Development of a low-harmonic vector hysteresis current controller

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Abstract. The increasing interest in the use of renewable energy sources for the generation of electrical energy makes it necessary to ensure that these type of installations do not jeopardize the global operation of the electrical system to which they are connected. Up until now, this safety has been achieved by imposing very strict limits to the percentage of "non-controllable" renewable energy that can be connected to the grid.

In order to increase these limits, new control schemes must be developed, focusing in power quality and, if possible, in trying to help grid stability.

The paper proposes two new control methods for the current injected by a variable-speed generation system and compares them to a traditional hysteresis control.

The first one obtains a table by using an algorithm that calculates the switching state that minimises switching frequency. The commutation is determined by a single comparator applied to the error vector, achieving a circular error area. The use of this table, along with the selection of a circular error area for the current vector makes that the current error remains always inside the specified error area.

The second method is a predictive one, based on the previous one, that decides the optimum switching vector in the precise time when the commutation occurs, taking into account the present state of the system.

Key words

Predictive current controllers, distributed power generation, power quality, renewable energies.

1. Introduction

The connection of variable-speed generation systems to weak grids can improve the operation of those grids, provided that some technical requirements are met [1]. Among these problems, the one referring to the harmonic content is one of the most important when dealing with the connection of variable speed generation system to weak grids, by means of power electronics [1,2]. There are many method to soften their effects, based in high switching frequency and appropriate filtering techniques [3,4,5].

There are many current control methods [5],[6] for VSI bridges. Among them, hysteresis controllers are the simplest and the ones showing a better dynamic response. However, they show some drawbacks [7]. and many controllers have been developed to solve them. The methods more widely used are vector controllers and among them, the ones based on a table have a large acceptance because of their simplicity.

The desired characteristics of a current controller are [7]: minimizing steady-state error in a wide frequency range, limited switching frequency spectrum, reduced harmonic distortion, fast dynamic response and maximum DC bus voltage utilization. All these features must be achieved with the lowest possible load knowledge requirements [8].

There are many current control methods and various classifications [7,9]. A possible one is dividing them into:

- Hysteresis controllers
- Delta-modulation controllers
- Vector current controllers
- Linear controllers

There is no consensus about which controller should be used in every application, taking into account that each application can have very different requirements. Even in similar applications, the particular characteristics of the installation can differ greatly. This is the reason why new controllers are continuously been developed, trying to achieve the optimum control for each applications.

2. Vector hysteresis controllers

The methods more widely used are vector controllers that allow the selective use of the switching vectors (figure 1). Among them, the ones based on a table have a large acceptance because of their simplicity. However, the variation of the system where they work can make them fail if some options have not been considered. In these cases the predictive methods, calculating the optimum switching state in the commutation instant, are more robust and more adaptable to system variations.

The hysteresis controller tries to keep current between to specified values called hysteresis band [8,10]. In particular, vector hysteresis controls make the decision of the commutation state taken into consideration the bridge as a global element and not the result of the state of every branch, selecting one of the eight possible states.

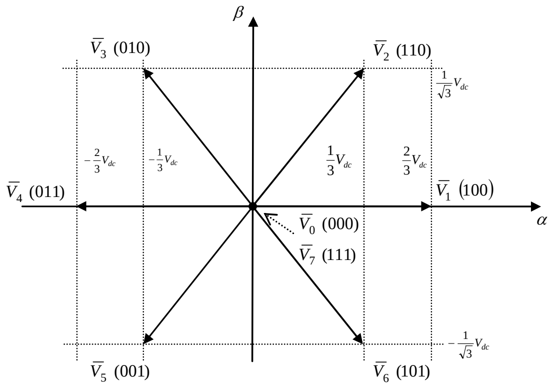

Fig. 1 .Graphic representation of the switching states.

The VSI output current will not show the exact desired evolution because the output voltage can only take seven values. The error phasor can be calculated as $\bar{\varepsilon} = \bar{I}^* - \bar{I}$ and its derivative as:

$$\frac{d\bar{\varepsilon}}{dt} = \frac{d\bar{I}^*}{dt} - \frac{d\bar{I}}{dt} = \frac{1}{L}(\overline{V}^* - \overline{V}_p) \qquad (1)$$

The switching state for the bridge is obtained from:

$$\overline{V}_p = \overline{V}^* - L\frac{d\bar{\varepsilon}}{dt} \qquad (2)$$

When a comparator is used for each phase, an hexagonal error area is obtained. If a single comparator for the current error phase is used, the error area becomes a circle.

2. Predictive control description

The proposed method is based on the same procedure as the table circular hysteresis control [11].

This method calculates the expected evolution of the current error phasor for each available switching voltage (figure 2) and chooses the one that, while keeping the error within the desired circular area, implies a lower switching frequency.

