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Technical Analysis of Current Controllers in Grid Tied Multi-level Converters

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Abstract

Current controller in grid connected multilevel converters, plays one of the most vital role in overall performance of the power system. Quality current controllers are the pioneers that enhances the working performance of the power system, by ensuring that they provide low harmonically distorted output current, regulating the dc-link capacitor voltages to an acceptable value, dynamic response improvement and in some special cases by providing bidirectional flow of power. Current controllers differs with each other on the bases of complexity of implementation, harmonic distortion content and dynamic response. This paper provide a thorough study of the current controllers that could be applied on the grid connected multilevel converters. For simulation purposes Simulink/MATLAB have been used.

Keywords: Current-Controller(CC); Multi-level Converter (MLC); Dynamic Response(DR); Harmonic Distortion (HD).

1. INTRODUCTION

Many of the high power and high voltage application prefer multi-level converters instead of traditional converters. This preference is given due to advantages such as high quality output waveforms, small switches losses, small electro-magnetic compatibility(EMC) and high-voltage capability concerns [1].

Multi-level inverter synthesizes near pure sinusoidal voltage waveform from numerous voltage levels, normally obtained from dc-link capacitor voltage-sources. By increasing number of voltage levels additional steps are added in to the output, producing a staircase waveform approaching the sinusoidal waveform with minimum addition of harmonic content [2], [3].

The first multi-level inverter was presented by Nabae et al. [4] in 1980 by developing Neutral point Clamped (NPC) inverter. It provides voltage transversely nonconducting switches, clamped by series capacitors string and diodes. It prevailed due to its ability to effectively double the voltage of device without requiring exact voltage matching. While increasing the voltage level it also provided better quality output voltages thus increasing the efficiency. Despite the mentioned advantages, NPC inverter is limited due to reverse blocking ability of each of the connected diode being proportional to level for which they are used for clamping purpose. Thus, requiring additional serially connected diodes increasing the cost and complexity of design.

Alternate topology by the name of Flying-Capacitor (FC) inverter was developed by Foch and Meynard in 1992 [5]. This design includes flying capacitors instead of clamping diodes, in doing so it provides redundant states that could be used to produce same voltage levels by using different switching states. This design also require additional capacitor to equally divide the stress across apiece capacitor increasing the cost and complexity.

In order to remove the extra elements (capacitors and diodes) anew topology has been proposed by the name of Cascaded H-bridge multilevel inverter (CHB-MI). CHB-MI utilizes serially connected modular inverters having isolated DC-sources corresponding to the number of level required to be produced at the output. Modular approach utilized in CHB-MI has seen increased usage in the fields of drive and reactive-power compensation [6] [7].

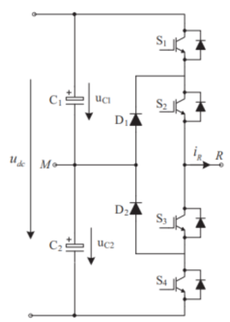

Fig.1(a).

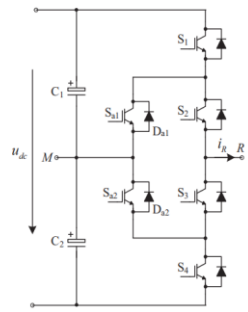

Fig.1(b).

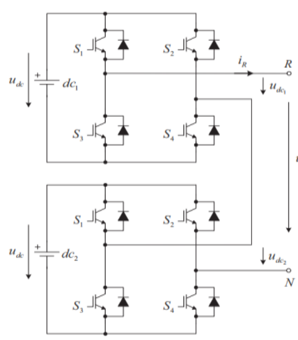

Fig.1(c).

Fig.1 (a) Diode Clamped Multilevel Inverter, (b) Capacitor Clamped Multilevel inverter, (c) Cascaded H-Bridge Multilevel inverter.

2. Current Controller Strategies

The voltage output by the current controller is often achieved by the comparison of the current inputs. One of them is measured current $i_{g,i}$ and other being the set reference current $i_{g,I,reference}$. The resulting error signal is $\Delta i_{g,i}$, used for the purpose of either directly generating the switching states for switch or controlling the modulator. The schematic diagram of the current controller is given in Fig.2.

