLI is calculated on the basis of the network parameter, the initial voltage and the generated reactive power. As these parameters remain the same in all simulated derating mechanisms, the pdf of SLI stays the same. The full extent of the impact that these discrete derating processes have on other topologies is not explored within the manuscript due to space limitations and in order to focus the discussion on the interdependency of different power system stabilities.

The interdependency between stability metrics when the different derating processes are considered is shown in Fig. 19. This is for the complete topology at a loading level of 1.0 p.u. The most noticeable impact of the higher derating capacity is the alteration of a previously negative correlation into a positive correlation in all of the frequency stability-related interdependencies. Large-signal stability-related interdependencies are reduced except for...
A particular focus should be paid to the SLI – RoCoF interdependency. The implementation of the discrete derating significantly alters the correlation coefficient from previously a negligible correlation coefficient ($\sim -0.02$) into high and very high positive correlation (0.67 and 0.89 for the per 100 MW and per 250 MW discrete deratings respectively). Further assessment of the interdependency between SLI – RoCoF is conducted with the results shown in Fig. 20 where its rank vs rank plot helps to shed some light on the phenomenon. During the continuous derating, there is no indicated pattern between SLI-RoCoF; however within per 100 MW and per 250 MW discrete deratings there are observable patterns with higher derating capacity yielding a more visible positive-correlation pattern. However, whether this phenomenon is in accordance with the fact described in Section V.C where the infeed VSC-HVDC (and its employed $V_{DC} - Q$ control mode) connection at the critical bus plays a pivotal role or it is a unique condition of the frequency stability due to higher inertia margin is subject of ongoing research and requires further investigation.

VI. CONCLUSIONS

A methodology to enable the systematic quantification of the interdependency of various stability types with respect to the addition of VSC-HVDC has been presented. A novel approach in defining stopping criterion for correlation between two stability types is used to guarantee the accuracy of results.

Based on the illustrative simulation results, it is apparent that the inclusion of parallel VSC-HVDC connections to support power system operation consistently increase the strength of interdependency between different stability phenomena compared to the initial system. However, the infeed VSC-HVDC, due to its $V_{DC} - Q$ control mode used, tends to reduce the strength of interdependencies for all voltage stability related. Moreover, the interdependency of parallel and infeed VSC-HVDC is also found out to be the aggregation between each topology with an emphasis on larger differences involving frequency stability due to higher changes in the system total inertia. Furthermore, these impacts are consistent with varying loading conditions.

Two different derating strategies, continuous and discrete are also simulated. These different derating mechanisms produce different observable trends with respect to increasing derating capacity. In all but transient stability response-related interdependency, the use of the discrete derating process increases the interdependencies. The frequency-related interdependency is significantly affected by the presence of higher inertia margin with interdependencies changed to positive from previously a negative correlation.

This methodology has shown that VSC-HVDC can have a significant impact on the interdependencies of power system dynamics. It is recommended that similar analysis is conducted for other significant technologies to fully understand their impacts and the need for stability enhancement or ancillary services.

REFERENCES

[1] J. L. Sawin, K. Seyboth, and F. Sverrisson, “Renewables 2016: Global Status Report” REN21, Paris, Rep. ISBN:9783981810707, 2016.
[2] Department of Energy & Climate Change, “National renewable energy action plan for the united kingdom article 4 of the renewable energy directive,” London, U.K., 2010.

[3] D. Jovicic and K. Ahmed, High Voltage Direct Current Transmission - Converters, Systems and DC Grids, 1st ed. Hoboken, NJ, USA: Wiley, 2015.

[4] P. Bresesti, W. L. Kling, R. L. Hendriks, and R. Vailati, “HVDC connection of offshore wind farms to the transmission system,” IEEE Trans. Energy Convers., vol. 22, no. 1, pp. 37–43, Mar. 2007.

[5] L. Wang and M. S. Nguyen Thi, “Comparative stability analysis of offshore wind and marine-current farms feeding into a power grid using HVDC links and HVAC line,” IEEE Trans. Power Del., vol. 28, no. 4, pp. 2162–2171, Oct. 2013.

[6] M. R. S. Tirtashi, J. Svensson, and O. Samuelsson, “VSC-HVDC application to improve the long-term voltage stability,” in Proc. IEEE Powertech, 2017.

[7] J. Renedo, A. Garcia-Cerrada, and L. Ruoco, “Active power control strategies for transient stability enhancement of AC/DC grids with VSC-HVDC multi-terminal systems,” IEEE Trans. Power Syst., vol. 31, no. 6, pp. 4595–4604, Nov. 2016.

