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Analysis and Performance Enhancement of Vector-Controlled VSC in HVDC Links Connected to Very Weak Grids

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***Abstract*—Voltage source converter (VSC)-based high-voltage direct current (HVDC) transmission systems have been employed widely in recent years. However, connecting a VSC-HVDC link to a very weak grid (a high-impedance grid) is challenging. A vector-controlled VSC is incapable of injecting/absorbing its maximum theoretical active power in such grids. A simple yet effective control system for a standard vector-controlled VSC in a very weak grid condition has not been reported in the literature. This paper, benefiting from a comprehensive small-signal model, presents a detailed analysis of the VSC dynamics and shows how the assumptions made for designing VSC regulators in strong grids are no longer valid in very weak grids. The paper then proposes and compares two straightforward solutions: retuning the control parameters and using an artificial bus for converter-grid synchronization. Both methods enable the VSC to operate at the maximum theoretical active power at a very weak grid condition (i.e., at unity short-circuit ratio) by minimal modification in the widely accepted vector control method. The advantages and disadvantages of each method are discussed. The analytical results are verified by detailed nonlinear time-domain simulation results.**

***Index Terms*—HVDC, PLL, VSC, vector control, very weak grid, artificial bus, small signal analyses.**

I. Introduction

HIGH-VOLTAGE direct current (HVDC) transmissions have gained significant attention in recent years [1], partly because of increased offshore wind power generation and the high capability of HVDC to interface with this type of generation [1]–[3]. The implementation of HVDCs has increased so much that some countries have decided to standardize and regulate their application [4]. Modern HVDC systems are expected to exhibit a generator-like behavior in terms of frequency support and low-voltage ride-through.

HVDC systems face several problems, which have been discussed at length [5]. Research on line-commutated converters (LCC) is still ongoing [6]; however, voltage source converters (VSCs), despite their higher cost, seem to be more successful in resolving the problems of LCC-based HVDC systems [3], [4], [7]. VSCs suffer much less from output harmonic content and do not require reactive power consumption. They also perform better when connected to weak grids. However, problems occur when VSC-based HVDCs are connected to very weak grids [8]. Many efforts have been made to improve the performance of a very weak grid connected VSC. The authors of [9] tried to approach the problem by enhancing the ac-bus voltage regulation performance. However, later references such as [10] have argued that the problem stems from phase locked loop (PLL) performance in very weak grids. VSCs usually employ vector control, which requires a PLL [8]. PLLs have been investigated for a long time, and many different types have been introduced [11]–[14]. Most articles have paid attention to the impacts of PLL on converter behavior, and some articles have even suggested rules of thumb for PLLs' utilization [15]. On the other hand, other research has concentrated on how a converter controller could also affect the performance of PLLs [16], [17]. Reference [18] showed that even in a strong grid with a high short-circuit ratio (SCR), under special circumstances such as faults, a PLL could be considerably influenced by the converter controller.

These factors convinced researchers to focus more on PLLs and their interaction with a VSC to improve its performance in very weak grids. The authors of [10] used only the PLL parameters to enhance the overall converter performance and stability, significantly decreasing the PLL bandwidth to prevent its interaction with other modes of the system. Although the system remained stable, its performance was very poor. It also suffered from a lack of robustness. In other words, in case of a change in the power system SCR—i.e., switching or faults—the converter stability was not verifiably guaranteed.

Another interesting solution that eliminated the PLL by emulating the inherent synchronization behavior of synchronous machines in a VSC was developed in [19], [20]. However, the control scheme was completely changed and did not match the standard vector control scheme. In addition, similar to the previous method [10], this method did not achieve 1.0 per unit (pu) power injection in very weak grids ($\mathrm{SCR} = 1$).

The newest efforts are still using vector control. In [21], the authors proposed the design of 35 H_∞ controllers for one converter and one specific SCR. These 35 controllers were related to the different operating points of a VSC that covered its entire operating range and guaranteed a smooth performance. However,

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the overall vector control system was very complex. Further, this research focused on only active power regulation. Dc-link voltage regulating has also been investigated in the literature [9], [10], [22], [23], but the maximum possible active power injection/absorption does not appear to have been reached.

Reference [24] suggested referring the PLL measurement point to a point with lower observing grid impedance; however, the study neglected any reactive power and/or ac-voltage regulation. Therefore, the VSC could not absorb/inject the maximum possible active power with a reasonable converter output voltage.

All of these deficiencies motivate the search for new yet simple solutions. This paper proposes solutions that not only remain faithful to vector control, but are also simple and straightforward and maximize power injection/absorption and ensure robustness. Small-signal analysis of a very weak grid-connected VSC shows that the dominant modes are strongly influenced by the states of the PLL and ac-bus voltage controller. Therefore, the first solution is based on simultaneous tuning of the PLL and ac-bus voltage controller gains. The second solution proposed in this paper is based on the use of an artificial bus for grid/converter synchronization to reduce the effective grid impedance as viewed by the VSC. The small-signal analysis is employed to (1) study the dynamics of a grid-connected VSC under weak and very weak grid condition, and (2) evaluate the performance of the proposed methods and their impacts on different aspects of VSC performance, such as voltage regulation, desired active power/dc voltage tracking, and system frequency measurement. The contributions of this paper to the field are as follows:

1) A thorough analysis of the dynamics of a VSC with either active power or dc-voltage regulating controllers, and connected to a very weak grid, and the impacts of the controller parameters on the overall system stability.
2) A detailed analysis of the maximum capabilities and limitations of conventional vector control.
3) The development of the artificial bus method to stabilize the performance of a vector-controlled VSC and maximize its power injection/absorption capability in a very weak grid condition.
4) An investigation of the robustness of the proposed method and a comparison with a retuned conventional vector controller.

This paper is organized as follows. In Section II, a complete model for a VSC is introduced and used for the analysis of a very weak grid. Section III presents the proposed solutions and investigates them in detail. The next section presents the time-domain simulation results to validate the analytical results. Finally, Section V reports the conclusions.