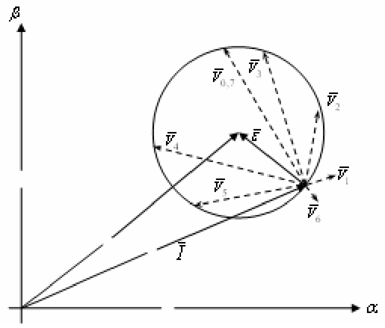

Fig. 2. Graphic representation of the selection procedure

The current error trajectory is given by (3), where the error is obtained from (1)

$$M_{\bar{I}} = \bar{I}_0 + \frac{d\bar{\varepsilon}}{dt}t = \left(i_{0\alpha} + \frac{d\varepsilon_{0\alpha}}{dt}t\right) + j\cdot\left(i_{0\beta} + \frac{d\varepsilon_{0\beta}}{dt}t\right) \qquad (3)$$

The results are obtained for a given set of operating conditions (dc bus voltage, output current, band and inductance) and are stored in a table. If actual conditions differ from the ones used in the calculation, the evolution of the system can be worse than expected causing the current error phasor to leave the band. That is the reason why, usually, the table-based methods have a second external band to force current into the assigned limits.

The main difference in the predictive control is that in this case the algorithm that selects the switching state is calculated in the precise instant when the error phasor reaches the limit of the allowed band. To do this, the system receives: bus voltage, band value, current error phasor, reference voltage phasor and the current switching state.

Another situation that makes current go out of limits occurs when the resulting vector state for the prefixed conditions of instant k+1 is the same as the previous one (instant k). In this case, there is no switching state variation, not preventing the current from going out of the desired limits. To avoid this problem, the selection of the switching state in the predictive method is done as follows:

At time k+1 it is calculated the switching state that, while keeping the error phasor inside the tolerance band, minimises switching frequency. If the new state is the same as the present state (time k), a different state is selected, also keeping error into the limits. By doing this, a change in switching state occurs and the current error phasor does not leave the circular area.

However, in some situations, if bus voltage is low, it may happen that there is only one switching state that ensures that the current phasor error stays within the desired area. Knowing that, it is necessary to use a second external band, like in the table-based mehod, to force the error to return to the circular area. Even then, the state can be the same as in time k, so in this case the new switching state is recalculated every 0,33 ms to determine the instant when there is a different available switching state.

3. Comparison

The proposed method has been compared totraditional hysteresis and circular table controls. The three methods have been simulated using MATLAB for a generation system connected to a 400 V grid, having a 700 V DC bus and an inductance of 0,8 mH. The effect of inductance résistance has been neglected. In the three methods a 5 μs blocking time has been used.

In order to compare its behaviour under diverse circumstances, the operation at 650, 350 and 150 A hs been tested. The internal and external bands are respectively 10% and 12% of the effective current. The tests have been carried out varying dc voltage from 710 V down to the minimum value required for the bridge to work properly. Each voltage level has been kept during 0.2 seconds and the tests have been repeated four times.

A. Comparison to traditional hysteresis control

Figure 3 represent average THD over 10 cycles for the three current levels and different dc voltages. It can be noticed that predictive control is clearly better than traditional hysteresis control.

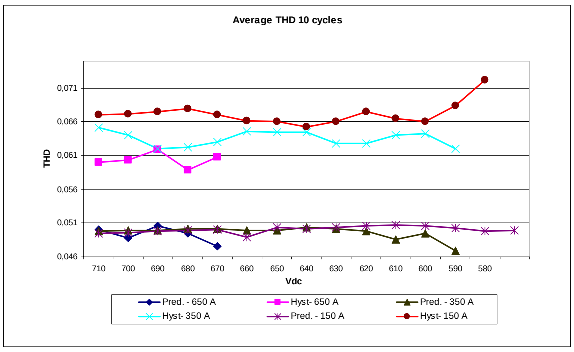

Figure 3. Average output current THD for traditional and predictive hysteresis controllers.

However, in all cases switching frequency is higher using predictive control, as shown in figure 4. The cause is that using traditional hysteresis control, a current going out of the allowed band not always forces a switching, making it possible that the error doubles the desired band [10].

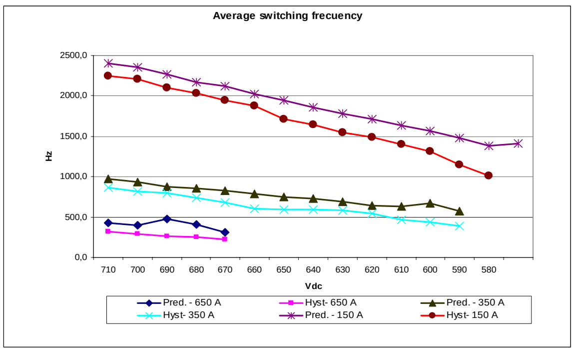

Fig. 4. Average switching frequency for traditional and predictive hysteresis controllers.

