



MODELING OF SIX-PULSE RECTIFIER OPERATING UNDER UNBALANCED SUPPLY CONDITIONS

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ABSTRACT

Modeling of the six-pulse rectifier bridge circuit, operating under practical operating conditions, when connected to an unbalanced three-phase supply is presented in this paper. The time domain model takes full account of system losses and supply impedance on circuit current and voltage waveforms, allowing for DC current ripple and the changing states of conduction of the converter devices. The analysis is valid for all types of loads and converter conduction modes, including mode 3 overlap when the angle of overlap extends beyond 60° and the number of conducting devices alternate between 3 and 4. The proposed results are very close to the simulation results.

Keywords: modeling, six-pulse rectifier, supply, balanced and unbalanced.

INTRODUCTION

In a large number of power electronics applications, including ac motor variable speed drives, static frequency converters, dc servo drives and so on, the ac power supply, in the form of the 50 or 60 Hz sine wave voltage provided by electric utility, is converted to a dc voltage using a six-pulse, three-phase diode bridge converter (Figure-1). Different models have been developed for this circuit operating under balanced [1-6] or unbalanced [7-9] supply conditions. The earliest analysis [1] presents an investigation onto the performance characteristics of mercury-arc rectifier allowing for the effects of supply reactance. An analytical time domain model of the bridge circuit allowing for the effects of supply impedance and the switching states of the converter devices has also been proposed [2], but the analysis ignored the effects of the dc load assuming an infinite value of dc side inductor.

A different analytical approach based on a frequency-domain analysis to calculate ac harmonic currents for both continuous [3] and discontinuous [4] dc current modes has also been proposed, taking into account the ac and dc side impedances. However, the derivation of the ripple part of the dc-link current in the above analysis is not an easy task. Also, the switching function defined in these models does not take the current commutation process into account [5]. A method to determine the harmonic distortion level produced by six-pulse thyristor bridge converter has also been proposed [6] taking into account the dc ripple content and the commutation process but assuming that the dc load is a constant dc source.

Another model to analyze the performance of the six-pulse diode bridge rectifier operating with balanced and unbalanced line voltages, based on the frequency domain and the switching function method, has also been proposed [7]. In this model, the dc current was assumed to be ripple-free and the commutation overlap angle was neglected. The method of symmetrical components has also been used to approximate the fundamental frequency characteristics of line-commutated converters during unbalanced operating conditions [8], ignoring the effects

of commutation overlap. Another study [9], presents a model for the six-pulse rectifier to estimate the emission of non-characteristic line harmonics in the presence of high DC current ripple. The commutation angle was again assumed to be neglected in this analysis.

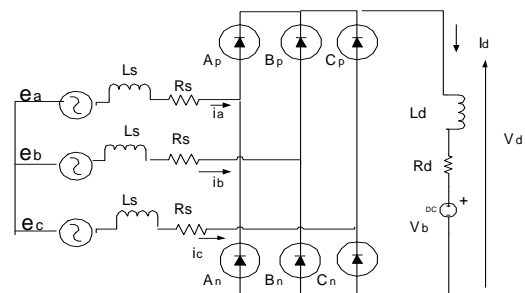


Figure-1. Three-phase bridge rectifier.

All published converter models are based on different simplifying assumptions, e.g. assuming that the effects of the dc current ripple or of the current commutation process in the bridge circuit were negligible. In this paper, a new analysis technique is proposed for modeling of the circuit behavior under balanced and unbalanced supply conditions. The proposed analysis, which may be applied to both balanced and unbalanced operating conditions, is based on time-domain methods and takes into account all circuit parameters with no simplifying assumptions including the effects of supply resistance and reactance, the voltage drops across the converter devices, the effects of commutation overlap including mode 2 and mode 3 overlap, the characteristics of the dc load and the changing topology of the effective converter circuit.

In the proposed method, the system is modeled without assuming a constant DC current (infinite inductance) or a constant dc voltage (infinite capacitance), but by solving the system differential equations for different diode conduction states allowing fully for the impedance of the load (inductive or capacitive), the



impedance of the supply (including supply resistance), diode voltage drops, and supply voltage unbalance. System differential equations are derived for each converter conduction state (i.e. based on the effective circuit as determined by which diodes are conducting) and then solved to obtain system currents, voltages, power flows, etc. On detecting a change in diode conduction states, a new set of differential equations needs to be solved, and so on.

Using Kirchoff's voltage and current laws to model converter circuits are normal and known since along time. But the proposed model uses this method with differences from old models. These differences could be summarized as follows:

- The proposed model takes into account all circuit parameters (V , R , L and C) with no major assumptions. These parameters are: The commutation angles where the proposed model uses the values without approximation. Also, it takes into account the drop on the valves (diodes, thyristors, IGBT, etc.) and does not assume them as ideal switches.
- The proposed model do not need to calculate commutation angle, which is the normal case in old models but rather than the conduction mode specified by conducted diodes.
- The model is valid not only for balanced system, which is the case in old models, but for unbalanced system too.
- It is easy to develop model equation for any parameters connected to the load, which most time difficult in old models.

POSSIBLE OVERLAP MODES

In the diode bridge, current cannot transfer immediately from one supply phase to the next because of supply inductance; the angle of overlap μ is determined by the time taken to complete commutation. As in many other diode applications where the source has high reactance, rectifier overlap can be prolonged and may extend into more complex modes [10].

