Some Topologies of High Quality Rectifiers

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Abstract—Several basic classes of three-phase high-quality rectifiers are described. Both single-switch and six-switch three-phase rectifier topologies can be derived from parent dc-dc converters. Single-switch rectifiers are compared with the basic six-switch PWM rectifiers performing similar power conversion functions, using the measures of total semiconductor stress and active semiconductor utilization. The single-switch approach is shown to utilize the semiconductor devices more effectively. Zero current switching and multi-resonant approaches are found to exhibit low switch stress over a wide range of operating points, with low THD.

1. Introduction

High-quality low-harmonic rectification is becoming increasingly required, to meet regulations which limit ac line current harmonic content, such as IEC-555 and IEEE-519. The application requirements of three-phase high-quality rectifiers are varied. In some simple cases, it may be necessary only to produce a dc output voltage nearly equal the peak input line-to-line voltage. In other cases, an output voltage of variable and controlled magnitude, substantially smaller or larger than the input line-to-line voltage, may be required. Isolation of the dc load from the ac line is also a requirement in applications such as battery charging in the telecommunication or electric vehicle areas. High-frequency EMI and common-mode currents, generated by non-isolated low-harmonic rectifiers, is also a major concern.

Figure 1 illustrates the desired properties of an ideal three-phase rectifier, which presents a balanced resistive load to the utility system. A three-phase converter system is controlled such that resistor emulation is obtained in each input phase. The rectifier three-phase input port can then be modeled by per-phase effective resistances \( R_e \), as illustrated in Fig. 1. The harmonic content of the ac input currents therefore match the harmonic content of the applied ac input voltages, and hence are correspondingly low. The instantaneous powers apparently consumed by these effective resistors are transferred to the rectifier dc output port. The rectifier output port can therefore be modeled by a power source equal to the total three-phase instantaneous input power as shown in Fig. 1 [1-3].

The various active approaches to high-quality three-phase rectification fall into two classes. The first comprises PWM converters operating in the continuous conduction mode (CCM), with the three ac line currents independently and actively regulated. These converters usually contain six or more active devices, and are capable of bidirectional power flow. The second class may contain as little as one active device, and input resistor emulation is obtained via the natural response of the converter reactive elements to the high-frequency switching of the active device. In this paper, both approaches are discussed, and the utilizations of their active semiconductor devices are compared.

2. Three-phase PWM rectifiers operating in CCM

A variety of 3øac-dc PWM rectifiers are known; a few of the many references on this subject are listed here [4-10]. The most well-known topology is the three-phase ac-to-dc boost rectifier, illustrated in Fig. 2. This converter requires six SPST current-bidirectional two-quadrant switches. The inductors and capacitor filter the high-frequency switching harmonics, and have little influence on the low-frequency ac components of the waveforms. The switches of each phase are controlled to obtain input resistor emulation, either with a multiplying controller.
scheme employing average current control, or with some other approach. To obtain undistorted line current waveforms, the dc output voltage $V$ must be greater than or equal to the peak line-to-line ac input voltage $V_{L, pk}$. In a typical realization, $V$ is somewhat greater than $V_{L, pk}$. This converter resembles the well-known voltage-source inverter, except that the converter is operated as a rectifier, and the converter is controlled via high-frequency pulse-width modulation.

The three-phase boost rectifier of Fig. 2 has several attributes which make it the leading candidate for most 3øac-dc rectifier applications. The ac input currents are nonpulsating, and hence very little additional input EMI filtering is required. As in the case of the single-phase boost rectifier, the rms transistor currents and also the conduction losses of the three-phase boost rectifier are low relative to other 3øac-dc topologies such as those of Fig. 3. The converter is capable of bidirectional power flow. A disadvantage is the requirement for six active devices; when compared with a dc-dc converter of similar ratings, the active semiconductor utilization is low. Also, since the rectifier has a boost characteristic, it is not suitable for direct replacement of traditional buck-type phase-controlled rectifiers.

Three-phase ac-to-dc rectifiers having buck, buck-boost, or other characteristics, are possible, but find much less use than the boost topology. An example is the 3øac-dc buck rectifier illustrated in Fig. 3(a). Unlike the single-phase case, in three-phase applications the buck topology can supply constant power to a dc load, with negligible distortion of the ac line current waveforms. When the voltage of one phase is zero, the other two phases have nonzero voltage and can supply the dc load power. This converter can produce a controlled dc output voltage $V$ that is less than the peak line-line ac input voltage. This converter resembles what is known as the current-source inverter, except that the converter is operated as a rectifier, and the converter is controlled via high-frequency pulse-width modulation.

Two-quadrant voltage-bidirectional switches are required in this converter. A disadvantage of the 3ø buck rectifier is the higher conduction losses induced by the series connection of devices. Also, the rms transistor currents are greater than in the 3ø boost rectifier; this further increases the conduction loss. The converter is capable of operation in inverter mode by reversal of the polarity of the output voltage $v(t)$. A substantial input filter is usually required to smooth the pulsating ac line currents.