II. Conventional Voltage Source Converters

The conventional VSC system, shown in Fig. 1(a), is connected to the point of common coupling (PCC) via the passive inductive filter Z_f, and the grid line impedance Z_g is intermediating between the PCC and the grid. The capacitance C_f connected to the PCC is ignored in some studies [20]. It is argued

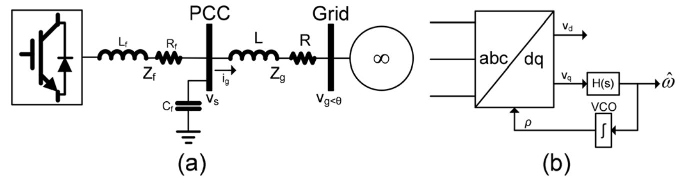

Fig. 1. (a) Schematic diagram of a grid-connected VSC. (b) Block diagram of PLL.

that this capacitance is usually small and does not play a significant role in the stability of a very weak grid. However, for the sake of evaluating the complete system dynamics, it is not ignored in the models in this paper. The parameters of the VSC system in Fig. 1(a) are given in the Appendix and are used in the analysis and simulation studies.

A. Modeling

The modeling of a VSC has been discussed by many researchers [9], [10], [19]–[28]. Most of their models were based on linear small-signal modeling using different methods. For example, [15] utilized input/output admittance, whereas [19] and [20] employed a Jacobian matrix. A complete state-space model consisting of all controllers dynamics as well as line current and voltage equations was used in [21], [25], [26]. All of these methods are equivalent; however, for particular studies, some offer better features. In this paper, the complete state-space model is adopted.

The model with active power and dc-voltage regulating, respectively, is shown in (1) and (2), where the states are introduced as a vector x, which contains 13 or 14 states representing all controllers (current controllers, PLL, ac-bus voltage controller, and active power controller) and power circuit dynamics in the dq-frame. Whereas the grid voltage magnitude $|V_g|$ and dc-link voltage fluctuations v_{dc} (in a dc-voltage regulating VSC, the external power P_{ext} plays the role of the disturbance) can be considered as disturbances, the reference active power$P*$ (or reference dc-link voltage, V_{dc}^*) and reference PCC voltage magnitude $|V_s|^*$ are the desired inputs. Reference [20] proved that a VSC connected to weak grids works much better as a PV bus (regulating active power and PCC voltage) rather than a PQ bus (regulating active and reactive output powers of a VSC). The modeling details of a conventional VSC are available in the literature [25] and, therefore, will not be repeated here. However, some key points in the modeling are worth discussing. As reported in [24], the active power and dc-regulating controllers show similar behaviors, thus, and because of lack of space, the analyses are focused mainly on the former, whereas the results of the dc-voltage regulating controller are also shown wherever doing so is necessary. See (1) and (2) at the bottom of the next page.

The standard vector control structure is based on cascaded proportional-integral (PI) regulators. The active and reactive power PI regulators generate the desired current components, whereas the ac-bus voltage PI regulator generates the reactive power reference. Two PI current controllers are used to generate

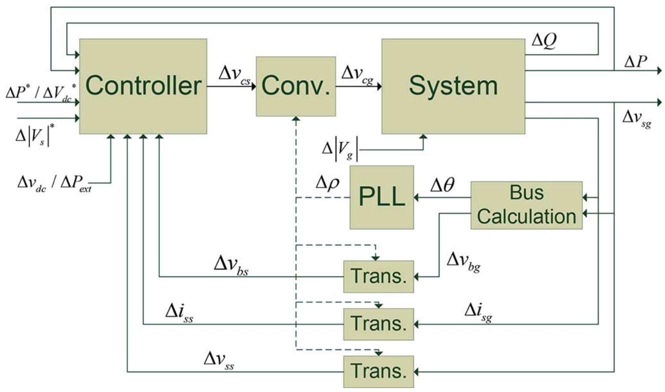

Fig. 2. Block diagram of the small-signal modeling of a grid-connected VSC.

the converter modulating signals in the dq-reference frame. A standard three-phase dq PLL is used to generate the synchronization angle needed to transform the control variables between the stationary and rotating reference frames [26]. A PLL utilizes the voltage of the PCC to determine the system frequency and synchronization angle ρ as shown in Fig. 1(b).

In strong grids, a PLL is usually considered to be ideal and is neglected. However, it plays a vital role in weak grids. Fig. 2 shows the block diagram of the small-signal model in which the impact of the PLL is shown by the "*Trans.*" and "*Conv.*" blocks. Equation (3) introduces their function before linearization. They essentially map the voltage and current vectors, which are represented by u, from one frame whose d-axis coincides with v_g to the other whose d-axis is synchronized with v_s (or vice versa). The PLL output ρ deviates from the exact angle of the grid voltage v_s in transient and dynamic conditions. If the system remains stable and the PLL is perfectly locked, the angle ρ converges to the grid voltage angle θ.

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \begin{bmatrix} \cos\rho & \sin\rho \\ -\sin\rho & \cos\rho \end{bmatrix} \begin{bmatrix} u_{gd} \\ u_{gq} \end{bmatrix}. \quad (3)$$

The impact of the PLL can now be reflected in the complete model. Although the analysis will be verified in detail in the time-domain simulation section, Fig. 3 is included here to show the accuracy of the small-signal model used in the analysis. Obviously, the linearized model exhibits a very high level of coincidence. In light of such a model, detailed analysis of the system is possible.

B. Analysis

Equation (4) indicates the boundaries of the active power, which could be injected by a VSC into the PCC in the steady state. The negative sign indicates absorption.

$$\frac{R|V_s|^2 - |Z_g||V_s||V_g|}{|Z_g|^2} \le P \le \frac{R|V_s|^2 + |Z_g||V_s||V_g|}{|Z_g|^2}. \quad (4)$$

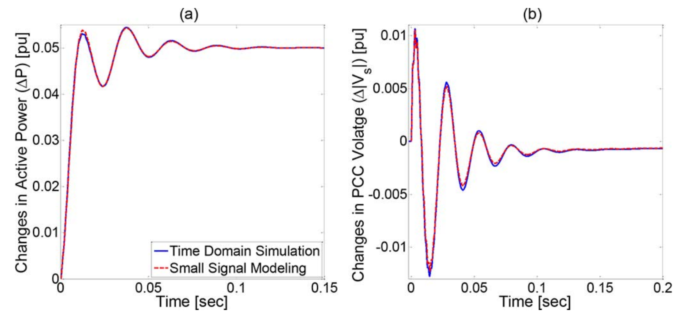

Fig. 3. Response of the VSC to a 0.05 pu change in the reference active power. (a) Changes in VSC active power output. (b) Changes in PCC voltage. SCR $=$ 1, $P_0 = 0.5$ pu.

