A DC Power System Stabilizer Based on Passivity-Oriented DC bus Impedance Shaping

Ali Asbafkan\textsuperscript{1*}, Hossein Mokhtari\textsuperscript{2}
Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran
Email:\textsuperscript{1} a.turbodesign@gmail.com, \textsuperscript{2} mokhtari@sharif.edu
Telephone:\textsuperscript{2} +982166165962

Abstract— High penetration of Power Electronic (PE) converters in DC power grids has caused new stability challenges due to dynamic interactions among a network’s subsystems. Dynamic interactions can be avoided by the impedance coordination between the subsystems through the modification of control loops or passive elements inside a grid. Impedance coordination is a very complex and time-consuming task with no adaptations to dynamic changes in a power grid. In this paper, the concepts of dynamic interaction and passivity are explained and combined together to provide an online stability measure in terms of the DC bus impedance characteristics. A novel DC Power System Stabilizer (PSS) is proposed which is connected to a DC bus as a separate module passivizing the bus impedance at non-passive interaction frequencies. The interaction frequencies are detected through a broadband online identification process. The PSS working principle, topology, modeling, and control designs are explained in detail. Finally, the functionality and performance of the proposed stabilizer are validated by simulation results.

Keywords—Dynamic interaction, passivity, power system stabilizer, system identification.

I. INTRODUCTION

Medium Voltage DC (MVDC) grid technology has gained much attention for electric power distribution systems and micro grids over the past decade. DC grids are beneficial due to their high power-density, efficiency, less harmonic pollution, fast dynamic responses, and better integration into renewable energy sources and energy storage systems. DC technology has been utilized in railway [1], aerospace [2], marine, offshore industries [3], and is being developed for the expansion of the grid infrastructures at transmission and distribution levels [4].

DC power distribution systems are highly penetrated by PE converters which are characterized by non-linear dynamics. In practice, PE converters are designed to provide high dynamic performance with optimized stability margins [5]. However, when they are connected to each other in a multi-converter system, new stability challenges occur. Due to the tight regulation of the control loops, a non-minimum phase dynamic is introduced at the input terminal of the PE loads which can lead to instability [6]. This phenomenon is introduced as the Constant Power Load (CPL) destabilizing effect. But, the CPL behavior is not the worst-case scenario, and some incidents of instability at light load conditions are also reported in industries which are due to the interactions among the control loops of the interconnected converters [7]. In this case, the instability arises from a totally different phenomenon than the CPL effect, yet both result in a negative impedance at the input terminal of the PE loads [8].

The history of the stability analysis for multi-converter systems dates back to the Middlebrook’s work on filter design [9] and its Nyquist derived extensions to the Gain and Phase Margin Criterion, the Opposing Argument Criterion, and the Energy Source Analysis Consortium (ESAC) Criterion which are all reviewed and compared in [10]. These criteria have been used for the impedance coordination among PE converters in aerospace [2] and marine industries [11]. The criteria define various forbidden regions in the polar plot of the so-called minor-loop-gain (MLG) which is the impedance ratio of the source subsystem to that of the load subsystem. Impedance coordination is a very complex and time-consuming task which is based on the frequency response measurement of each subsystem at various operating points [2], [12]. Unfortunately, these criteria lead to a conservative design and are sensitive to components grouping, system uncertainties, load conditions, and power flow direction in a network [10].

Recently, a novel Passivity-Based Stability Criterion (PBSC) has been proposed which is based on the passivity of the overall DC bus impedance from any arbitrary point [13]. There are some earlier works on the passivity of the overall DC bus admittance which were developed for railway industries and have led to the Input Admittance Criterion (IAC) [14] and the EN50388 standard [15]. It is worth mentioning that the observability of an unstable
mode from any arbitrary point in a power network is still an open problem, but initial investigations on practical power systems indicate that any unstable mode is propagated throughout the grid without any zero/pole cancellations [14].

