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Supply perturbation compensated control scheme for three-phase neutral-point clamped bi-directional rectifier

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ABSTRACT

In this paper, an improved performance three-phase neutral-point clamped bidirectional rectifier with modified control scheme is proposed. The proposed control strategy takes into consideration the amount/degree of deviation of source voltage from desired rated value during supply perturbation and accordingly modifies the reference current template for each phase individually which is termed as compensated reference current. In other words, magnitude, shape and phase of compensated reference current waveform for each phase are different depending on amount of deviation of that phase. A complete mathematical model of rectifier using PWM technique is developed. The performance of the converter is evaluated in terms of near unity input power factor, low input current THD, reduced ripple factor of the regulated DC output voltage and particularly the neutral point voltage balance under different load conditions both for rectification and inversion modes of operation. It is shown that the three-level ac to dc converter with proposed control scheme displays better performance under source voltage perturbations such as voltage sag, swell, unbalance, harmonics, frequency variations as well as phase angle deviations which are regularly encountered in practical environment.

1. Introduction

AC/DC power converters are extensively used in various applications like power supplies, dc motor drives, front-end converters in adjustable-speed ac drives, HVDC transmission, SMPSs, UPSs, utility interface with non-conventional energy sources and power supplies for telecommunications systems, aerospace, etc. Traditionally, AC–DC power conversion has been dominated by diode or phase-controlled rectifiers which act as non-linear loads on the power systems and draw input currents which are rich in harmonics and have poor supply power factor, thus creating the power quality problems for the power distribution network and for other electrical systems in the vicinity of rectifier. The other associated problems with these converters include: large reactive power drawn by the rectifiers, voltage drops at buses, increased losses in the equipments, deteriorated performance of induction motors in terms of poor efficiency and torque pulsations, nuisance operation of protective devices including false tripping of relays, lower rectifier efficiency due to large rms values of input current, neutral burning due to the operation of single-phase bridge rectifiers and so on.

In view of above drawbacks, regulatory agencies have issued several strict standards such as IEEE-519 and IEC555 [2,3] and are being enforced on the consumers. IEEE-519-1992 "Recommended Practices and Requirements for Harmonic control in Electrical Power Systems" provide guidelines for determining, what are acceptable limits. To meet these standards and improve the power quality, use of passive filters, active power filters and hybrid filters [7–9] has been made along with conventional rectifiers, especially in high power rating and already existing installations. However, these filters are quite costly, bulky, suffer from other problems and make the entire system less efficient. In some cases, the rating of active power filter is almost close to the rating of load which makes the system costlier.

To overcome these drawbacks, Improved Power Quality Converters (IPQCs) are included as an inherent part of the AC–DC conversion system which produces higher efficiency, reduced size, and well regulated dc output. Three-phase Multi-Level Converters (MLCs) are gaining widespread popularity among the power factor correction converters because of their excellent performance like unity input power factor, low input current THD, reduced ripple factor of the regulated DC output voltage, reduced voltage stress, dv/dt stress and hence low EMI emissions [1,4–6,10,11,13,14].

All PWM control schemes involve an outer voltage control loop to regulate the output voltage of rectifier which consists of PI voltage controller to provide (I_m^*) which is multiplied by a unit current template derived from source voltage generally by dividing it by

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the peak value. This forms the desired current and the PI current controller provides V_{control} based on error signal after comparing desired and actual current. The said control scheme performs well as long as supply is perfectly balanced, of rated value, and frequency. But this is not always the true in practical working conditions (industrial environment), thus resulting in deteriorated performance of front end rectifiers.

Another approach is to generate unit sine template using Phase Locked Loop (PLL) [12] which provides insensitivity to supply voltage disturbances. This approach demands very fast dynamic response from finely tuned PI current controller and results in improved performance compared to conventional control schemes. The main drawback of this scheme is that it provides complete insensitivity to supply voltage perturbations and generate unit sine templates displaced by 120° irrespective of supply conditions. In other words, it is unable to sense and compensate for the same in individual phases, thus converter performance is affected during supply perturbations especially during large unbalance as well as phase angel shift. Another reason for poor performance is upper limit of dynamic response of PI current controller as error signal changes very fast when supply voltage is rich in harmonics. This forms the basis of proposed control scheme which instead of insensitivity, senses the supply voltage disturbances and accordingly modifies the reference current for each phase resulting in improved performance of rectifier which is verified later in this paper by simulation results.

2. Control scheme

The compensated template generator as shown in Fig. 4 takes into consideration the rated system voltage and at the same time it continuously measures the time period of input voltage. These parameters are used for generating unit template (V_{xu}) as well as reference voltage waveforms of rated magnitude at instantaneous supply frequency. This reference voltage waveform is used to determine the degree of deviation by comparing it with supply waveform as measured by voltage sensor. The difference in reference and actual waveform is the error voltage, whose instantaneous magnitude depends upon degree of sag, swell, unbalance and amount of harmonics present in input signal. This error voltage when divided by rated peak value and processed by proportional controller generates compensation template (V_{xc}). The shape of various waveforms discussed above are shown in Fig. 5(a and b).