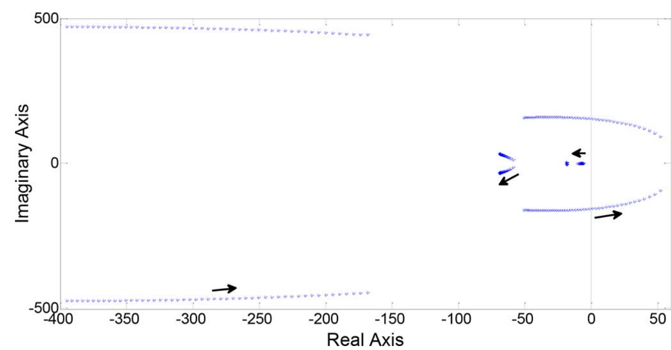

Fig. 4. Dominant eigenvalues of the system when SCR decreases to 1.

In a grid with SCR $= 1$, the magnitude of the grid impedance will be 1.0 pu. Without the loss of generality, if the grid and PCC voltages are assumed and controlled to be 1.0 pu, the maximum power injection and absorption will be limited to 1.1 pu and 0.9 pu, respectively. In other words, the maximum active power that can be injected into a very weak grid is close to 1.0 pu according to static analysis. However, in reality, this amount is even less. Eigenvalue analysis can reflect these differences as shown in Fig. 4. In fact, many researchers discuss this point; however, they usually omit the other challenges of a VSC connected to a very weak grid.

Before proposing any solution, a better understanding of the dynamics of a VSC connected to a very weak grid is necessary. The model allows a thorough investigation of the system dynamics. However, many factors may play significant roles.

One of the most important challenges when connecting a VSC to a very weak grid is the loss of controller independence. Fig. 5 shows the response of the PLL to the changes in the voltage magnitudes (reference ac-bus voltage V_{ref} and ac system internal voltage V_g). Here, the system frequency is kept constant while the voltage magnitude is changed. Obviously, by increasing the SCR, the changes in the reference value of the PCC voltage have less impact on the PLL output frequency in terms of the settling time and maximum deviation index. In other words, the interference of the voltage regulator in the

$$\Delta\dot{x}_p = A_p\Delta x_p + B_{1p}\Delta|V_s|^* + B_{2p}\Delta P^* + B_{3p}\Delta|V_g| + B_{4p}\Delta v_{dc}. \quad (1)$$

$$\Delta\dot{x}_v = A_v\Delta x_v + B_{1v}\Delta|V_s|^* + B_{2v}\Delta V_{dc}^* + B_{3v}\Delta|V_g| + B_{4v}\Delta P_{ext} \quad (2)$$

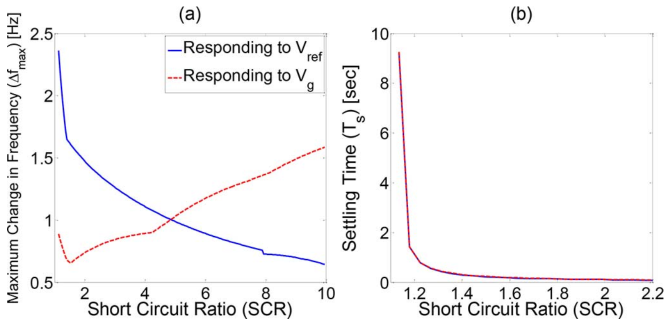

Fig. 5. Impact of voltage magnitude disturbance on the PLL performance in different SCRs. A 10% changes in the voltage magnitude is applied in all the cases whereas the active power operating point is set to zero.

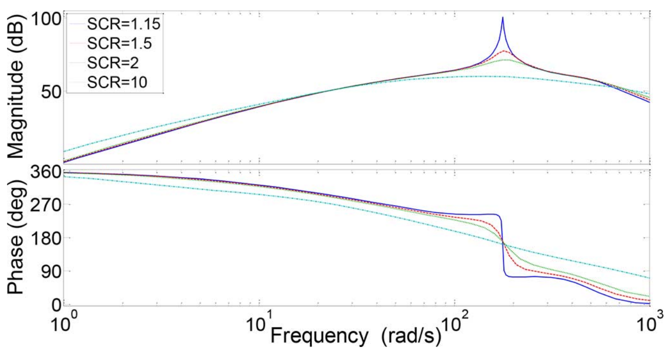

Fig. 6. Frequency response of the output active power of a VSC responding to changes in the reference voltage of PCC.

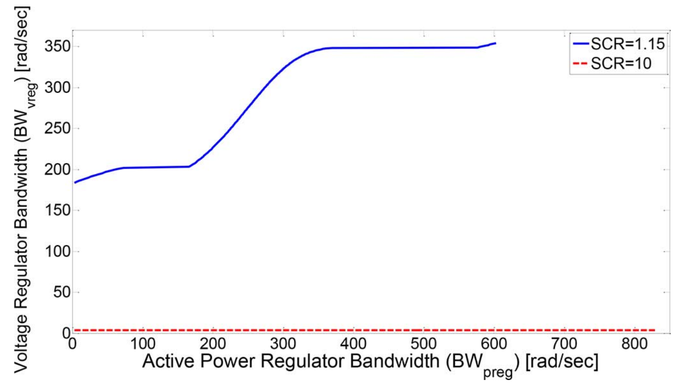

Fig. 7. Impact of active power control bandwidth on the ac-bus voltage control bandwidth.

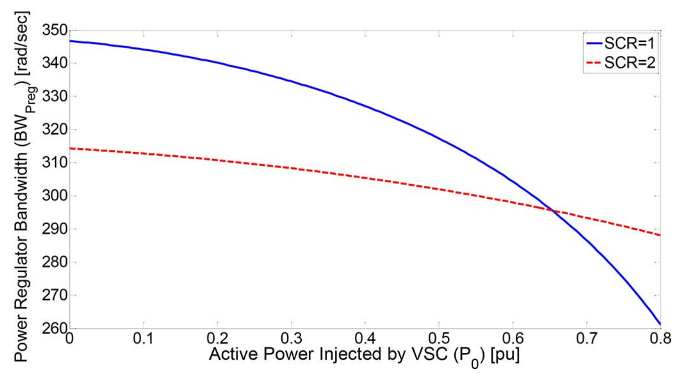

Fig. 8. Impact of operating point on the VSC active power regulation.