Many stabilization techniques have been proposed in the literature among which active damping methods are preferred due to their higher efficiency and lower costs. General approaches of active damping methods are to modify the impedance characteristics of PE converters at the load-side or the source-side to fulfill the stability criteria. Virtual impedance techniques [16], [17], passivity-oriented admittance shaping [18], and DC bus voltage feed-forwarding [19] are some general methods of active damping applied to the load-side converters. Other solutions such as feedback linearization [20], back-stepping control [21], synergistic control [22], and multi-agent stabilizing control [23] are the nonlinear stabilizing techniques which can provide large signal stability. But nonlinear solutions are complex and highly dependent on the system model and parameters. A passivity-based stabilizing control has been proposed in [24] which adds a supplementary positive feed-forward loop to the load-side converter. However, the control design is highly computational and dependent on the converter unterminated model and transfer functions. In [25], a passivity-based stabilizing control is implemented on the source-side converter which is very simple in design and calculations. In this method, a notch filter is added to the voltage control loop in order to enhance the DC bus stiffness at the interaction frequency. However, the bandwidth of the voltage loop is limited and the notch filter cannot be implemented in a wide frequency range.

All the aforementioned stabilizing methods, whether they are applied to the load-side or the source-side, impose the oscillatory damping power disturbances to the network subsystems, leading to their performance degradation or increased cyclic stresses at their mechanical drive trains. Furthermore, such control modifications cannot be applied to commercial PE converters with a limited access to their firmware. These shortcomings call for a centralized stabilizer in a DC grid.

The idea of centralized stabilizer has been proposed in [26] for the modification of the source-side impedance. But in practice, the source-side converter is not decoupled from the rest of the network and the explicit form of its output impedance is not known for the stabilizer. Another centralized stabilizer is proposed in [27] which uses the Second-Order-Generalized-Integrator (SOGI) for shaping its output impedance around the specific resonance frequency. However, due to the lagging function of the SOGI filters at higher than notch frequencies, an inductor-like impedance is introduced to the grid which may lead to new unexpected LC resonance modes.

In this paper, a DC Power System Stabilizer (PSS) is introduced which is connected to a DC bus as a separate module. The PSS works on the principle of shaping the DC bus impedance with the enforcement of the passivity condition at the non-passive interaction frequencies. The interaction frequencies are detected through a broadband impedance identification process which is done by the local measurements. The approach has several advantages as follows: centralized implementation with no modifications to the grid structure in terms of software, hardware or communication related aspects; well-defined design and simple calculations; and adaptation to the network dynamic changes with a fixed control structure.

This paper is organized as follows: In section II, the concept of dynamic interaction among PE converters is introduced and combined with the PBSC to provide guidelines for the stability assessment of DC grids in terms of their equivalent bus impedance. In section III, the PSS working principle, functionality, and sequences are explained. In section IV, the PSS is modeled and its control loops are designed. Finally, in section V, the PSS performance is evaluated by the simulation results.

II. DYNAMIC INTERACTION AND STABILITY ANALYSIS

Power systems with a high penetration of PE converters are prone to voltage oscillations or instabilities. PE converters are controlled-devices with nonlinear dynamics, which in a small signal sense, they are modeled by complex transfer functions in the canonical form [28]. The terminal characteristics of the PE converters are related to their control parameters, operating point, and filter components. A DC power distribution system can be considered as an interconnection of an upstream source and a downstream load subsystem. As depicted in Fig. 1, the source and the load subsystem impedances are denoted by $Z_S$ and $Z_L$, respectively. The equivalent DC bus impedance is:

$$Z_{bus} = \frac{Z_S \cdot Z_L}{Z_S + Z_L} = Z_S \left[ \frac{1}{1 + Z_S/Z_L} \right]$$  \hspace{1cm} (1)

According to (1), the bus impedance is represented by $Z_S$ multiplied by a correction factor which is a function of $Z_S/Z_L$ (MLG). The network is stable if $Z_S$ and $Z_L$ are individually stable and the Nyquist contour of the correction factor does not encircle (-1,0). In practice, $Z_S$ dominates the bus impedance at low-frequency ranges, where the bandwidth of the source subsystem is wide enough to support the load dynamics. At high-frequency
ranges, the bus impedance is also dominated by the source-side capacitor banks. In both low and high frequency ranges, the MLG magnitude is very small and thus \( Z_{bus} \approx Z_S \).