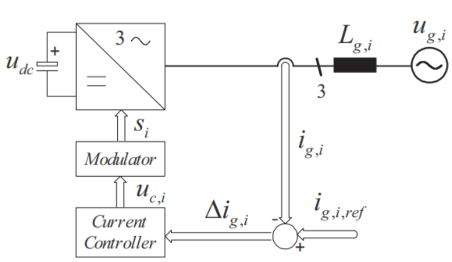

Fig.2. Current Controller

Existing techniques regarding the current controller has unique set of their own strengths and characters, making them suitable for particular application. Additionally, properties regarding the switching patterns, utility current distortion and the dynamic behavior sometime contradict one another. Therefore, choosing the best controller is dependent open the comparison between the pros and cons regarding certain properties and the type of application it is going to be used for.

2.1 Ramp Comparison Control The Ramp Comparison current controller strategy utilizes Potential Integrator (PI) compensator and fix-frequency carrier of triangular waveform for generating the switching signals for power switches of the converter [8][9]. Based on generated current error ($\Delta i_{g,i}$), PI controller stems modulating signal ($u_{c,i}$) that is compared with the carrier triangular signal. This process is represented in fig 3.

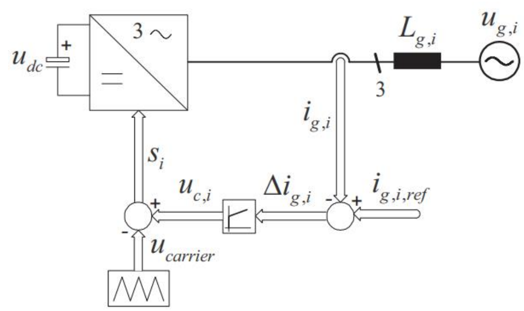

Fig.3. Ramp Comparison current controller

Constrains have to be imposed on the designed controller for guarantying the proper functioning. Even though, gain of the current controller should be kept high for allowing the reduction in tracking error, and in some cases should be as minimum as possible to avoid the amplitude of control signal exceeding the carrier signal.

Fig. 4 illustrates the output generated from the ramp comparison current controller. The output voltage of the controller is u_{dc} whenever the control signal $u_{c,i}$ is greater than the carrier signal $u_{carrier}$. Similarly, output voltage of the controller is $-u_{dc}$ whenever the control signal $u_{c,i}$ is lesser than the carrier signal $u_{carrier}$.

The intersecting points define switching patterns for the power switches. This maintains constant switching frequency since the triangular carrier wave has constant frequency. Despite the simple nature and the obvious advantages the controller has the inherent problems of phase and amplitude tracking error.

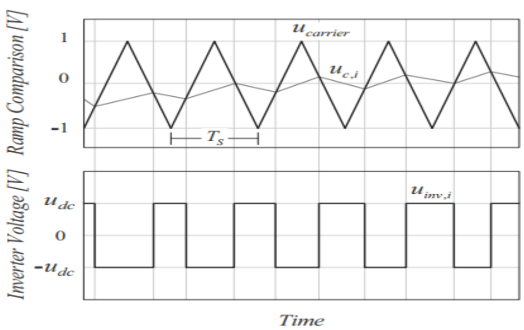

Fig.4. Output of Ramp Comparison Current Controller

2.2 Hysteresis Current Controller Hysteresis controller current controller works on the principle that whenever control signal rises above a certain value or falls below a particular value, controller switches the output voltage to be at u_{dc} or $-u_{dc}$ respectively [10] [11]. Current error signal ($\Delta i_{g,i}$) generated as the result of comparison between the measured control current and the set reference current. $\Delta i_{g,i}$`s are independently controlled using three hysteresis comparators are independent from each other. This is shown in the Fig.5,

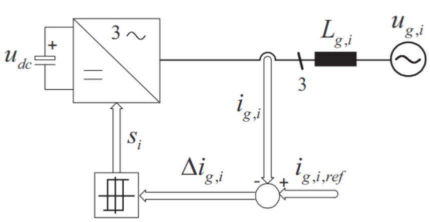

Fig.5. Hysteresis Current Controller

Hysteresis current controller strategy is directly produces switching patterns by using hysteresis comparators, this ensures the quickest dynamic response of the system, only limited by the time response of the switches themselves. Furthermore load independence, simple design and robustness makes this controller to be most used controller in wide range of applications.