PLL performance has decreased significantly. On the other hand, in the stronger grid, the grid voltage disturbance leads to higher fluctuations in the PLL output. Although the magnitude of this deviation has increased, its settling time has decreased severely. This result means that the deviation will decay very quickly. Further, this result could also be explained by the voltage regulator. Lower SCRs allow tighter control of PCC voltage, which bypasses the disturbances from the grid voltage. Therefore, the input of PLL, PCC voltage, is less influenced by the grid voltage.

The voltage regulator also interferes with the active power regulation. Conventionally, independence of these two regulators is desired and expected. However, as Fig. 6 reveals, a very weak grid behaves differently. The resonance, distinguished as a spike in the frequency response, was expected from Fig. 4, in which the conjugate poles are moving toward the right half-plane. Their impact will appear as fluctuations on the VSC active power output whenever the PCC voltage magnitude reference input $|V_s|^*$ is changed.

On the other hand, the parameters of the active power regulator also affect the ac-bus voltage regulation. Fig. 7 reveals this impact more clearly. The integral gain of the active power regulator is changed here to gain different bandwidths for the closed-loop power control dynamics. In a strong system with $\mathrm{SCR} = 10$ (red dashed line), this gain has almost no impact on the voltage regulator bandwidth; however, it results in huge changes to voltage regulator performance in a very weak grid.

The situation becomes more complicated when the operating point of the system is also considered as a factor. In a weak grid with $\mathrm{SCR} = 2$, changes of initial power injection from zero to almost one per unit lead to a change of less than 7% in the active power regulator bandwidth. This change is negligible; however, in a very weak grid with $\mathrm{SCR} = 1$, the same changes in the operating point lead to changes of more than 24% in the controller bandwidth (see Fig. 8). In other words, the operating point cannot be excluded in studies of very weak grids.

Although all these facts are not explicitly mentioned in [21], they forced its authors to undertake the complicated process of designing 35 H_∞ controllers for a single converter.

III. Solutions

The main aim of any solution is to enable 1.0 pu power injection in a very weak power system. A solution must be robust and should be the least complicated alternative.

A. Retuning

One of the first solutions to be examined is the retuning of the controller parameters. The previous attempts in the literature failed to reach the main goal of this present paper. In [10], the authors focused only on the PLL bandwidth; however, the analysis in Section II showed that the independence of different regulators, observed in strong grids, no longer functioned in very weak grids.

By benefiting from the experiences reported in [9] and [10]—which emphasize the speeding up of the voltage regulator and the slowing down of the PLL, respectively—the desired goal becomes reachable, as Fig. 9 indicates.

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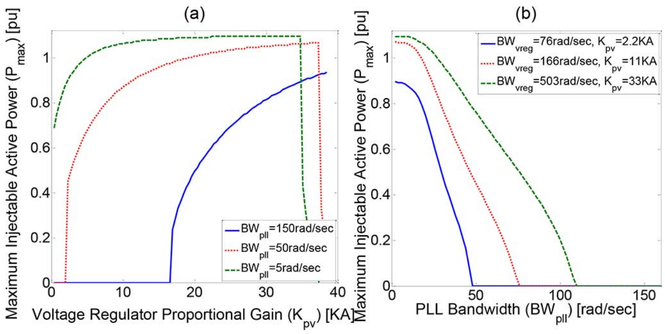

Fig. 9. Maximum injectable active power at SCR $= 1$ with retuning the parameters of voltage controller and PLL.

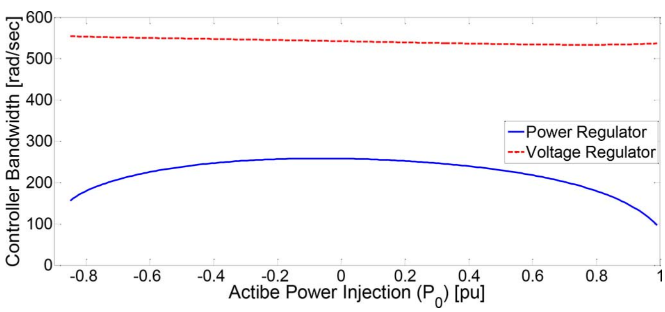

Fig. 10. Impact of the system operating point on the retuned VSC performance.

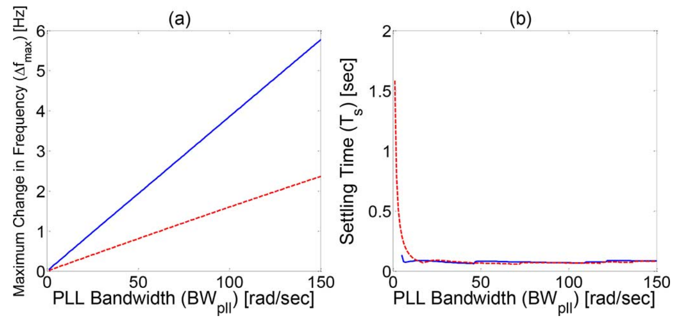

Fig. 11. PLL output frequency responding to a 10% change in the grid voltage, $|V_g|$, (red dashed line) and the input reference voltage for PCC, $|V_s|^*$, (blue solid line).

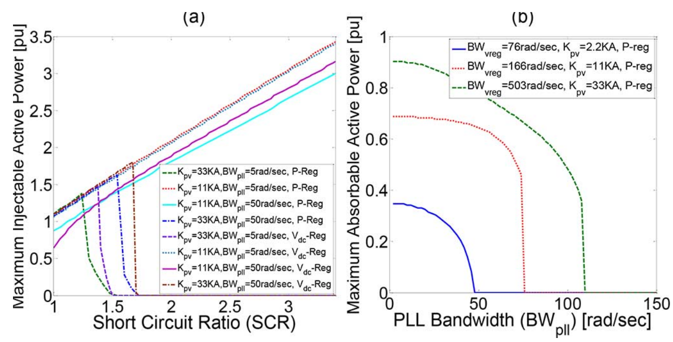

Fig. 12. (a) Impact of the strength of the grid on the retuned controller. (b) Maximum absorbable active power by VSC in very weak grid utilizing the retuned controller.