Dynamic interaction may happen at a mid-frequency range, where the bandwidth of the source-side is limited, and thus \( Z_S \) and \( Z_L \) are comparable in magnitude but with an obtuse angel. The \( Z_{bus} \) peaking phenomenon occurs when the phase difference of \( Z_S \) and \( Z_L \) exceeds 120°. For the phase differences of more than 150°, the amount of resonance peak exceeds 6 dB and the associated bus ringing and performance degradation occur due to the amplification effect of the correction factor [2]. As compared in Fig. 2, this condition is similar to the resonance phenomenon but in this case, feedback control loops interact with each other and either of \( Z_S \) or \( Z_L \) exhibits a negative real-part which reduces the network damping.

Any resonance peak in the \( Z_{bus} \), be it originated from the interaction of the physical LC components in the grid, or from the PE converters control loops, is the candidate for a network instability. The system stability at a resonance peak depends on the net damping of a power grid. Depending on the passivity condition of \( Z_{bus} \), the sign of the net damping can be determined. Network instability is identified when the \( Z_{bus} \) phase angle varies around 180° at a resonant peak. Preventive actions can be taken before the oscillations start and the phase angle is still less than 180°.

In a small signal sense, a DC bus is passive if \( Z_{bus} \) is a positive real transfer function [29], in other words:

\[
\text{Re}[Z_{bus}(\sigma + j\omega)] \geq 0, \forall \sigma > 0, \forall \omega. \tag{2}
\]

Checking for the positive real property in the Right Half Plane (RHP) is a very complex and formidable task. According to the real part corollary of the maximum modulus theorem [30], the minimum value in (2) will be found on the boundary of the RHP, i.e., the imaginary axis, provided that there is no singularity inside the RHP region. Therefore, the bus impedance is passive if and only if:
- \( Z_{bus}(s) \) has no RHP poles,
- and the Nyquist contour of \( Z_{bus}(j\omega) \) completely lies in the RHP.

The first condition stands for the system stability, but passivity is more than stability. Passivity can provide robust stability which is important in practical systems with delays and uncertainties [13]. The RHP Nyquist contour can be evaluated by the following phase constraint:

\[
-\frac{\pi}{2} \leq \text{arg}(Z_{bus}(j\omega)) \leq \frac{\pi}{2}, \forall \omega. \tag{3}
\]

Passivity is a sufficient condition for a network stability which means that a system could be stable even if there are some non-passive frequency ranges in the \( Z_{bus} \) spectrum. Therefore, it is not required to check for the passivity condition in the whole frequency ranges.

### III. PROPOSED STABILIZING METHOD

The main idea of the proposed stabilizer is to enforce the passivity condition to \( Z_{bus} \) at non-passive resonance frequencies. The task can be done actively by modifying the bus impedance around the resonance frequency such that the passivity phase constraint in (3) is satisfied. As shown in Fig. 3, the DC PSS injects a damping current \( (I_{damp}) \) to the DC bus which emulates a virtual damping impedance \( (Z_{damp}) \) that is paralleled to \( Z_{bus} \). The damping impedance is designed to be passive and dominant to the DC bus impedance \( (Z_{damp} \approx Z_{bus}) \) at the resonance frequency. Therefore, the total bus impedance \( (Z_{bus, new}) \) follows the \( Z_{damp} \) characteristics which is passive and thus stable. The amplitude of the damping current is proportional to the DC bus voltage oscillations and decays to zero as the grid voltage oscillations damp.

