On Control Schemes of Voltage Source Converters

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Abstract—This paper discusses some aspects of control schemes for voltage source converters under abnormal conditions. The control schemes are developed specifically for the situations when one or more system parameters vary significantly to the extent that the system becomes unstable with a conventional controller. The paper will present some recent works on control of grid-interactive converters for parameter variations in weak grid. The paper will also discuss some methods under abnormal dc-bus variation. Finally, the paper focuses on the control schemes suitable for ac-dc converters that addresses input frequency, voltage and load variation. All the discussed control schemes have shown robust performance under abnormal conditions.

Index Terms—voltage source converters, abnormal conditions, dc-bus voltage variation, weak-grid, unbalanced grid, frequency variation, robust controller.

I. INTRODUCTION

Voltage source converters are gradually becoming integrated parts of our life. Application of the voltage source converters can span from grid-interactive inverters, to household appliances, to versatile forms of electric vehicles [1]-[4]. The grid-interactive inverters enable high integration of renewable energy sources while also allowing for remote and dynamic control [5]-[10]. Many states in North America have integrated renewable energy resources in their power system planning for the future. Los Angeles, California aims to achieve 100% of renewable electricity by 2045 along with aggressive electrification targets for buildings and vehicles [11]. Furthermore, California’s total solar power generation is nearly 13%, with certain places generating as much as 25% [12]. In [13], it is reported that California has set a goal of generating 50% of its energy from renewable sources by 2030. This increasing penetration of DGs allows for greater flexibility in power networks, where grid-interactive voltage source converters are the most important part of the modern power grid [14]-[17]. Likewise, the transportation system has already started moving toward electrification of technologies, i.e., more electrification instead of mechanical controls, replacement/modification of power-trains, replacement of combustion engines [18]-[19], etc. With modern power-electronic technologies, the ultimate goal is to obtain high fuel efficiency, low emission, and low maintenance costs. Therefore, this technological transformation can be achieved through the voltage source converters. Notice, this massive integration of voltage source converters in different aspects has brought up many challenges, which have been and are being solved through many different types of control scheme. This paper specifically focuses on the recent trend in research in the control scheme of voltage source converters under abnormal conditions, i.e., parameter variation in internal and external abnormalities, dc-bus voltage variation, weak and unbalanced grid, rapid frequency, voltage, and load variation, etc. The following paragraphs will focus on the abnormal conditions in different categories of application of voltage source converters.

The widespread use of DGs has many advantages, but it also poses new issues in terms of power system stability and reliability [20]-[23]. An inertia-less inverter-based DG results in low-inertia microgrids. Specifically, in a weak grid, an inverter could become unstable and, therefore, would have to be disconnected from the system [24]. Weak grid results from large grid impedance seen at the point of common coupling (PCC). When the PCC voltage contains harmonic components at the filter’s natural frequency, instability may occurs [25]. The variation of weak-grid’s grid-impedance can cause instability from unwanted resonances [26]. Even more, the voltage feedforward path used in conventional voltage source controller for smaller response time can also cause instability under grid-impedance variation. Furthermore, the grid-distortion can affect with controller in weak grid [27]. Moreover, the phase-angle estimation capability of the phase-locked loop also deteriorates under unbalanced and distorted grid conditions [28].

Inverters should have the ability to identify the internal and the external abnormal conditions and must have the control techniques to operate effectively [29]-[30]. The conventional two-level three-phase dc/ac voltage source converter offers less opportunities for fault tolerant control in comparison to the multi-level three-phase inverters. Specifically, the cascaded H-bridge (CHB) multi-level inverter is mostly preferred for high-power, medium voltage operations because of its inherent fault tolerant capability. On the other hand, the performance of the CHB can be negatively impacted by the variation of dc-bus voltage and hence impacting the conventional PWM methods [31]. In addition, while injecting active and reactive power to the grid, the voltage converters may incur dc bus variation. This may result fluctuation in power injection with conventional PWM reference. Under this condition, the PWM reference should be adjusted so that, the available DC bus utilization is maximized [32]-[35].

The voltage source converters in electric vehicles presents new challenges to the researchers. One of the major challenges is to obtain the capability to adapt for rapid input-frequency/voltage variations, load fluctuations, and extreme ambient conditions changes while regulating the desired parameters with seamless dynamics and satisfactory power quality by the voltage source converters. In literature, different power converter control schemes have been developed for more electric power-trains. The controller needs to be fast and accurate irrespective of the system parameter. Hence, the controller needs to be adaptive also [36], [37].