[8] J. Renedo, A. Garcia-Cerrada, and L. Ruoco, “Reactive-power coordination in VSC-HVDC multi-terminal systems for transient stability improvement,” IEEE Trans. Power Syst., vol. 32, no. 5, pp. 3758–3767, Sep. 2017.

[9] Y. Wen, J. Zhan, C. Y. Chung, and W. Li, “Frequency stability enhancement of integrated AC/VSC-MTDC systems with massive infeed of offshore wind generation,” IEEE Trans. Power Syst., vol. 33, no. 5, pp. 5135–5146, Sep. 2018.

[10] Y. Li, Z. Xu, J. Østergaard, and D. J. Hill, “Coordinated control strategies for offshore wind farm integration via VSC-HVDC for system frequency support,” IEEE Trans. Energy Convers., vol. 32, no. 3, pp. 843–856, Sep. 2017.

[11] U. T. V. Nguyen et al., “An automated method for retinal arteriovenous nicking quantification from color fundus images,” IEEE Trans. Biomed. Eng., vol. 60, no. 11, pp. 3194–3203, Nov. 2013.

[12] L. Estrada, A. Torres, L. Sarlabous, and R. Jane, “Onset and offset estimation of the neural inspiratory time in surface diaphragm electromyography: A pilot study in healthy subjects,” IEEE J. Biomed. Health Inform., vol. 22, no. 1, pp. 67–76, Jan. 2018.

[13] A. A. Loch and E. A. Chianca, “Poverty, low education, and the expression of psychotic-like experiences in the general population of São Paulo, Brazil,” Psychiatry Res., vol. 253, pp. 182–188, 2017.

[14] M. M. Mukaka, “A guide to appropriate use of correlation coefficient in medical research,” Malawi Med. J., vol. 24, no. 3, pp. 69–71, 2012.

[15] K. N. Hasan, R. Preece, and J. V. Milanovic, “Priority ranking of critical uncertainties affecting small-disturbance stability using sensitivity analysis techniques,” IEEE Trans. Power Syst., vol. 32, no. 4, pp. 2629–2639, Jul. 2017.

[16] Gamesacorp, Gamesa G114-2.0 MW datasheet, Gamesacorp, Zamudio, Spain, 2012.

[17] P. Kundur, Power System Stability and Control. New York, NY, USA: McGraw-Hill, 1994.

[18] G. Rogers, Power System Oscillations. New York, NY, USA: Springer, 2012.

[19] R. F. Mochamad and R. Preece, “Impact of HVDC integration on the dynamic security of power systems,” in Proc. 10th MedPower Conf., 2016.

[20] OFGEM, Distribution code: DC0079(Phase 2) 1- frequency changes during large disturbances and their impact on the total system, OFGEM, London, U.K., 2018.

[21] R. D. Zimmerman, C. E. Murillo-S’anchez, and R. J. Thomas, “Matpower: SteadyState operations, planning and analysis tools for power systems research and education,” IEEE Trans. Power Syst., vol. 26, no. 1, pp. 12–19, Feb. 2011.

[22] I. Hiskens, “IEEE PES task force on benchmark systems for stability controls,” Tech. Rep., Nov. 2013. [Online]. Available: http://sites.ieee.org/pes-resource-center/files/2015/08/PES_TR18_Benchmark-Systems-for-Small-Signal-Stability-Analysis-and-Control.pdf

[23] P. Kundur et al., “Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions,” IEEE Trans. Power Syst., vol. 19, no. 3, pp. 1387–1401, Aug. 2004.

[24] Gridwatch, “Gridwatch: UK national gridwatch status Jan 01 2015 - Dec 31 2015.” 2016. [Online]. Available: http://www.gridwatch.templar.co.uk/. Accessed on: Feb. 24, 2016.

Rian Fatah Mochamad received the S.T. and M.Eng. degrees in electrical engineering from Universitas Gadjah Mada, Yogyakarta, Indonesia, in 2012 and 2013, respectively. He is currently working toward the Ph.D. degree in electrical engineering from the University of Manchester, Manchester, U.K. His areas of interest include power system stability and renewable energy.

Robin Preece (M’13–SM’18) received the B.Eng. and Ph.D. degrees from the University of Manchester, Manchester, U.K. He is a Senior Lecturer in Future Power Systems with the School of Electrical and Electronic Engineering, University of Manchester, where he has been an academic since July 2014. His research is focused on the stability and operation of future power systems.