Despite of the beforementioned advantages, hysteresis controller has the disadvantage that frequency of the modulation varies over the fundamental inverter period. The main cause of the issue is the switching frequency is highly dependent upon the parameters that are fix like dc link voltages, inductance of output filter, current ripple desired and also ac grid variation also plays its own part shown by the equation 1.

$$f_{\mathrm{sw,i}} = \frac{u_{\mathrm{inv,i}} - u_{\mathrm{g,i}}}{L \,.\, \Delta \mathrm{i}_{\mathrm{g,i}}} \quad (1)$$

These fluctuations in the switching frequency causes spreading of un-desirable harmonics in ripple current, complicating the output filter design. Thus, generating resonance in the grid that is unwanted [12].

Another factor that influences the frequency of the switches is the interaction of commutation in-between the three phases, inherent to the without neutral connection three phase system.

Interacting phases also lead to instantaneous currents exceeding the limits of tolerance, in certain cases it may reach to be double of original value. This situation can be avoided if we can reverse the voltage of one of the phases but this is also limited because other two phases doesn`t allow for this to occur. Owing to this the error keeps on accumulating unless it reaches double bandwidth.

2.3 Voltage Oriented Current Controller(VOCC) VOCC uses the concept of dq-reference frame with the purpose of ensuring zero steady state (SS) current error. Transformation of AC phase quantities into dq-reference frame (DC quantities) allows the PI-Controller to lead them to desired value without the introduction of any static error [13][14].

In the scheme of VOCC, orientation of synchronous transformation is such that d-axis is aligned to the vector of grid voltage shown in Fig.6. Load current $i_{g,}$ is dissolved into rectangular components $i_{g,d}$ regulating the active power and $i_{g,q}$ regulating the reactive power.

Fig. 7 shows the principle working of the VOCC. Measured current outputs taken from the three phases, using synchronous ref. frame transformation are converted to dq-components (DC quantities). Further they are compared with the set reference values of their respective phase currents.

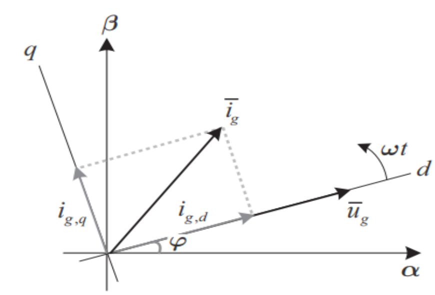

Fig.6. Dq reference frame aligned to gird voltage.

Two PI-controllers are used respectively on the d and q quantities with the purpose of error compensation by generating apposite voltage signals u_{dq} used for controlling. This voltage u_{dq} is then converted back to the three phase quantities, used by the modulator for generating the switching scheme for the power switches.

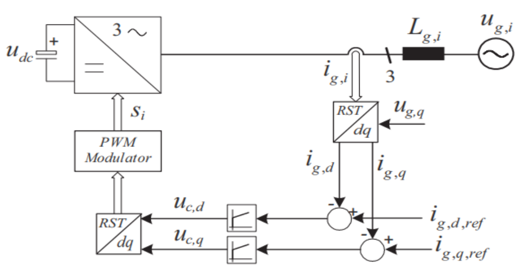

Fig.7. Voltage Oriented Current Controller.

Although, this VOCC scheme allows for competent regulation of reactive as well as active power by using two different distinct loops with their own PI-controllers, but they are not entirely intendent from each other. There exist a cross-coupling terms in both the d and q components that distorts the overall functioning of the controller. Equation 2, shows the three phase grid dq voltages.