Huge changes in the voltage angle result in problems for the PLL. A slow tracking can prevent these angular stability problems but will result in a poor PCC voltage profile. Fast voltage regulation is necessary to guarantee acceptable voltage magnitude in the presence of such a slow PLL.

However, to achieve the main goal, the decoupled design of controllers, one of the main assumptions in the strong grid is neglected. In fact, such a strategy responds to the lack of decoupling between the voltage and frequency stabilities experienced in strong grids. In other words, the PLL and voltage regulator parameters are designed together, not separately. Although this strategy enables 1.0 pu power injection, it also necessitates complete modeling of the system. This requirement is much more complicated than the requirements of the standard strong grid design.

The robustness of the controller is another important concern. Fig. 10 reveals the active power and voltage regulator bandwidths at different operating points. Although some changes can be observed in the power controller speed, it always remains reasonable.

Fig. 11 focuses on another aspect, the impact of the voltage regulator on PLL performance. Not surprisingly, with decreasing PLL bandwidth, smaller deviations in the PLL output frequency occur. However, these results are obtained by slowing down the PLL. Such slow behavior is also reflected in the prolonged settling time of the fluctuations shown in Fig. 11(b). In other words, PLL performance is now very slow, and the voltage regulator is very fast so that their interactions no longer destabilize the system.

Despite these advantages, some issues challenge the capabilities of the retuned controller. Fig. 12 illustrates the situation more clearly. Part (a) shows how the proposed method is sensitive to the strength of the grid. Indeed, by decreasing the impedance of the grid, tight control of the PCC voltage will not be possible, so that the system will become unstable. On the other hand, systems that remain stable (like the red dashed curve in the figure) utilize very small bandwidths. Such slow phase tracking is not desired, especially if the output frequency of the PLL is needed for other applications such as frequency regulation. In fact, adopting such a small bandwidth is very similar to the idea of removing the PLL, with all its advantages and disadvantages [19]. This figure also depicts the dc-voltage regulating VSC behavior, which is similar to that of the active power regulating controller.

The other notable observation is related to the absorption rather than injection of power. Sinking active power is not usually needed for HVDCs interfacing with wind generators; otherwise, such power is very practical and possible. As Fig. 12(b) shows, very low PLL bandwidths and very fast voltage regulation are needed to enable maximum static absorption. A comparison to Fig. 9(b) reveals that the lower ac-voltage regulation bandwidths were also able to use the entire available capability of the converter for injection. In other words, designing a retuned controller for a VSC with both injection and absorption of active power is even more complicated and also is restricted to smaller ranges of parameters.

B. *Artificial Bus*

The conflicts discussed regarding the retuned controller motivate the search for a new solution that attempts to address the problem's main source, which is the high impedance between

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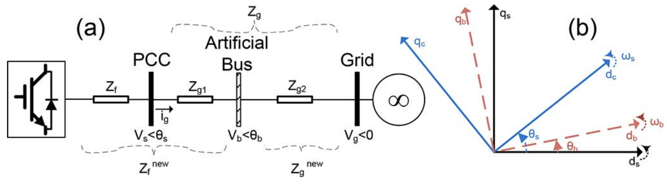

Fig. 13. (a) Schematic view of the concept of the artificial bus method. (b) dq-reference frames.

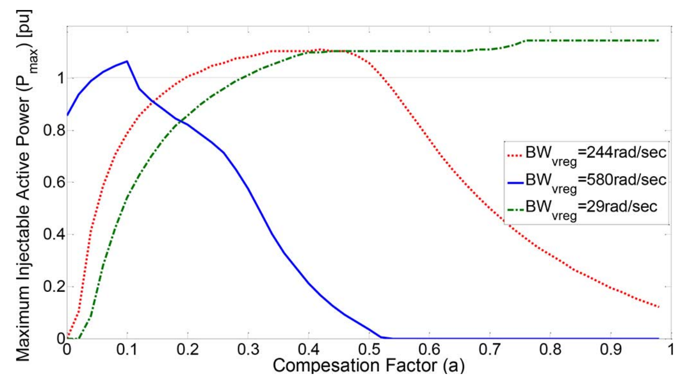

Fig. 14. Impact of applying the artificial bus method on the maximum power injection of the converter. Bandwidth of PLL is set to at 150 rad/s.

the reference bus of the PLL and the grid voltage. As depicted in Fig. 13(a), if the reference bus can be moved to some artificial point between the PCC and the grid, a VSC with high filter impedance but lower grid impedance will be attained. Consequently, the converter no longer faces a very weak grid, whereas the higher Z_f does not cause any problem owing to the high degree of current control.

The remaining concerns are voltage and power regulation. Choosing the hypothetical impedance Z_{g1} between the PCC and artificial bus to be purely inductive solves the problem of power regulation. This solution means that the active power injections (absorptions) at the PCC and the new artificial bus are identical.

Because the voltage of this new bus has no significant meaning for grid operators, the controller can still be set to control the PCC voltage. Conventional synchronous generators inspired this idea. Sometimes, in conventional generators, instead of the voltage magnitude of the real generator bus, the voltage of some artificial bus inside the generator is fed into the exciter of the generator [29]. This method is known as "*reactive-current compensator*."