It is evident from the discussion of the previous paragraphs, that the capability of the recent controllers for the voltage source converters should not be limited to the conventional output signal generation. Rather, the controllers should be adaptive, fast, and accurate to overcome different adverse scenarios. In this respect, this paper focuses on some state-of-
the-art control for voltage source converters that addresses the aforementioned challenges. Apart from the introduction, the rest of the paper is organized as follows. Section II discusses on some advanced control strategies under weak-grid conditions. Section III discusses on the corrective schemes of multi-level inverters and control strategies under dc-bus variation. Section IV focuses on voltage source controller under rapid frequency and load variation. Finally, section V concludes the paper with a discussion of future research scopes.

II. VOLTAGE SOURCE CONTROLLER FOR WEAK GRID PARAMETER VARIATION

This section discusses on some advanced control methods for voltage source converters under weak grid scenarios. Several advanced techniques are available to ensure the stable operation in weak grid. The most common approach includes modified feedforward paths in the controller [18], [38]-[40]. The authors in [39] introduced a capacitor voltage feedforward method for improving the adaptability of the voltage converter. There, a delay compensation link has been added to the voltage feedforward path that reduces the interaction between the grid-distortion and the control scheme. An impedance-phase compensation strategy is proposed in [40]. In [41], PCC voltage feedforward is employed through a filter and a gain block. It is shown that for the modified voltage feedforward, with a suitable value of the gain block, the converter exhibits improved performance in weak grid. It is mention worthy that, all these methods have a tradeoff between the steady-state performance of the closed-loop grid-tied system.

In [42], a virtual inductance feedforward control scheme is developed to enhance the stability of grid-tied VSIs in weak grids. A virtual inductance term is derived emulating the impact of the additional grid-side filter without adding large filter inductors. In this method, the measured current is fed to the inner current control loops through a gain block, known as the virtual inductance. Fig. 1 shows a controller equipped with virtual inductance for stability enhancement of a grid-interactive inverter under weak grid. Notice, the controller does not require any additional measurements/sensors. Notice, despite the feedforward technique in [42] demonstrates improved performance in weak grids, it requires manual adjustment of the feedforward term. Implementation of the techniques may become difficult if the grid-impedance of the system is unknown. Hence, in [43] and [44], two methods have been introduced where the gain parameters. The adaptive techniques use the same principles as the previously described. In addition, the gain parameters of the feedforward paths are updated adaptively. In [45] a direct model reference adaptive method (MRAC) is integrated to the virtual inductance feedforward scheme to adaptively vary the virtual inductance for changes in grid impedance in weak grids. The direct MRAC method is integrated to the PQ controller to develop a modified PQ controller with adaptive virtual inductance feedforward. In [45], an adaptive control scheme to enhance the stability of inverters is presented based on the online estimation of grid impedance. For larger values of grid impedance, the PLL bandwidth was lowered to keep the inverter in the stable region. However, the PLL bandwidth had to be lowered considerably to ensure stability, thus introducing a tradeoff between stability and dynamic performance. In [45], an active damper is added to the system, which essentially introduces an additional resistive term in the inverter circuit that can be varied adaptively to make the inverter more robust against changes in grid impedance. Among the control methods discussed above, the methods derived in [43] is the only method that does not require a parameter estimation stage and can adapt the virtual inductance value according to a stable reference model and hence, is more robust. A detailed derivation and analysis of the method in [43] is also available in [46]-[48].

III. VOLTAGE SOURCE CONTROLLER FOR TIME-VARIANT DC SOURCES

In this section, some corrective scheme-based control for voltage source converters are presented. Specifically, this paper section is focused on the CHB controller capable to operate under dc-bus variation under abnormal conditions. As the conventional multi-level PWM techniques are unable to effectively utilize the time-variant DC sources with unequal voltage magnitudes in CHB, many applications ensure the equal magnitudes of the sources. In [49] a double star connected converter, and in [50], a boost inverter (see [51], [52] for details) topology has been presented. These methods do not directly address the time-variant source problems and hence, can make the topology more complex. The time variant nature of the dc sources can be resolved through dc-dc converter topologies to regulate the input dc voltage [49]-[50], [53]. Although this provides a solution to the problem, the additional circuitry introduces extra weight, cost, size and loss to the whole system. Another solution is to implement the active balancing techniques [54], [55], which either requires
additional components and control structure, or connection between multiple dc sources, eliminating the isolation between sources required for CHB converters. To compensate for the dc-bus oscillation, an approach is to add common-mode component to the line-to-neutral output voltages of three-phase three-wire voltage source converters without affecting the converters’ current [56], [57]. A number of techniques for creating appropriate common-mode components have been developed and are suitable for implementation in a wide range of converter topologies [58], [59]. A well-known method is to inject the third-harmonic components. In [60], the common-mode components to ensure linear-modulation is determined as the mean value of a set of common mode elements. However, this method only considers implementation in balanced system.