The proposed stabilization method is not dependent to the \( Z_{bus} \) explicit transfer function. It relies on the \( Z_{bus} \) frequency spectrum which can be achieved from the non-parametric online identification. Wideband identification of \( Z_{bus} \) is performed by perturbing the grid voltage with a Pseudo-Random-Binary-Sequence (PRBS) signal. The PRBS signal is a digital approximation of the white noise, exciting all the frequencies of interest over a fraction of time [31]. The DC bus impedance frequency spectrum is obtained after applying the Discrete-Fourier-Transform (DFT) to the perturbed signals [32]. Based on the identified \( Z_{bus} \), the non-passive resonance peak (if any) is detected and the required \( Z_{damp} \) is calculated. It is worth mentioning that the identification process can be activated conditionally as the DC bus voltage deviates a predefined threshold. But if online stability monitoring and preventive actions are of concern, the DC bus can be identified all the time. The flowchart of the stabilizing process is shown in Fig. 4.

### IV. DC PSS STRUCTURE AND CONTROL DESIGN

As shown in Fig. 5, the PSS involves two power circuits which are the stabilizing circuit and the perturbing
circuit. The stabilizing circuit injects the damping current to the grid, while the perturbing circuit is responsible for exciting a network with the PRBS signal. Both circuits are implemented in a half-bridge topology. The DC PSS capacitor voltage is regulated by the stabilizer at a higher level than the grid voltage ($V_C > V_{bus}$). The higher voltage is required for the bidirectional current control capability and the provision of a duty cycle margin to avoid the modulator saturation in the perturbing circuit.

The control structure of the stabilizing circuit is comprised of the cascaded voltage and current control loops. The stabilizer reference current is tracked by an internal control loop and the PSS capacitor voltage ($V_C$) is regulated by an external control loop.

The control loop of the perturbing circuit regulates the current at nil in order to block the circulating current between the two half-bridge converters. The PRBS signal is added to the modulator of the perturbing circuit and is also feed-forwarded to the reference signal in order to ensure that it is not rejected by the control action at low frequency ranges. The stabilizer reference current calculation, modeling and control design are explained in the following sections:

A. Calculation of the Passivizing Reference Current

The damping impedance ($Z_{damp}$) should:
- exhibit a high impedance at low frequency ranges.
- exhibit a dissipative (passive) behavior in the resonance frequency
- and not exhibiting an inductive behavior at higher than the interaction frequency in order to avoid unexploited LC resonance between the stabilizer and the grid.

The $Z_{damp}$ is designed to be a series RC-branch with the parameters tuned based on the identified $Z_{bus}$ at the resonance frequency. The RC-branch corner frequency is designed to be one decade below the resonance frequency ($f_{res}$) with the impedance value to be one order of magnitude smaller than the grid impedance peak value at the resonance frequency ($Z_{peak}$). Therefore, the parameters of the RC-branch are:

$$R = \frac{Z_{peak}}{10}, C = \frac{10}{2\pi f_{res}}.$$  \hfill (4)

The stabilizer reference current is calculated in (5):

$$I_{damp}(s) = \frac{V_{bus}(s)}{Z_{damp}(s)} = \frac{V_{bus}(s)}{R + \frac{1}{Cs}}.$$  \hfill (5)

Where “$s$” denotes the Laplace variable.

Using the Backward-Euler discretization method with a time step of $T_s$, the discrete form of the passivizing current is:

$$I_{damp}(k) = \left(\frac{C}{T_s+RC}\right) \cdot [V_{bus}(k) - V_{bus}(k-1)] + \left(\frac{RC}{T_s+RC}\right) \cdot I_{damp}(k-1).$$  \hfill (6)

where “$k$” denotes the $k$th control iteration.

B. Current Control Loop

In order to track the calculated reference current with fast dynamic response, a deadbeat current controller is adopted [30]. In this control method, the actual current converges to the reference value after the two sample time delays ($2^{-2}$). The control rule is derived in [33] and is represented here in terms of the stabilizer DC link voltage ($V_C$), reference current ($I_{ref}$), actual current ($I_L$), grid voltage ($V_{bus}$), and the converter switching frequency ($f_{SW}$).