Whereas the same voltage and power can be controlled by the HVDC, nothing has changed but the reference frame used for the controller, shown in Fig. 13(b). Thus, the only needed modification is the input voltage of the PLL, distinguished in Fig. 2 by the block named "*Bus Calculation.*"

Equation (5) formulates the artificial bus voltage, v_b. The parameters here are in vector space representing all three phases. Because the implementation of a pure derivate is not possible, a high-pass filter with a relatively small time constant τ_c is utilized. Further, Z_{g1} is chosen to have no active power consumption, so it is represented by an inductance equal to aL', where L' is equal to the inductance L between the grid and the PCC at SCR $= 1$, and a is the compensation factor restricted between 0 and 1. v_b is then fed into the PLL to track its phase.

$$\vec{v}_b = \vec{v}_s - aL' \frac{s}{\tau_c s + 1} \vec{i}_s. \tag{5}$$

The only modified part of the controller is the current controller, which is changed to consider the new filter impedance. This procedure can be accomplished simply by changing its proportional gain as formulated in (6) and (7). K_{pc}, K_{ic}, and τ_i are the proportional and integral gains and time constant of the current controller, respectively. L_f and R_f are the inductance and resistance of the AC filter Z_f, respectively. By assigning zero to a, the controller will be simply restored to the conventional VSC controller.

$$K_{pc} = \frac{L_f + aL'}{\tau_i}. \tag{6}$$

$$K_{ic} = \frac{R_f}{\tau_i}. \tag{7}$$

Obviously, the implementation of the method is easy and straightforward; the rest of this section is devoted to analyzing its performance. Fig. 14 shows the impact of the proposed solution on the maximum injectable active power. Obviously, not only is the converter capable of injecting the maximum static active power, calculated in (4), but the high-speed voltage regulator is not needed; this advantage prevents problems for the proposed method at higher SCRs. The interesting point about this figure is that the bandwidth of the PLL is set to be as high as 150 rad/s, which is much higher than the bandwidths used in the retuned method. In other words, by the proper selection of the compensation factor, which Fig. 14 reveals to be a relatively large range, the rest of control parameters can be designed as if the converter is connected to a strong grid. Similar to strong grids, very fast voltage regulators can degrade the overall converter performance as shown by the solid blue curves in Fig. 14.

Fig. 15 measures the abilities of the artificial method, which eliminates the previous method's serious weaknesses. Here, all controller parameters, including a and L', are kept constant, whereas the SCR of Z_g and, consequently, L and R are changing. Obviously, the system remains stable. Thus, a sudden change in the line SCR, caused by switching, does not impact the stability of the converter. In addition, the controllers that can maximize the injection of the VSC are capable of maximizing the power absorption, leading to a simpler design. The results for the dc-regulating VSC are shown in order to verify their resemblance to those for the active power regulating case.

Figs. 14 and 15 address another concern about the controller, which is the inaccurate measurement of L'. The high ranges of the compensation factor and SCRs, which allow the maximum injection and absorption of active power, imply that by proper selection of a, the practical inaccuracies in L' do not cause a serious problem for the converter.

The interference of the regulators was discussed as a characteristic of the performance of a VSC connected to a very weak grid. The impact of adopting the artificial bus for this feature is presented in Fig. 16. This impact is especially important because it is claimed that this method is similar to reducing the weakness of the grid. As was expected, by increasing a equivalent to the

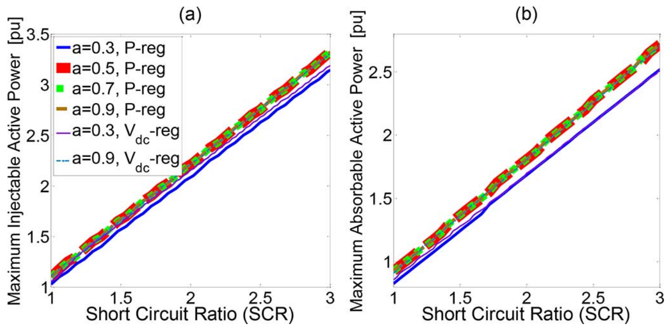

Fig. 15. Impact of the grid strength on the performance of VSC. (a) Injecting, (b) Absorbing active power. PLL and voltage regulator bandwidths are 150 rad/s and 29 rad/s, respectively.

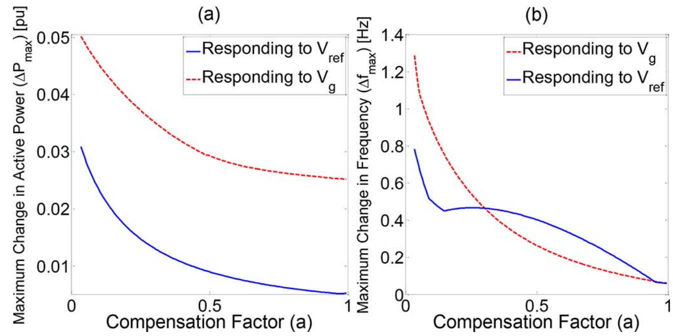

Fig. 16. Impact of the compensation factor on interference of voltage regulator with the (a) power regulator and (b) PLL.

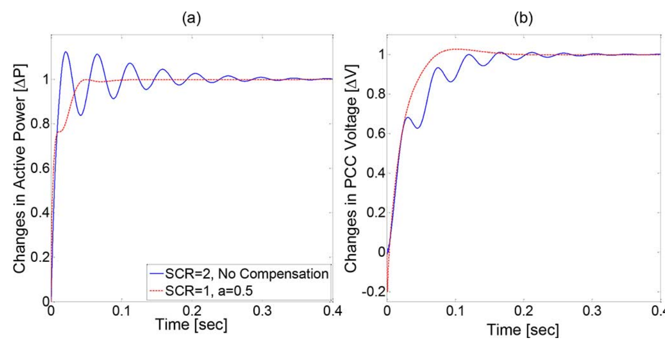

Fig. 17. Comparing the response of conventional converter at SCR $= 2$ with a VSC with artificial bus working at SCR $= 1$ with a compensation factor $= 0.5$.

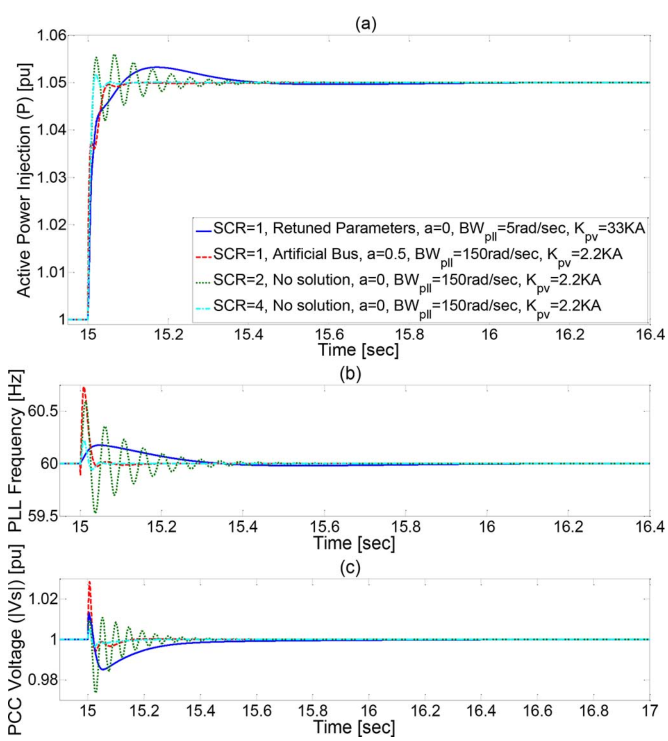

Fig. 18. VSC performance when the reference injected power is changed from 1.0 pu to 1.05 pu by a step.

increase in the strength of the system, the interferences decrease so that the regulators take back their independence.

