Study on PWM Converter Control under Unbalanced Network Condition

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Abstract

This paper focuses on study on PWM converter control under unbalanced network condition. Voltage unbalance in a three-phase system causes the performance deterioration by producing 120 Hz voltage ripples in the DC link and 120 Hz ripple in reactive power. To eliminate the ripples, both positive and negative sequence currents should be controlled simultaneously. In this paper four PI controllers on synchronous reference frame is implemented to control D and Q currents in both positive and negative sequence. Positive and negative sequence signal extraction is done using delay signal cancellation method. Simulation results show satisfactory performance in suppressing 120 Hz ripples.

1. Introduction

Many power electronic devices, including PWM converters, are installed in remote or rural areas. These remote areas usually have electrically weak power grids, characterized by low short circuit ratios and unbalanced voltage conditions. In PWM converters, if the voltage unbalance is not taken into account in the control system, a small 120 Hz voltage ripple in the DC link and 120 Hz reactive power ripple appears.

Control and operation of PWM converter under unbalanced network voltage conditions have been studied in [1], [2], [3]. Nam and Song [4] implemented a dual current control scheme to reduce ripples. Two synchronous reference frames (SRF) are used; in positive SRF, pure DC positive sequence signal is obtained by eliminating the negative sequence signal using a 120 Hz notch filter; in negative SRF, pure DC negative sequence signal is obtained by eliminating the positive sequence signal using a 120 Hz notch filter respectively. Separately measured currents are used for two feedback proportional integral (PI) controllers. One regulates only the positive sequence current in positive SRF, the other regulates only the negative sequence current in the negative SRF. However, the filter usage decreases stability.

In this paper, we propose a positive and negative sequence extraction using a method called delay signal cancellation [5]. This method is known to be very exact in nature and eliminates the need of any filters. Simulation results show satisfactory performance in suppressing 120 Hz ripples.

2. Mathematical model of PWM converter under unbalanced condition

Therefore, unbalanced signal without a zero sequence can be represented by

$$F_{\alpha\beta} = e^{j\omega t} F_{dq}^{p} + e^{-j\omega t} F_{dq}^{n} \tag{1}$$

PWM converter under unbalanced condition in stationary reference frame can be modeled by

$$E_{\alpha\beta} = V_{\alpha\beta} + L\frac{dI_{\alpha\beta}}{dt} + RI_{\alpha\beta} \tag{2}$$

where

$$E_{\alpha\beta} = e^{j\omega t} E_{dq}^{p} + e^{-j\omega t} E_{dq}^{n} \tag{3}$$

$$I_{\alpha\beta} = e^{j\omega t} I_{dq}^{p} + e^{-j\omega t} I_{dq}^{n}$$

$$V_{\alpha\beta} = e^{j\omega t} V_{dq}^{p} + e^{-j\omega t} V_{dq}^{n}$$

Apparent power is given by

$$S = \left(e^{j\omega t} E_{dq}^{p} + e^{j\omega t} E_{dq}^{n}\right)\left(e^{j\omega t} I_{dq}^{p} + e^{j\omega t} I_{dq}^{n}\right)^{*} \tag{4}$$

Solving (4) and referring to $S=P+jQ$, we obtain the real power

$$P(t) = P_0 + P_{\cos 2}\cos(2\omega t) + P_{\sin 2}\sin(2\omega t) \tag{5}$$

Where

$$P_0 = 1.5\left(E_d^p I_d^p + E_q^p I_q^p + E_d^n I_d^n + E_q^n I_q^n\right)$$

$$P_{\cos 2} = 1.5\left(E_d^n I_d^p + E_q^n I_q^p + E_d^p I_d^n + E_q^p I_q^n\right)$$

$$P_{\sin 2} = 1.5\left(E_q^n I_d^p - E_d^n I_q^p - E_q^p I_d^n + E_d^p I_q^n\right)$$

From instantaneous reactive power theory,

$$Q(t) = Q_0 + Q_{\cos 2}\cos(2\omega t) + Q_{\sin 2}\sin(2\omega t) \tag{6}$$

Where

$$Q_0 = 1.5\left(E_q^p I_d^p - E_d^p I_q^p + E_q^n I_d^n - E_d^n I_q^n\right)$$

$$Q_{\cos 2} = 1.5\left(E_q^n I_d^p - E_d^n I_q^p + E_q^p I_d^n - E_d^p I_q^n\right)$$

$$Q_{\sin 2} = 1.5\left(E_d^p I_d^p - E_q^n I_q^p - E_d^p I_d^n + E_q^p I_q^n\right)$$