The switching duty-cycle ($d$) of the stabilizer circuit modulator is:

$$d(k+1) = -d(k) + \left(I_{ref}(k) - I_L(k)\right) \frac{L \cdot f_{SW}}{V_C(k)} + \frac{2}{V_C(k)} V_{bus}(k).$$  \hfill (7)

C. Voltage Control Loop

The DC PSS voltage control is achieved through the control of the stabilizer current. Using the average model
of the half-bridge topology, the DC PSS dynamics is:

\[ \mathcal{C} \frac{dV_c}{dt} = -d \cdot I_{damp} - d \cdot I_{PRBS} \]  

(8)

where \( \mathcal{C} \) and \( V_c \) are the stabilizer DC link capacitance and voltage respectively. The small-signal linearization of (8) is:

\[ -\mathcal{C} \frac{dV_c}{dt} = d_o \cdot I_{damp} + \dot{d} \cdot I_{damp} + \ddot{d} \cdot I_{damp} + \text{dist. term} \]  

(9)

where “~” and “O” denote the small signal variable and the operating point respectively. The perturbing circuit does not participate in the PSS voltage control and thus the \( I_{PRBS} \) is modeled as a disturbance term (\( \text{dist. term} \)) in (9).

Neglecting the second order signal perturbation in (9), the transfer function from the stabilizer output current to the DC link capacitor voltage can be written as:

\[ \frac{\tilde{V}_c(s)}{I_{damp}(s)} = \frac{-d_o}{\mathcal{C} s} \]  

(10)

In order to regulate \( V_c \) at the reference value, a Proportional-Integral (PI) controller is used:

\[ \text{PI}(s) = K_p \left( 1 + \frac{1}{T_i s} \right) \]  

(11)

where \( K_p \) is the proportional gain, and \( T_i \) is the integration time constant.

The PI controller parameters are tuned using the Symmetrical Optimum Criterion [5]. The stabilizer model and control hierarchy are depicted in Fig. 6. The root locus of the voltage loop is shown in Fig. 7. The PSS power circuit ratings and control parameters are listed in Table I.

V. SIMULATION RESULTS

A DC power distribution system of the cascaded source and load subsystems is presented in Fig. 8. The power system consists of an Active-Front-End (AFE) rectifier as the source subsystem, and a metro traction motor drive as the load subsystem. The simulations are done in Matlab/Simulink environment with a time step of 2x10^-6 s.

The current control loops of the AFE rectifier and traction drive are designed based on the Optimum Modulus criteria [5]. The bandwidth of the AFE rectifier is intentionally reduced such that a dynamic interaction between the two subsystems occurs within the nominal power range of the grid. The parameters of the AFE rectifier and the traction motor drive are presented in Table II. The PRBS parameters are tuned based on the system noise level, degree of non-linearity, time constants, and the desired frequency resolution [34]. In this paper, the PRBS wave is generated by a 4700 Hz 10-bit linear-feedback-shift-register (LFSR) with a resolution of 4.6 Hz. The PRBS signal amplitude is designed large enough to excite the DC bus dynamics at the whole frequency ranges, and small enough to reduce the small-signal modeling errors originated from the system non-linearity. In practice, the PRBS amplitude is designed to perturb the DC bus voltage around 3% to 5%.

In the first simulation, the stability of the power grid is investigated at different load conditions. The DC bus voltage is regulated at 750V by the AFE rectifier and the traction motors are accelerated with a constant torque. The PSS is connected to the DC bus, but only the perturbing circuit is operational for the sake of the stability monitoring. The DC bus voltage and power at the rectifier terminal are shown in Fig. 9. As seen in this figure, an unstable oscillation starts at 200 kW load power.

In order to investigate the network stability in the frequency domain, the identified \( Z_{bus} \) is plotted in Fig. 10 for different load conditions. As indicated in this figure, there is a resonance mode at 118 Hz which refers to the traction drive input LC filter. This mode is passive and stable for all load conditions. As the load power increases, a bus peaking phenomenon occurs at 32.2 Hz which is not originated from the passive elements inside the grid. This oscillation mode refers to the dynamic interaction between the AFE rectifier and the traction drive. The passivity condition is violated at 200 kW load power for this oscillation mode.