In [32] and [33] an atypical PWM technique has been presented to compensate for the dc-bus voltage variation for CHB converters. The common-mode component injected into PWM references is based on the available dc bus voltages and enables references to be adjusted in real-time, without requiring lookup tables. In [2] a similar atypical PWM technique has been presented to voltage source converter that can provide symmetrical and asymmetrical ancillary services during dc-bus oscillation. The technique provides harmonic compensation as symmetrical ancillary services, and negative sequence compensation while providing asymmetrical ancillary services. Notice, for both techniques, the PWM signals are modulated as per the dc-bus fluctuation, so that the fluctuation is compensated. Fig. 2 shows the block diagram utilizing the negative sequence controller for grid-following inverters.

IV. VOLTAGE SOURCE CONTROLLER FOR RAPID INPUT FREQUENCY VARIATION

The voltage source converter may undergo rapid input frequency variation. Specifically, the ac/dc converters used in the electric vehicles, i.e., more electric aircrafts, where the mechanical energy conversion system has been partially, or completely replaced by the voltage source converters. One of the major requirements of these voltage source converters is to be applied for variable-speed operations. This variable-speed operation needs to generate a wide-range variable-frequency/constant-amplitude or a variable-frequency/amplitude set of voltages, which constitutes an entirely novel operation scenario for power converters that are typically implemented at constant industrial frequency levels in grid-tied [38], [61]-[63], stand-alone applications [30] or narrower variable frequency ranges in motor drives or renewable energy interfacing [64]. In following paragraph, the recent voltage source control schemes for variable input frequency variation has been highlighted.

The voltage source converters for electric vehicles can be of different types based on their tasks, i.e., DC/AC, AC/DC, DC/DC, and AC/DC power converters [19], [36]-[37]. The voltage converter used for motor drive control the propulsion motor and hence, need to operate bi-directionally to utilize the advantage of regenerative braking [65]. Some fault-tolerant motor drives have been extensively discussed in [66]-[68]. These methods are robust under symmetric conditions. However, with any variation in input frequency these controllers will not be helpful. Some direct and indirect matrix converters can be used as ac/ac converters to be utilized in-between for frequency variation [69], [70]. Nevertheless, this add extra circuitry, weight, and size in the system, which is not expected for electric vehicles.

In [29], a step-ahead model predictive controller for has been proposed to perform under input frequency variation. This controller can exhibit ultrafast dynamics in dc-bus and power factor regulation when the converter is operated for variable-frequency/constant-amplitude input voltage. Its fast dynamics has been achieved from the combination of the model predictive control and instantaneous phase-angle detection technique. However, the model predictive control schemes may suffer from performance degradation under model parameter mismatch and parameter variation [75-76]. The control method in [36] may become erroneous as it requires accurate parameter values to correctly switching the duty ratios. Hence, in [37], an adaptive filter parameter estimation technique is adopted in addition to the contribution of [36]. Herein, the dynamic performance can be improved by adopting Lyapunov-based adaptive parameter estimation algorithm, which can provide accurate-fast tracking of the parameters of the system and then fed to the step-ahead controller. The only drawback of these types of estimations is, it introduces steady-state tracking error in input reactive power. The drawbacks have been resolved in [71] and [72], where a direct model reference adaptive controller (MRAC) is presented. This new controller is capable

![Fig. 2. Utilization of negative-sequence controller for grid-following inverter.](image)

![Fig. 3. Block diagram of a direct model reference adaptive controller.](image)
of seamlessly regulate the output dc-bus voltage and input reactive power during ultrafast frequency/voltage variations. In this technique, the controller's gains are automatically adjusted to the external perturbations regardless of parameter values of the system. Fig. 3 depicts a block diagram of the controller presented in [72].

V. CONCLUSION

In this article some recent control schemes for different types of voltage source converters performing under variable input/output parameters have been discussed. Specifically, the paper highlighted the contributions on robustness of the controller under system parameter variation in weak grid, input dc-bus voltage variation in unbalanced grid, and input frequency variation in the voltage source converters in the more electric vehicles. A direct model reference adaptive method (MRAC) has been found effective under grid-parameter variation during weak grid condition. The controller can adaptively estimate the virtual inductance based on the change in the grid impedance in a weak grid and add the estimation to the feedforward path to eventually ensure a stable control. Then, an atypical PWM technique has been highlighted, that effectively compensate for the dc-bus voltage variation for CHB converters. The technique can provide harmonic compensation as symmetrical ancillary services, and negative sequence compensation while providing asymmetrical ancillary services. Finally, a direct model reference adaptive controller (MRAC) under wild frequency variation has been discussed. The controller can automatically adjust the gains to the external perturbations regardless of parameter values of the system. All the aforementioned voltage source controllers have shown impressive robust performance under one or more parameter fluctuation scenarios and have potential to be extended to any applications in power grid, motor drive, and electric vehicle technologies.

VI. REFERENCES

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