As we can see from (5) and (6), the components P_{cos2}, P_{sin2}, Q_{cos2}, and Q_{sin2} are the ones that generate oscillations. To keep the constant DC level, all coefficients of P_{cos2}, P_{sin2}, Q_{cos2}, and Q_{sin2} needs to be eliminated. Since there's also a need to control P_0 and Q_0 and limited by the degrees of freedom, one can only control 4 variables at a time

$$\begin{bmatrix} 2/3\,P_0 \\ 2/3\,Q_0 \\ 2/3\,P_{\sin 2} \\ 2/3\,P_{\cos 2} \end{bmatrix} = \begin{bmatrix} E_d^p & E_q^p & E_d^n & E_q^n \\ E_q^p & -E_d^p & E_q^n & -E_d^n \\ E_q^n & -E_d^n & -E_q^p & E_d^p \\ E_d^n & E_q^n & E_d^p & E_q^p \end{bmatrix} \begin{bmatrix} I_d^p(t) \\ I_q^p(t) \\ I_d^n(t) \\ I_q^n(t) \end{bmatrix} \tag{7}$$

By setting P_{cos2}, P_{sin2}, and Q_0 to 0, one can get

$$\begin{bmatrix} I_d^p(t) \\ I_q^p(t) \\ I_d^n(t) \\ I_q^n(t) \end{bmatrix} = \frac{2P_0}{3D} \begin{bmatrix} E_d^p \\ E_q^p \\ -E_d^n \\ -E_q^n \end{bmatrix} \tag{8}$$

where $D = \left[(E_d^p)^2 + (E_q^p)^2\right] - \left[(E_d^n)^2 + (E_q^n)^2\right]$. Hence one can fulfill the control objectives by flowing both positive and negative sequence currents.

3. Control scheme

First, one needs to measure the signals in both SRF. The measured signals in stationary reference frame is

$$F_{\alpha\beta} = e^{j\omega t} F_{dq}^p + e^{-j\omega t} F_{dq}^n \tag{9}$$

By multiplying the signals with $e^{-j\omega t}$ and $e^{j\omega t}$

$$\begin{aligned} \bar{F}_{dq}^p &= F_{dq}^p + e^{-2j\omega t} F_{dq}^n \\ \bar{F}_{dq}^n &= e^{2j\omega t} F_{dq}^p + F_{dq}^n \end{aligned} \tag{10}$$

Eliminating the oscillating terms is necessary to obtain pure DC signal, but the elimination of oscillation using filters decreases stability, therefore one can use the delay signal cancellation method. Using this theory, we can establish the positive and negative stationary reference frame as

$$\begin{bmatrix} F_\alpha^p(t) \\ F_\beta^p(t) \\ F_\alpha^n(t) \\ F_\beta^n(t) \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} F_\alpha(t) \\ F_\beta(t) \\ F_\alpha\left(t-(T/4)\right) \\ F_\beta\left(t-(T/4)\right) \end{bmatrix} \tag{11}$$

Then we can easily obtain the positive and negative SRF as

$$\begin{aligned} F_{dq}^p &= F_{\alpha\beta}^p e^{-j\omega t} \\ F_{dq}^n &= F_{\alpha\beta}^n e^{j\omega t} \end{aligned} \tag{12}$$

If we solve (3) to (2), we will get PWM converter model under unbalanced condition in positive and negative SRF.

$$\begin{aligned} E_{dq}^p &= V_{dq}^p + L\frac{dI_{dq}^p}{dt} + RI_{dq}^p + j\omega LI_{dq}^p \\ E_{dq}^n &= V_{dq}^n + L\frac{dI_{dq}^n}{dt} + RI_{dq}^n - j\omega LI_{dq}^n \end{aligned} \tag{13}$$