In the second simulation run, the perturbing and stabilizing circuits of the PSS are both operational. The required \( Z_{damp} \) is calculated based on the identified \( Z_{bus} \) and the passivating reference current is applied to the stabilizer current control loop. As shown in Fig. 11, the DC Bus is stabilized at 200 kW load power after the injection of the passivating current. In this simulation run, the grid power increases up to 250 kW to check for the robust stability. In Fig. 12, the stabilizer terminal voltage and current are shown at a closer look. At 7.75s, the
passivizing current is injected to the DC bus with an opposite phase to the voltage oscillations. Therefore, the damping power is absorbed from the grid at the interaction frequency, meanwhile, a decaying current offset is also injected to the DC bus, balancing the amount of the input and output energy at the PSS port. In order to investigate the function of the stabilizer from the frequency point of view, the identified \( Z_{\text{bus}} \) spectrum before and after the stabilization is plotted in Fig. 13. Before the stabilization, there is a resonant peak at 32.2 Hz with the magnitude of 25 dB and the phase angle of 176\(^\circ\). After the stabilization, the bus impedance magnitude is reduced to -10 dB with the passive phase angle (0\(^\circ\)) characteristic. The bode plot of the stabilized \( Z_{\text{bus}} \) at 250 kW load power is also plotted in Fig. 13. As it can be seen in this figure, the sensitivity of the stabilized \( Z_{\text{bus}} \) is very low under the load power variation.

In the next simulation run, the PSS dynamic response is evaluated for the step load changes. The traction motor reference current is increased from 100 A to 300 A at 2s, and is decreased back to 100 A at 2.9s. At first, the PSS is intentionally disabled. The DC bus voltage and power in response to the load steps are plotted in Fig. 14. The DC bus oscillations start right after the load increases from 60 kW to 300 kW. The simulation is repeated again when the PSS is operational. As shown in Fig. 15, the DC bus is stabilized at 2.25s after the passivizing current has been injected to the grid. The passivizing current decays to zero as the voltage oscillations are damped. The DC PSS response is limited to the perturbation and identification process time which is 0.217s in this simulation.

VI. DISCUSSION

The novelty of this paper is about the methodology of the DC bus stabilization. In contrast to the proposed methods in [16-25], the stabilizing function is implemented by a separate module in a DC grid. Therefore, the control loops and bandwidths of other load or source converters in the grid are not affected by the stabilizing function. Compared to the proposed method in [24], the computational effort is very low because the control algorithm is independent of the converter unterminated model (g-parameters). Due to the deadbeat current control, the stabilizer current loop model is fixed and known \((z^{-2})\) at the whole frequency ranges. Therefore, the PSS control adaptation is done only by the reference current variations.

In [25] and [27], the bus impedance at resonance frequency is modified by the notch or SOGI filters, which from the circuit point of view, exhibit an RLC branch impedance to the grid. The RLC branch behaves like an inductor in the high frequency ranges which can resonate with the network capacitor banks. The proposed stabilizer exhibits an RC branch which is stable in the whole frequency range. In contrast to [25] and [27], the control structure of the proposed stabilizer is fixed in case of the grid resonance frequency variations. The proposed PSS has a bidirectional power flow capability which injects the absorbed damping power back to the network with a decaying DC current offset. Therefore, there is no need for any battery storage or dissipative dummy loads inside the PSS. Along with the abovementioned advantages, the proposed PSS reduces the network power quality due to the PRBS perturbations.

VII. CONCLUSION

In this paper, the concepts of dynamic interaction and passivity are combined together to provide a sufficient condition for the detection of a DC power grid instability in terms of its DC bus impedance characteristics. A novel power system stabilizer is proposed which is connected to a grid as a separate module, passivizing the DC bus impedance at interaction frequencies. The stabilizing method is based on the local measurements for the online identification of the DC bus Impedance. The stabilizer adopts a fixed control structure which emulates a damping impedance with adaptations to the power grid dynamic changes. The stabilizer functionality, circuit topology, modeling and control designs have been explained in detail. The performance and effectiveness of the proposed stabilizer have been validated by the simulation results. The results show that the proposed stabilizing method is a promising technology for the future DC power grids and microgrids characterized by a high penetration of PE converters, changing load profiles, and uncertainties.