PWM 3øac-dc rectifiers which resemble most other dc-dc converter topologies are also possible. Two examples are the 3øac-dc rectifier circuits of Figs. 3(b) and 3(c), based on the dc-dc buck-boost [9] and Cuk converters. These converters can be viewed as being derived from parent dc-dc converters via a transformation in which the dc input and switch network are replaced by a three-phase input and six-
switch bridge network. High-frequency isolation transformers can be incorporated into most of these converters, in a manner similar to that used to obtain isolation in the parent dc-dc converters.

3. Some other approaches to three-phase high-quality rectification

The CCM three-phase rectifier approaches described in section 2 require six or more active devices. Compared with conventional low-power-factor passive rectifier approaches, the increased active silicon area and reduced semiconductor utilization of the six-switch approach can be expensive. In view of this, one might ask what is the minimum active silicon area required to perform the desired functions of the ideal rectification application. It is well known that low-harmonic 3øac-dc rectification can be performed using a conventional passive six-diode rectifier and a harmonic trap filter. Hence fundamentally, no semiconductor devices other than diodes are required. When control of the output voltage is requisite, at least one active device is needed. If it is desired to avoid the use of low-frequency filter elements, then a source of high-frequency switching harmonics is needed, again necessitating inclusion of at least one active device. So a single active device is the minimum needed to synthesize low-harmonic 3ø rectifiers containing no low-frequency reactive elements, having control of the output voltage, and having unidirectional power flow. Several single-switch approaches to three-phase rectification are known. Depending on the application, some of these approaches may exhibit better active switch utilization and reduced semiconductor area than six-switch approaches. On the other hand, these single-switch approaches generally require additional high-frequency reactive elements.

A single-switch 3øac-dc rectifier based on the DCM boost converter [11,12] is illustrated in Fig. 4. The input current waveform $i_a(t)$ is illustrated in Fig. 5(b). Transistor $Q_1$ is controlled in the same manner as a dc-dc boost converter. Inductors $L_1$, $L_2$, and $L_3$ are of equal small value, such that they operate in the discontinuous conduction mode in conjunction with diodes $D_1$ - $D_6$. At the end of the transistor $Q_1$ conduction subinterval, the inductor currents reach peak values which are also proportional to the applied three-phase line-to-neutral voltages. When transistor $Q_1$ turns off, then diode $D_7$ becomes forward-biased and the inductors release their stored energies to the dc output. Since the peak input currents are proportional to the applied input line-to-neutral voltages, then the average values of the input currents are also approximately proportional to the input line-to-neutral voltages. Approximate three-phase input resistor emulation is obtained. The three-phase DCM boost rectifier does generate a modest amount of low-frequency input current harmonics; the THD can be reduced by increasing the dc output voltage.

The three-phase DCM boost rectifier has the advantage of very simple control. The transistor can operate at constant switching frequency. Variation of the duty cycle allows control of the dc output power. Only a single active device such as a MOSFET or

![Fig. 5. Input current waveforms of various single-switch three-phase rectifier circuits: (a) input line-to-neutral voltage $v_{an}(t)$; (b) 3ø DCM boost; (c) 3ø DCM flyback; (d) zero-current-switching quasi-resonant buck; (e) phase a tank capacitor voltage, multi-resonant zero-current-switching buck.](image-url)
IGBT is needed. A disadvantage is the need for an input filter to remove the high-frequency components of the pulsating input currents. As in all single-switch three-phase rectifiers, bidirectional power is not possible.

A similar scheme, based on the DCM flyback converter [13,14], is illustrated in Fig. 6. A typical input current waveform is given in Fig. 5(c). This converter is effectively three independent single-phase DCM flyback rectifiers, which share a single transistor switch. The peak transformer magnetizing currents directly follow the applied ac phase voltages. This causes the average input currents to directly follow the applied line-to-neutral voltages, without generation of low-frequency current harmonics. The rectifier can both increase and decrease the voltage magnitude, and is inherently capable of inrush current limiting. In low-power applications, this is a simple way to obtain low-harmonic three-phase rectifier which incorporates high-frequency isolation transformers. It has the disadvantage of requiring an input filter for removal of the high-frequency components of the pulsating input current waveforms.

A buck-derived single-switch rectifier [15] is illustrated in Fig. 7. This converter is based on the zero-current-switching (ZCS) quasi-resonant dc-dc buck converter. A resonant inductor \( L_r \) is placed in each input phase. As illustrated in Fig. 5(d), when transistor \( Q_1 \) conducts, the resonant inductors \( L_r \) ring in conjunction with resonant capacitor \( \text{C}_r \). Input currents \( i_d(t) \), \( i_b(t) \), and \( i_c(t) \) are approximately sinusoidal pulses, having peak amplitude proportional to the applied line-to-neutral voltages \( v_{an}(t) \), \( v_{bn}(t) \), and \( v_{cn}(t) \), respectively. The average values of \( i_d(t) \), \( i_b(t) \), and \( i_c(t) \) are therefore approximately proportional to the respective applied line-to-neutral voltages. At full load, a THD of approximately 13-14% is observed; nearly all of the THD can be attributed to the fifth harmonic. The THD can be reduced to less than 10%, by use of any control scheme that leads to constant instantaneous power flow.