For both controller to work independently it is of utmost important that they should be free from the influence of each other. For this purpose de-coupling terms are introduced consisting of ωL information, illustrated in Fig. 8.

$$u_{\mathrm{inv,d}} = R.\,i_{\mathrm{g,d}} + L\,.\frac{di_{\mathrm{g,d}}}{dt} + u_{\mathrm{g,d}} - \omega.\,L.\,i_{\mathrm{g,q}}$$

$$u_{\mathrm{inv,q}} = R.\,i_{\mathrm{g,q}} + L\,.\frac{di_{\mathrm{g,q}}}{dt} + u_{\mathrm{g,q}} - \omega.\,L.\,i_{\mathrm{g,d}} \qquad (2)$$

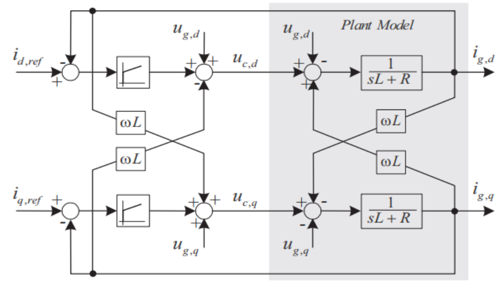

Fig.8. Voltage Oriented Current Controller with Decoupling and feedforward

Feedforward voltages taken from the grid can effectively reduce the amount of harmonic disturbances in the grid. Including the decoupling terms as well as the feedforward terms the transfer function between the input i_g to output voltage u_c comes out to be,

$$\frac{i_{\mathrm{g}}(s)}{u_{\mathrm{c}}(s)} = \frac{1}{L.\,s + R} \qquad (3)$$

Consequently the PI-Controller`s parameters can conveniently calculated by the method of classical design. Zeros and poles should be calculated such that adequate dynamic and static system performance.

Only disadvantage that VOCC has that is sensitive to parameters of load effecting the dynamic but this do offer acceptable steady state accuracy. Charm that the VOCC offers particular advantage of independently controlling the dq current components that ultimately controls the reactive and active power.

Table 1. Comparison of Current Controller Techniques

Technique	Dynamic Response	Stability	Simplicity	Harmonic content
Ramp Comparison CC	Slow	Load Dependent	Relatively Simple	Well defined spectrum
Hysteresis CC	Extremely Fast	Robust	Very Simple	Spread Spectrum
Voltage Oriented CC	Slow	Load Dependent	Relatively Complex	Well Defined Spectrum

3. Simulation

Number of techniques have been developed and used in the industry, but none of the them is considered to be as standard and optimum control scheme. The needed performance considering harmonic content, stability, simplicity along-with ease of implementation and transient behavior are in many cases contradictory in time response.

For Cascaded H-Bridge multilevel inverter, the performance parameters of voltage oriented current controller is most suitable. CHB-MI has been simulated in Simulink/MATLAB. Three phase fault has been introduced in the grid tied CHB-MI to check the response of VOCC.

The scheme of simulated setup has been in the Fig.9-11. The output of the VOCC is used for producing the switching patterns for power electronic switches. For maintaining the stability of the grid tide CHB-MI, the working of VOCC must be lest harmonically effected and fast enough to meet the time constraints for dynamic response.

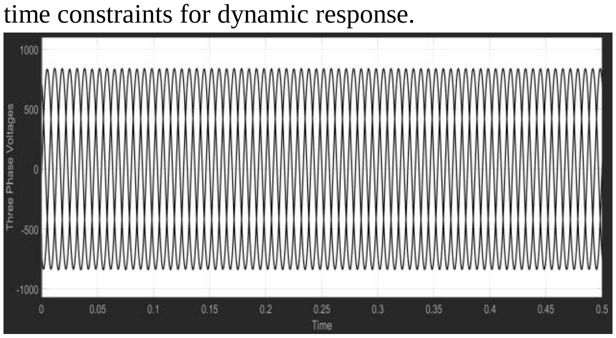

Fig.9. Voltage output of Multilevel Inverter Grid Tied System.