Figure 5 shows the difference between the current error phasor area in both cases and how, using the traditional hysteresis control, the error goes over the band. (65 A, 700 V dc bus).

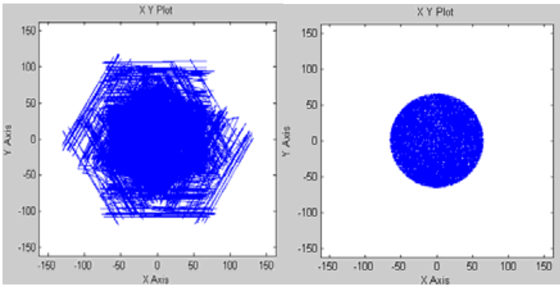

Fig 5. Error area for traditional hysteresis and predictive hysteresis controllers. I_{out}=650 A, B=65 A, V_{dc}=700 V.

B. Comparison to table circular hysteresis control

Figure 6 shows THD at the specified three load levels for both methods. It can be noticed that the difference on THD among them is not very important, being slightly better using the predictive method.

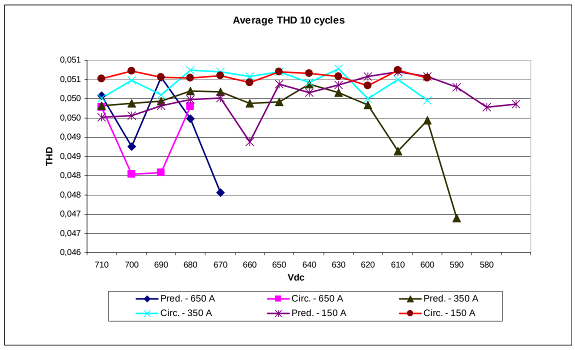

Fig. 6. Average output current THD for table and predictive circular hysteresis controllers.

Figure 7 shows switching frequency in the same conditions of figure 1. In this case it can be noticed that at 650 A, both methods have almost the same frequency but, as reference current decreases, the predictive method clearly shows a lower switching frequency. The reason is that with this method the calculation of the switching vector is always optimal, whereas the table has been computed for maximum current.

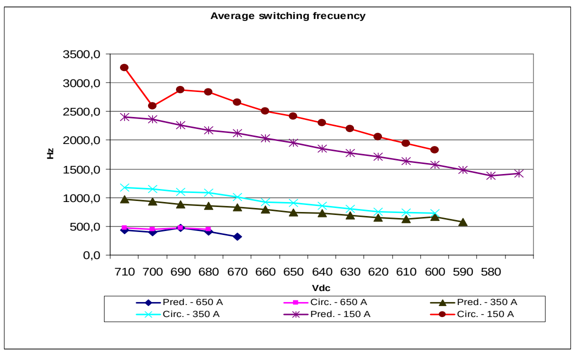

Fig. 7. Average switching frequency for table and predictive circular hysteresis controllers.

Besides the predictive control makes possible operating at lower dc voltages than using the table method. This also provides a better transient behaviour when fast reference changes occur. Figure 8 shows the error phasor area for both methods at 150 A and a 660 V dc bus.

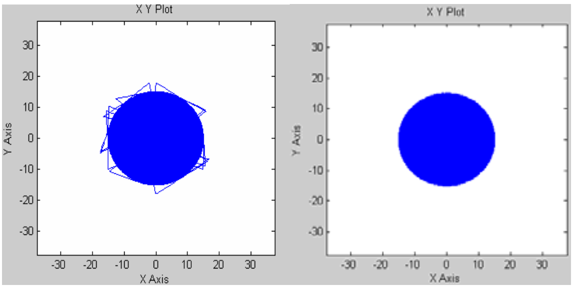

Fig. 8. Error area for table and predictive circular hysteresis controllers. I_{out}=150 A, B=15 A, V_{dc}=660 V.

4. Conclusions

The paper describes a predictive control method that suppresses the main drawbacks of table circular hysteresis control [11] which are: non optimal operation in conditions different from the ones used in the calculation of the table, and not taking into account the previous switching state. Due to this circumstances the current phasor error leaves the desired error area until it reaches the dynamic or security external band.

The proposed method avoids this drawbacks, on the one hand by calculating the next switching state in the precise instant that the commutation takes place, using the actual parameter values, and on the other, by taking into consideration the previous state.

Simulation results show that the predictive method has lower THD than the traditional hysteresis method in all three simulated conditions, but higher switching frequency. The behaviour of both circular methods is similar when operating at rated current, but when the output current decreases, the predictive method show lower THD and switching frequency, as expected from its possibility of adaptation to the new conditions.

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