Transistor \( Q_1 \) operates with zero current switching. An IGBT, inverter-grade SCR, or other device can be used. The peak voltage stress on \( Q_1 \) is equal to the applied peak input line-to-line voltage, while the peak current is approximately twice the dc output current.

Transistor \( Q_1 \) operates with an approximately constant on-time, equal to the length of the resonant current pulse. The output power is controlled by variation of the transistor off-time, and hence the converter operates with a variable switching frequency. The rectifier requires an input filter, to remove the high-frequency components of the pulsating input current waveforms.

Another buck-type single-switch 3\(^{\circ}\)ac-dc rectifier [16,17] is illustrated in Fig. 8. This is a multiresonant rectifier, in which diodes \( D_1 - D_7 \) operate with zero voltage switching, while transistor \( Q_1 \) operates with zero current switching. Input capacitors \( \text{C}_r \) and dc-side waveforms.
capacitor \( C_{r2} \) form a resonant network, in conjunction with inductor \( L_r \). Inductors \( L_a \) and \( L_d \) operate in the continuous conduction mode, with small switching ripple. This converter exhibits nonpulsating input and output currents, and requires minimal additional filtering of the input current waveforms. This converter exhibits low EMI and low switching loss.

The phase \( a \) resonant capacitor voltage waveform \( v_{cd}(t) \) is illustrated in Fig. 5(e). This voltage is approximately sinusoidal, with peak amplitude proportional to the input current \( i_{d}(t) \). Approximate input resistor emulation is therefore obtained. The input current THD is a function of the value of \( L_a \); THD less than 4% can be obtained at full load. Transistor \( Q_f \) can be realized using an IGBT, SCR, or other device. The peak transistor voltage is typically twice the input line-to-line peak voltage. The dc load power is controlled by variation of the switching frequency.

A variety of other three-phase rectifier schemes having a reduced number of switches are known. In [18], a CCM PWM approach is described which requires only three active devices. An approach requiring two active devices which operate with zero-current switching is described in [19].

### 4. Comparison of six-switch vs. single-switch approaches

Consider an application in which it is desired to replace a phase-controlled rectifier system with a high-quality rectifier. It is therefore required that the output voltage be of variable and controllable magnitude, less than the peak input line-to-line voltage. Any of the approaches of Fig. 3 could be employed in this application; the buck topology of Fig. 3(a) is the simplest. The single-switch converters of Figs. 6-8 could also be employed. Let us compare the buck-derived single-switch rectifiers of Figs. 7 and 8 with the six-switch buck rectifier of Fig. 3(a).

The active switch blocking voltages and peak currents of the single-switch ZCS quasi-resonant buck rectifier (Fig. 7) and six-switch CCM buck rectifier (Fig. 3(a)) are compared in Tables 1 and 2, for a 25kW application [15]. The input voltage is 440Vac, and the load voltage and current are 370V and 67.5A, respectively. The total switch stress is also listed; this is defined as the product of the switch blocking voltages and peak currents, summed over all active switches in the converter. The switch stress is a measure of the total active silicon area required for realization of the converter. Also shown is the silicon utilization, defined as the converter output power divided by the total switch stress.

In the dc-dc case, the quasi-resonant switch approach is commonly thought of as restricted to low power applications, because of the increased peak switch stresses, poor switch utilization, and increased conduction losses. However, these arguments do not apply to the single-switch ZCS rectifier of Fig. 7, because the 2:1 increase in peak current due to resonant switching is more than offset by the 1:6 reduction in total active semiconductor area arising from the single-switch approach. The six-switch buck rectifier of Fig. 3(a) in Tables 3 and 4. The ac input voltage is 240V, and the load is 147V at 6kW - 0.6kW. The multiresonant rectifier exhibits the following advantages: (1) non-pulsating input currents, (2) very low input current THD (less than 4% has been demonstrated [17]), and zero voltage switching of all diodes.

### 5. Conclusions

Three-phase high-quality rectifiers can be derived from known dc-dc converter topologies. As a result, rectifiers sharing the properties of their parent dc-dc converters can be derived, including buck, boost, and...
buck-boost conversion ratios, as well as high-frequency transformer isolation. Both single-switch and six-switch 3ø inputs can be obtained. The single-switch approach utilizes the active semiconductor devices more effectively. Zero current switching of the active semiconductor devices, and zero voltage switching of diodes, can be obtained.

REFERENCES


Robert W. Erickson received the B.S., M.S., and Ph.D. degrees from the California Institute of Technology, Pasadena, CA, U.S.A., in 1978, 1980, and 1982, respectively. He then joined the Department of Electrical and Computer Engineering at the University of Colorado, Boulder, U.S.A., where he currently holds the rank of Associate Professor. He is the author of numerous conference and journal papers, as well as the soon-to-be-published textbook Fundamentals of Power Electronics.