VIII. REFERENCES


Ali Asbaifkan was born in Isfahan, Iran in 1987. He received the B.Sc. degree in electrical engineering from the Isfahan University of Technology, Isfahan, Iran, in 2010, and the M.Sc. degree (with Honors) in power electronics and drives from the University of Isfahan, Isfahan, in 2012. He is currently working toward the Ph.D. degree from the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran.

From 2009 to 2012, he was with the Turbo Design Team in Isfahan University of Technology. His research interests include dynamics and controls of power electronic converters, power quality, electric machines, and drive systems.
Hossein Mokhtari (M’03–SM’14) was born in Tehran, Iran, in 1966. He received the B.Sc. degree in electrical engineering from Tehran University, Tehran, in 1989, the M.Sc. degree in power electronics from the University of New Brunswick, Fredericton, NB, Canada, in 1994, and the Ph.D. degree in power electronics/power quality from the University of Toronto, Toronto, ON, Canada, in 1999. From 1989 to 1992, he was with the Consulting Division of Power Systems Dispatching Projects, Electric Power Research Center Institute, Tehran. Since 2000, he has been with the Department of Electrical Engineering in Sharif University of Technology, Tehran, where he is currently a Professor. He is also a Senior Consultant to several utilities and industries.

List of Figures:

- **Fig. 1** $Z_{bus}$ peaking phenomenon at an overlap frequency due to the amplification effect of the correction factor $(1/1+Z_S/Z_L)$ (a) angle of $Z_S/Z_L$ lower than $120^\circ$. (b) angle of $Z_S/Z_L$ exceeding $120^\circ$.
- **Fig. 2** Vector plots of $Z_S$ and $Z_L$ in case of resonance and dynamic interaction.
- **Fig. 3** DC bus impedance shaping at an interaction frequency by the proposed DC PSS. The DC bus impedance is modified to $Z_{bus-new}$ by adding a virtual damping impedance ($Z_{damp}$) in parallel to the grid impedance ($Z_{bus}$).
- **Fig. 4** Flowchart of the stabilizing process implemented by the DC PSS.
- **Fig. 5** DC PSS power circuit and control block diagrams.
- **Fig. 6** The stabilizer model and control hierarchy.
- **Fig. 7** Root locus of the stabilizer voltage control loop.
- **Fig. 8** Power circuit of the system under study.
- **Fig. 9** DC bus voltage (Top) and power (Bottom) at the terminal of the AFE rectifier. Oscillations start at 200 kW load power.
- **Fig. 10** Bode plot of $Z_{bus}$ at different load conditions.
- **Fig. 11** DC bus voltage (Top) and power (Bottom) at the terminal of the AFE rectifier. Oscillations damped after the injection of the passivizing current.
- **Fig. 12** The stabilizer terminal voltage (Top) and current (Bottom).
- **Fig. 13** Bode plot of $Z_{bus}$ before and after the injection of the passivizing current. The power grid is stabilized at the interaction frequency by the PSS.
- **Fig. 14** DC bus power (Top) and voltage (Bottom) responses to the step load variations.
- **Fig. 15** PSS dynamic responses to the step load variations.

List of Tables:

| TABLE I | CONTROL PARAMETERS AND RATINGS FOR DC PSS |
| TABLE II | PARAMETERS OF THE DC POWER DISTRIBUTION SYSTEM |
Fig. 1. $Z_{bus}$ peaking phenomenon at an overlap frequency due to the amplification effect of the correction factor \((1/1+Z_s/Z_L)\) (a) angle of $Z_s/Z_L$ lower than $120^\circ$. (b) angle of $Z_s/Z_L$ exceeding $120^\circ$ [2].

Fig. 2. Vector plots of $Z_s$ and $Z_L$ in case of resonance and dynamic interaction.

Fig. 3 DC bus impedance shaping at an interaction frequency by the proposed DC PSS. The DC bus impedance is modified to $Z_{bus\text{-}new}$ by adding a virtual damping impedance ($Z_{damp}$) in parallel to the grid impedance ($Z_{bus}$).
Fig. 4 Flowchart of the stabilizing process implemented by the DC PSS.