Then one can see that the positive and negative converter pole voltages are determined by

$$\begin{aligned} V_d^p &= E_d^p - (PI)(I_d^{p*} - I_d^p) + \omega LI_q^p \\ V_q^p &= E_q^p - (PI)\left(I_q^{p*} - I_q^p\right) - \omega LI_d^p \\ V_d^n &= E_d^n - (PI)(I_d^{n*} - I_d^n) - \omega LI_q^n \\ V_q^n &= E_q^n - (PI)\left(I_q^{n*} - I_q^n\right) + \omega LI_d^n \end{aligned} \tag{14}$$

It is obvious that we can control V_{DC} by using I_{DC} to control P_0. Using that approach, one can establish

$$P_0 = V_{DC}^*(PI)(V_{DC}^* - V_{DC}) \tag{15}$$

Therefore the current reference will be

$$\begin{bmatrix} I_d^{p*}(t) \\ I_q^{p*}(t) \\ I_d^{n*}(t) \\ I_q^{n*}(t) \end{bmatrix} = \frac{2}{3D} V_{DC}^*(PI)(V_{DC}^* - V_{DC}) \begin{bmatrix} E_d^p \\ E_q^p \\ -E_d^n \\ -E_q^n \end{bmatrix} \tag{16}$$

The overall control can be described by (14) and (16), and the reference of pole voltages can be fed to the space vector PWM after being transformed back to the stationary reference frame

$$V_{SVM} = V_{dq}^p e^{j\omega t} + V_{dq}^n e^{-j\omega t} \tag{17}$$

4. Simulation

Simulation parameters are shown in Table 1. Figures 1 and 2 show the generated DC voltage. They show that the oscillation of the DC voltage is lower under the proposed control. Figure 3 shows the reactive power at the grid. It shows that the reactive power, which is never averagely zero under conventional control, is averagely zero under the proposed control.

5. Conclusion

The proposed control generates satisfactory results in suppressing 120 Hz ripple in DC link voltage and reactive power at the grid side. Delay signal cancellation technique can be used to extract the positive and negative sequence signals without any additional stability problems.

TABLE 1. Simulation parameters.

Parameter	Symbol	Value
Line voltage magnitude	E_a, E_b, E_c	158.4, 100.8, 180V
DC link voltage	V_{DC}	600V
Load resistance	R_L	50Ω
Line inductor	L_{AC}	5mH
DC link capacitor	C_{AC}	550µF

Future works that need to be done include designing better performance current and voltage control to further reduce the oscillations.

Reference

[1] P. N. Enjeti, et.al, "A new control strategy to improve the performance of a PWM AC to DC converter under unbalanced operating conditions," *IEEE Trans. Pow. Electron.*, vol. 8, no. 4, pp. 493-500, Oct. 1993.

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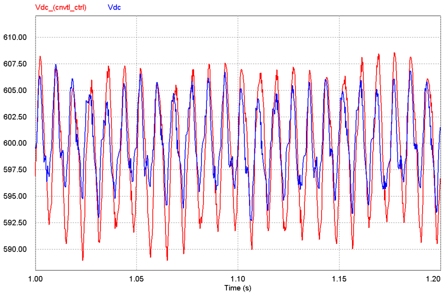

Fig. 1. V_{DC} under conventional control (red) and proposed control (blue)

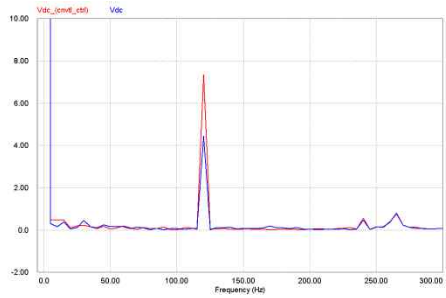

Fig. 2. V_{DC} spectrum analysis under conventional control (red) and proposed control (blue)

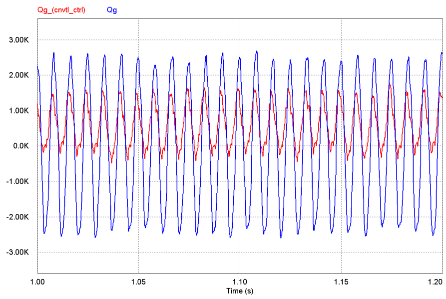

Fig. 3. Q under conventional control (red) and proposed control (blue)