These interferences are also functions of the operating point of the converter; however, in a constant operating point, increasing the compensation factor will lead to greater independence of the regulators, but in comparison to the differences in Fig. 5, a considerable difference can be observed. An increase of the compensation factor decreases the impact of the grid voltage, whereas in a stronger system, a higher influence of the grid voltage is expected.

In fact, the artificial bus method should not be considered as the exact equivalent of decreasing the SCR. Fig. 17 is used here to discuss this point in more detail. The blue solid curves show the performance of the VSC responding to changes in the reference active power and voltage when SCR $= 2$, and the red dashed curves represent the same when SCR $= 1$ and $a = 0.5$. Hypothetically, similar responses are expected, but obviously they do not greatly resemble each other. Much more important than their different AC filter impedance, one of these converters directly controls the input voltage of its PLL whereas the artificial bus method does not. Therefore, although the artificial bus method can be conceptualized as a decrease of the grid weakness, the use of this method does not necessarily decrease the impedance.

IV. Time-Domain Simulation Results

Whereas small-signal analysis allowed detailed evaluation, time-domain simulation is used in this paper to verify the discussions. The system shown in Fig. 1(a) is modeled here, and the parameters used are listed in the Appendix. The Matlab/Simulink® package is utilized for the simulation studies.

A. Injection and Absorption of Active Power

Fig. 18 shows the situation when the reference active power changes from 1.0 pu to 1.05 pu by a step. This figure reveals that the active power tracking of the system with the proposed solutions in the very weak grid is even better than the system with SCR $= 2$. Even the performance of the artificial bus method is comparable to that of a relatively strong grid. However, the voltage and PLL output frequency do not act similarly. The retuned method shows less deviation in these variables; however, it takes much longer to settle. The artificial bus has almost the same deviations as the system with SCR $= 2$, but much faster settling can be observed. The PLL frequency returns to 0.05% vicinity of the nominal frequency in less than 3 cycles.

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

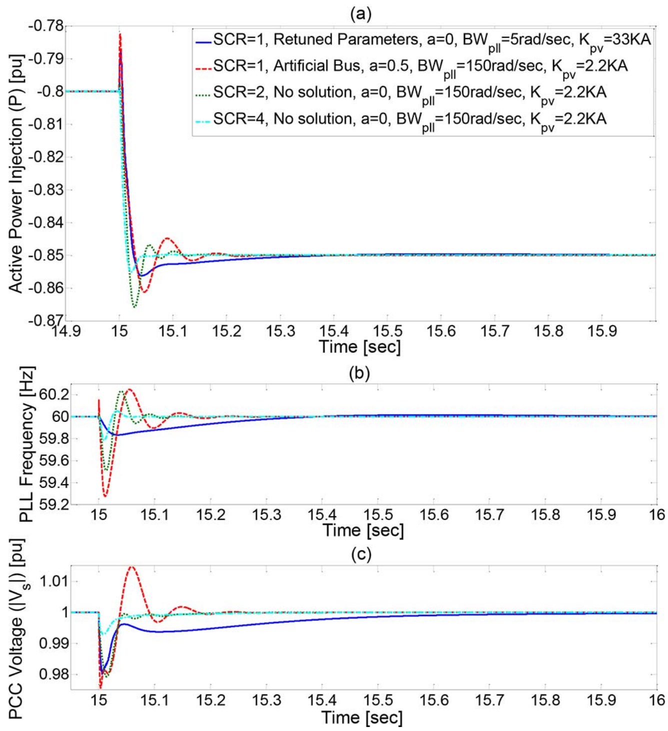

Fig. 19. VSC performance when the reference absorbed power is changed from 0.8 pu to 0.85 pu by a step.

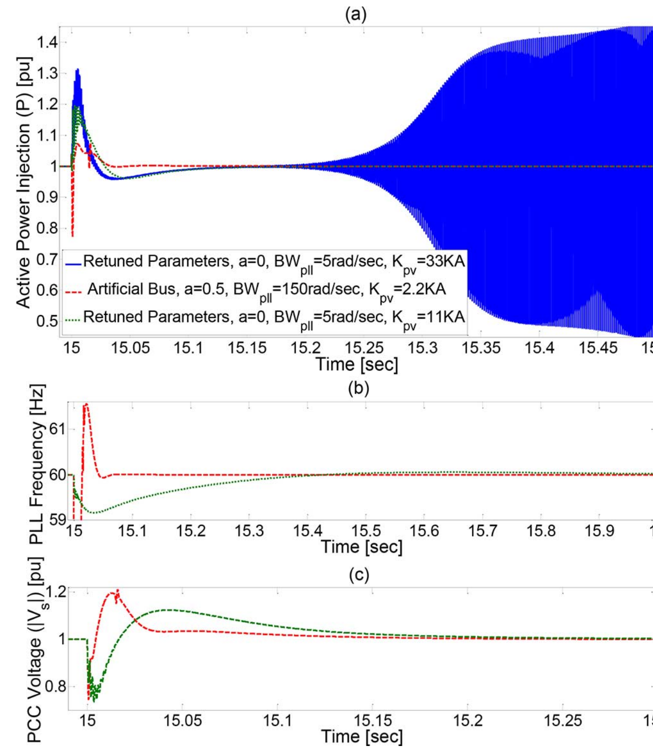

Fig. 20. VSC performance responding to the change of SCR $=1$ to SCR $=2$.