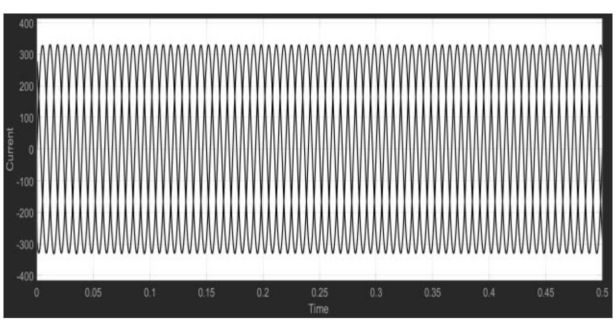

Fig.10.Current output of Multilevel Inverter Grid Tied System.

For checking the dynamic response of the VOCC, two 3-phase faults at different time intervals have been introduced and their dq-currents have been studied. Output voltages and currents are sown in Fig.12-15.

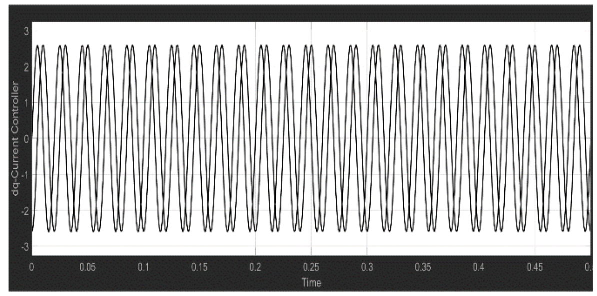

Fig.11. dq-Current Controller outputs of Multilevel Inverter Grid Tied System.

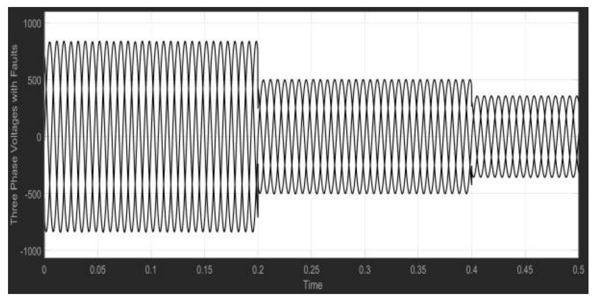

Fig.12. Voltage output of Multilevel Inverter Grid Tied System with 2 Three phase faults.

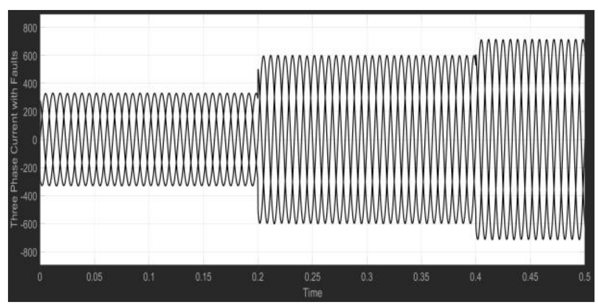

Fig.13. Current outputs of Multilevel Inverter Grid Tied System with 2 Three phase faults.

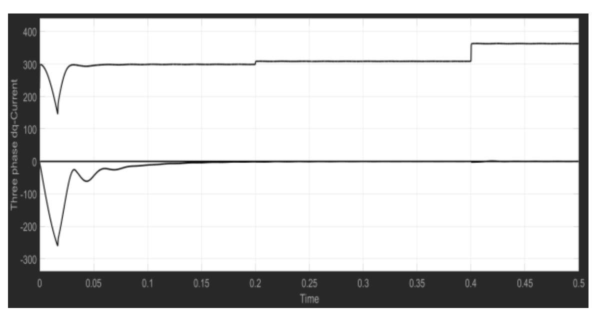

Fig.14. dq-Current outputs of Multilevel Inverter Gird Tied System with 2 Three phase faults.

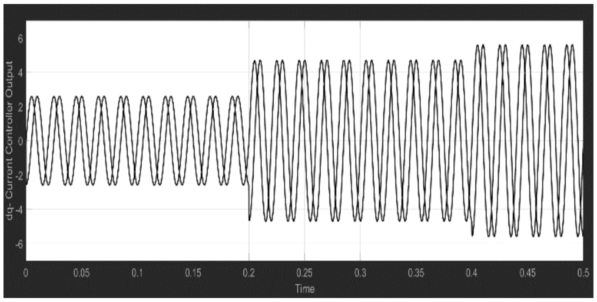

Fig.15. dq-Current Controller outputs of Multilevel Inverter Grid Tied System with 2 three phase faults.