Fig. 5 DC PSS power circuit and control block diagrams.
1/(Ls+R) + - do/Cs
PI + - Deadbeat
Control
Modulator
Z -2
Sample & Hold
CV 
dampI
()refIk
()busVk
()busVk
()LIk
()CVk
CV
()dk
( 1)dk 
()CVk
dampI
CV

Fig. 6 The stabilizer model and control hierarchy.

Fig. 7 Root locus of the stabilizer voltage control loop.

Fig. 8 Power circuit of the system under study.
Fig. 9 DC bus voltage (Top) and power (Bottom) at the terminal of the AFE rectifier. Oscillations start at 200 kW load power.

Fig. 10 Bode plot of $Z_{bus}$ at different load conditions.
Fig. 11 DC bus voltage (Top) and power (Bottom) at the terminal of the AFE rectifier. Oscillations damped after the injection of the passivizing current.

Fig. 12 The stabilizer terminal voltage (Top) and current (Bottom).
Fig. 13 Bode plot of $Z_{bus}$ before and after the injection of the passivizing current. The power grid is stabilized at the interaction frequency by the PSS.

Fig. 14 DC bus power (Top) and voltage (Bottom) responses to the step load variations.
Fig. 15 PSS dynamic responses to the step load variations.

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilizing circuit filter inductance</td>
<td>L1</td>
<td>2 mH</td>
</tr>
<tr>
<td>Perturbing circuit filter inductance</td>
<td>L2</td>
<td>1 mH</td>
</tr>
<tr>
<td>DC link capacitance</td>
<td>C3</td>
<td>4 mF</td>
</tr>
<tr>
<td>Voltage loop PI parameters</td>
<td>$K_P$, $T_i$</td>
<td>5.4, 1.5 Sec.</td>
</tr>
<tr>
<td>Perturbing circuit PI parameters</td>
<td>$K_P$, $T_i$</td>
<td>3, 10 Sec.</td>
</tr>
<tr>
<td>PRBS generation frequency</td>
<td>$F_0$</td>
<td>4700 Hz</td>
</tr>
<tr>
<td>PRBS bits</td>
<td>-</td>
<td>10 bits</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$F_{SW}$</td>
<td>4700 Hz</td>
</tr>
<tr>
<td>Control sampling frequency</td>
<td>$F_S$</td>
<td>4700 Hz</td>
</tr>
</tbody>
</table>
### TABLE II
**Parameters of the DC Power Distribution System**

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AFE Rectifier</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input filter</td>
<td>L_g, R_g</td>
<td>2 mH, 0.1 Ohm</td>
</tr>
<tr>
<td>DC link capacitance</td>
<td>C1</td>
<td>15 mF</td>
</tr>
<tr>
<td>Current loop PI parameters</td>
<td>K_p, T_i</td>
<td>2.8, 0.05 Sec.</td>
</tr>
<tr>
<td>Voltage loop PI parameters</td>
<td>K_p, T_i</td>
<td>9, 0.1 Sec.</td>
</tr>
<tr>
<td>PLL loop PI parameters</td>
<td>K_p, T_i</td>
<td>4.6, 0.5 Sec.</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>F_{SW}</td>
<td>3000 Hz</td>
</tr>
<tr>
<td>Line resistance</td>
<td>R_{line}</td>
<td>0.05 Ohm</td>
</tr>
<tr>
<td><strong>Motor Drive</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input filter inductance</td>
<td>L_{dc}</td>
<td>1.2 mH</td>
</tr>
<tr>
<td>Input filter capacitance</td>
<td>C2</td>
<td>1.5 mF</td>
</tr>
<tr>
<td>Output filter inductance</td>
<td>L_m</td>
<td>4 mH</td>
</tr>
<tr>
<td>Current loop PI parameters</td>
<td>K_p, T_i</td>
<td>9.3, 0.04 Sec.</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>F_{SW}</td>
<td>3600 Hz</td>
</tr>
</tbody>
</table>