If this is followed for each supply phase, then there are three error signals whose magnitude and shape may or may not be same depending upon amount of disturbance in each phase. Since these error signals are in-phase with their respective phases, they are able to determine the degree of phase shift between supply phases. Thus, sag or swell and harmonics are sensed individually where as unbalance and phase shift is evaluated collectively. These compensation templates are then used to modify reference current of respective phase depending upon amount/ degree of deviation from desired rated values, thus providing compensation for source voltage disturbances. In other words the reference current for three phases may not be a sine wave of equal magnitudes displaced by 120°, instead the magnitude, shape and phase angle of reference current waveform for each phase may be different depending on amount of deviation of that phase.

The proposed control scheme along with contribution of compensated template generator is shown in Fig. 3. Depending upon desired DC bus voltage, the PI voltage controller provides I_m^* which is multiplied by unit template V_{xu} and compensated for supply deviation by V_{xc}. On other hand $\Delta V = V_{C1} - V_{C2}$ is compared with reference voltage of zero magnitude and processed by proportional controller for the purpose of DC bus capacitor voltage balancing. These two signals are added to get compensated reference current I_{ref} (Fig. 5c), which is then compared with actual phase current I_x to generate the error signal. The error signal is then processed by PI current controller to get V_{control}. This V_{control} is finally compared with high frequency triangular carrier wave in PWM modulator to generate control pulses for devices of respective phase. This results in improved performance of three-level ac to dc converter in terms of unity input power factor, low input current THD, reduced ripple factor of the regulated DC output voltage and particularly the neutral point voltage balance as well as reduced voltage stress of the power semiconductor devices, both under dynamic source as well as load conditions which are regularly encountered in practical environment.

3. System modeling and description

Fig. 1 depicts a three-phase neutral-point clamped bi-directional Improved Power Quality Converter. Each power switch has a voltage stress of half the dc bus voltage instead of full dc bus voltage, the neutral point of the dc-link is connected to the neutral of three-phase ac source. The constraints for four power switches in an arm of the converter are defined so as to avoid the power switches conducting at the same time.

$$T_{Xi} + T_{Xi'} = 1 \tag{1}$$

where $x = a, b, c$ and $i = 1, 2$.

$T_{xi} = 1$ if the switch T_{xi} is turned ON and $T_{xi} = 0$ if the switch T_{xi} is turned OFF.

The equivalent switching function of the adopted rectifier is defined as,

$$s = \begin{cases} 1 & \text{if } T_{X1} = T_{X2} = 1 \\ 0 & \text{if } T_{X1'} = T_{X2} = 1 \\ -1 & \text{if } T_{X1'} = T_{X2'} = 1 \end{cases} \tag{2}$$

The supply side line-to-neutral voltage of the rectifier can be expressed as,

$$V_{x'} = \frac{S(S+1)}{2} V_{C1} - \frac{S(S-1)}{2} V_{C2} = \frac{S^2}{2} \Delta V + \frac{S}{2} V_o \tag{3}$$

where V_{C1} and V_{C2} are respective capacitor voltages, $\Delta V = V_{C1} - V_{C2}$ and $V_0 = V_{C1} + V_{C2}$ = DC-Bus voltage. If the two capacitor voltages V_{C1} and V_{C2} are equal, i.e., $\Delta V = 0$, then there are three voltage levels, $V_0/2$, 0 and $-V_0/2$, on the AC side (line-to-neutral voltages) of the rectifier. By proper combinations of the power switches of any arm, three different voltage levels are generated in the line-to-neutral voltage by the rectifier. The three valid modes for phase-leg A of the rectifier are described schematically in Fig. 2.

The adopted controller for the converter (using sinusoidal PWM technique) and the generation of gating pulses are shown in Fig. 3. The modified controller consists of compensated template generator which generate unit template (V_{xu}) like PLL as well as an additional compensation template (V_{xc}) to provide compensation for supply disturbances. The process of sensing supply disturbances, generation of unit template as well as compensation template by compensated template generator is shown in Fig. 4 and the related changes in various waveforms is shown in Fig. 5.

Apply Kirchhoff's voltage law (KVL) on phase 'a' (ac side) of the rectifier, we have

$$V_a = Ri_a + L\frac{di_a}{dt} + V_{a'} \tag{4}$$

From (3), for phase a ($x = a$),

$$V_{a'} = \frac{S^2}{2} \Delta V + \frac{S}{2} V_0 \tag{5}$$