4. Conclusion

Clamping elements(Capacitors and Diodes), are evaded by using serially connected modular design approach of cascaded h-bridge converter. But there also exist a limitation in regards of this approach i.e. it require large number of DC sources making its application limited. Voltage Oriented Current Controller has found to be a suitable scheme for controlling the dq quantities for producing the reference voltages for the modulator to produce the switching patterns used in the converter. Upon the introduction of three phase fault at 2 different intervals VOCC takes as low as 0.01 seconds for compensating the disturbances and maintaining the required voltages at the output.

References

[1] F. Blaabjerg, R. Teodorescu, Z Chen, and M. Liserre, “Power Converters and Control of Renewable Energy Systems”, in Proceeding of Internacional Conference on Power Electronics (ICPE’04), 2004.

[2] Lai Jih-Sheng and Peng Fang Zheng, “Multilevel Converters-A new Breed of Power Converters”, IEEE Transactions on Industry Applications, vol. 32, no. 3, pp. 509–517, 1996.

[3] J. Rodriguez, Lai Jih-Sheng, and Peng Fang Zheng, “Multilevel Inverters: A Survey of Topologies, Controls, and Applications”, IEEE Transactions on Industrial Electronics, vol. 49, no. 4, pp. 724–738, 2002.

[4] A Nabae, I Takahashi, and H Akagi, “A New Neutral-Point Clamped PWM Inverter”, IEEE Transactions on Industry Applications, vol. 17, pp. 518–523, 1981.

[5] T. A. Meynard and H. Foch, “Multi-level Conversion: High Voltage Choppers and Voltage-Source inverters”, in Proceeding of Power Electronics Specialists Conference (PESC ’92), 1992, vol. 1, pp. 397–403.

[6] H. Akagi, “Classification, terminology, application of the modular multilevel cascade converter (MMCC),” IEEE Trans. Power Electron., vol. 26, no. 11, pp. 3119–3130, Nov. 2011.

[7] W. Kawamura and H. Akagi, “Control of the modular multilevel cascade converter based on triple-star bridge-cells (MMCC-TSBC) for motor drives,” in Proc. IEEE ECCE, Sep. 2012, pp. 3506–3513

[8] M. P. Kazmierkowski and L. Malesani, “Current Control Techniques for Three-Phase Voltage-Source PWM Converters: A Survey”, *IEEE Transactions on Industrial Electronics*, vol. 45, no. 5, pp. 691–703, 1998.

[9] D. M. Brod and D. W. Novotny, “Current Control of VSI-PWM Inverters”, *IEEE Transactions on Industry Applications*, vol. 21, no. 3, pp. 562–570, 1985.

[10] M. Liserre, A. Dell’Aquila, and F. Blaabjerg, “An Overview of Three-Phase Voltage Source Active Rectifiers Interfacing the Utility”, in *Proceeding of Power Tech Conference Proceedings*, *2003*, 2003, vol. 3, pp. 8–14.

[11] D. M. Brod and D. W. Novotny, “Current Control of VSI-PWM Inverters”, *IEEE Transactions on Industry Applications*, vol. 21, no. 3, pp. 562–570, 1985.

[12] M. Cichowlas and M. P. Kamierkowski, “Comparison of Current Control Techniques for PWM Rectifiers”, in *Proceeding of International Symposium on Industrial Electronics (ISIE’ 2002)*, 2002, vol. 4, pp. 1259–1263.

[13] C. T. Rim, N. S. Choi, G. C. Cho, and G. H. Cho, “A Complete DC and AC Analysis of Three-Phase Controlled-Current PWM Rectifier Using Circuit d-q Transformation”, *IEEE Transactions on Power Electronics*, vol. 9, no. 4, pp. 390–396, 1994.

[14] D. M. Brod and D. W. Novotny, “Current Control of VSI-PWM Inverters”, *IEEE Transactions on Industry Applications*, vol. 21, no. 3, pp. 562–570, 1985.