Fig. 19 explores the absorption case where the converter is pushed to increase the sinking power from 0.8 pu to 0.85 pu by a step again. The maximum theoretical power absorption is restricted to 0.9 pu. Obviously, near the boundaries of system stability, both proposed methods still perform reliably. Moreover, in this case, the performance of the conventional controller at SCR $=2$ is comparable to the performances of the proposed methods at SCR $=1$. The conventional controller has a faster settling time, and its peak deviation is less than or at least comparable to that of the proposed controller. The comparison between Figs. 18 and 19 shows how the proposed solutions act asymmetrically in injection and absorption. In other words, the performance of the VSC is dependent on its initial operating point in very weak grids even with the proposed solutions.

B. SCR Changing

In this case, a line in parallel with Z_g is considered with exactly the same impedance connected through a normally open breaker between the PCC and the grid. At $t = 15$ s, the breaker closes; consequently, the grid short-circuit ratio changes from 1 to 2.

As predicted by the analysis, the retuned method with a very high-speed ac-voltage regulator cannot bear the new strength of the system and becomes unstable (see the blue solid curve in Fig. 20(a)). For the sake of clarity, the changes of the voltage magnitude and the PLL frequency of the unstable case are omitted in parts (b) and (c).

The artificial bus method demonstrates its superiority in active power regulation in terms of both maximum deviation and settling time indices, even when the retuned method is stable. In the case of PLL frequency, the situation is trickier where the fast PLL of the artificial bus shows a much higher deviation. However, it returns to ± 0.03 Hz of the nominal frequency in just 50 ms. The slow PLL of the retuned method takes much longer to settle in a similar vicinity to the final frequency.

The most interesting observation, however, is the PCC voltage. The much faster voltage regulator of the retuned method takes much longer to restore the voltage. Here, the impact of the slow PLL in the voltage regulator can be observed. As mentioned in the last section, in the retuned method, the PLL and ac-voltage regulator impact each other, but their response times are very different in order to minimize undesirable interactions.

C. Grid Voltage Disturbance

The last case examined here is a step change of the grid voltage magnitude from 1.0 pu to 0.9 pu. Based on the standards [30], the VSC should continue to work uninterrupted, although the grid voltage remains at this level. Fig. 21 represents the results. The operating point is selected to be 0.9 pu instead of 1.0 pu because, based on (4), the maximum injectable active power decreases with a decrease in the grid voltage.

Both methods show a relatively robust performance against the grid voltage. However, their performances are not similar. In active power regulation, the artificial bus experiences less deviation and settles faster, but in the cases of frequency and voltage tracking, the situation is different. Whereas the PLL of the artificial bus method deviates much more from the nominal frequency, it returns to 0.095% vicinity in less than 3.5 cycles. The same damping takes more than 39 cycles in the retuned method with its ultraslow PLL. A very similar situation can be observed in the voltage regulation, even though the ac-voltage

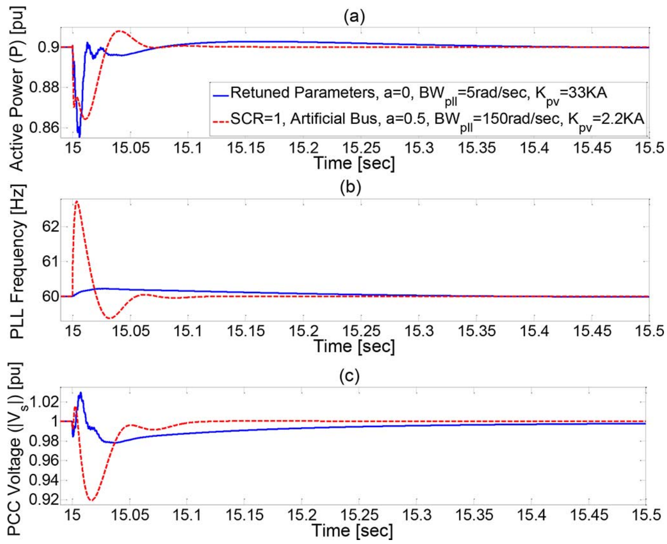

Fig. 21. VSC responds to the sudden changes of grid voltage magnitude from 1.0 pu to 0.9 pu when SCR = 1.

controller of the retuned method is set to be much faster than that of the other solution.

V. Conclusion

By employing detailed small-signal analysis, the concerns about connecting a VSC to a very weak grid were described, and straightforward solutions were proposed and compared.

This study showed the following. (1) In a very weak grid, the active power, voltage regulators, and PLL interfere with one another's functions much more than they do in the strong grid cases, so that their independent tuning does not lead to the desired results. (2) By retuning the VSC controllers, parameters reaching the maximum theoretical active power injection/absorption are possible, as opposed to claims in the present literature. (3) The retuned method uses very fast voltage regulation and a very slow PLL, which can make it sensitive, or even unstable, to a change of SCR in the system. In addition, this method's utilization necessitates the complete modeling of the VSC. (4) By selecting an artificial bus between the real PCC and the grid as a reference point of the PLL, the VSC controller can operate as if it is facing a strong enough system. (5) The proposed method achieves the goal of maximum active power injection and absorption and is robust against changes of the system SCR. This advantage allows the regulators of the VSC to be designed independently. Detailed nonlinear time-domain simulations verified the analytical results and the effectiveness of the proposed solutions.

Appendix

$P_{nominal} = 350$ MVA, $V_{nominal} = 195$ kV, $f_{\text{nominal}} = 60$ Hz, X/R ratio $= 10$, $K_{pv} = 2.2$ kA, $K_{iv} = 98.92$ kA/s, $K_{pp} = 2.09 \times 10^{-3}$/MV, $K_{ip} = 789.3$/(MV.s), $K_{pq} = 0.419$/MV, $K_{iq} = 209.4$/(MV.s), $\tau_i = 0.796$ ms, $K_{ppll} = 0.0013$/(V.s), $K_{ipll} = 0.1413$/(V.s^2), $L' = 0.2868$ H, $\tau_c = 0.01$ ms, $R_f = 1.089\ \Omega$, $L_f = 0.0575$ H, $C_f = 1.22\ \mu$F, $C_{dc} = 166.7\ \mu$F, $V_{dc} = 350$ kV.

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