In total, there are three possible overlap modes. Mode 1 overlap corresponds to the normal operation of the bridge circuit in which the commutation overlap angle μ is less than 60° and the number of conducting diodes alternates between two and three (while overlap is in progress). As the load, and hence the mean value of converter dc current, increases the circuit may move into mode 2 overlap operation where the value of commutation overlap angle μ remains constant at 60° and the number of conducting diodes at any time is always 3. Further increases in dc load current will move the bridge circuit into mode 3 overlap where μ is greater than 60° and overlap effectively starts before the previous commutation process has been completed. The number of conducting devices duration this overlap mode alternates between 3 and 4.

Mode-1. Conduction states and system equations

For mode 1 operation, the number of conducting diodes alternates between 2 and 3. Hence, there are twelve possible converter conduction states and one non-conducting state (state 0) in which no diode conducts, as can happen when the dc link current become discontinuous. Table-1 lists all possible conduction states and the conducting diodes in the upper and lower row of the converter as identified in Figure-1.

Table-1. Possible diodes conducting states for mode 1 overlaps.

Conduction state	Upper row	Lower row
1	C_p	B_n
2	A_p, C_p	B_n
3	A_p	B_n
4	A_p	C_n, B_n
5	A_p	C_n
6	B_p, A_p	C_n
7	B_p	C_n
8	B_p	A_n, C_n
9	B_p	A_n
10	C_p, B_p	A_n
11	C_p	A_n
12	C_p	B_n, A_n
0	None	None

The twelve conducting states fall into two types, each repeated cyclically six times. The odd numbered states occur when only two diodes conduct and overlap is not in progress. The even numbered states occur when three diodes conduct, i.e. with commutation still in progress. Transitions from one input state to the next depend on the relative magnitudes of supply voltages and the values of diode currents. Figure-2 shows the effective circuit during a conduction state in which only two diodes conduct (conduction state 1), shown for a converter feeding an inductive RL load. The diodes are modeled as a constant voltage V_f and resistance R_f in series. E_b is the dc load back emf.

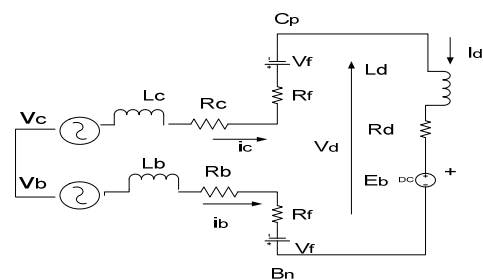


Figure-2. Effective converter circuit during conduction state 1 (mode 1 overlap).



Applying Kirchoff's voltage and current laws, the operation of the circuit may be represented by the following three equations:

$$i_a = 0 \tag{1}$$

$$i_b + i_c = 0 \tag{2}$$

$$(v_c - v_b) - [R_d + 2R_f + R_c + R_b + (L_d + L_c + L_b)p]i_c - (E_b + 2V_f) = 0 \tag{3}$$

Similarly, Figure-3 shows the effective circuit during a conduction state in which three diodes conduct (conduction state 2) and overlap is in progress between diodes A_p and C_p . Once again, the circuit may be represented by the following three equations:

$$i_a + i_b + i_c = 0 \tag{4}$$

$$(v_a - v_c) - (R_f + R_c + L_c p)i_c - (R_f + R_a + L_a p)i_a = 0 \tag{5}$$

$$(v_c - v_b) + [R_d + R_f + R_b + (L_d + L_b)p]i_b - (R_f + R_c + L_c p)i_c - (E_b + 2V_f) = 0 \tag{6}$$

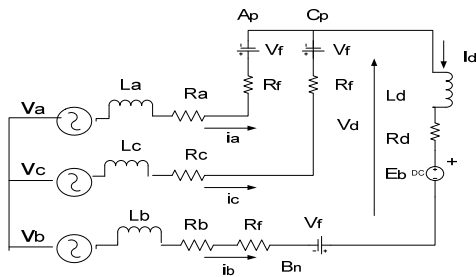


Figure-3. Effective converter circuit during conduction state 2 (mode 1 overlap).

Circuit equations for the remaining states could be written in the same way.

Mode-2. Conduction states and system equations

For mode 2 operation, three diodes conduct at all times resulting in a total of six possible conduction states corresponding to the overlap states during mode 1 operation, as listed in Table-2. System equations for these conduction states are of course identical to those describing the system's operation during mode 1 overlap states.

Table-2. Possible diodes conducting states for mode 2 overlap.

Conduction state	Upper row	Lower row
2	A_p, C_p	B_n
4	A_p	C_n, B_n
6	B_p, A_p	C_n
8	B_p	A_n, C_n
10	C_p, B_p	A_n
12	C_p	B_n, A_n

Mode-3. Conduction states and system equations

For mode 3 operation, the number of conducting diodes alternates between 3 and 4 and there are twelve possible converter conduction states as shown in Table-3. Conduction states 2, 4, 6, 8, 10 and 12 correspond to the normal overlap states and are described by the equations derived above (for example, equations 4-6 for state 2).

Table-3. Possible diodes conducting states for mode 3 overlap.

Conduction state	Upper diode	Lower diode
2	A_p, C_p	B_n
13	A_p, C_p	C_n, B_n
4	A_p	C_n, B_n
14	B_p, A_p	C_n, B_n
6	B_p, A_p	C_n
15	B_p, A_p	A_n, C_n
8	B_p	A_n, C_n
16	C_p, B_p	A_n, C_n
10	C_p, B_p	A_n
17	C_p, B_p	B_n, A_n
12	C_p	B_n, A_n
18	A_p, C_p	B_n, A_n

Figure-4 shows effective circuit conditions during state 17 during which diodes C_p, B_p, B_n and A_n are conducting. The three equations describing the operation of the circuit can similarly be derived by applying Kirchoff's law.

$$(v_c - v_b) - [R_c + 2R_f + R_b + (L_c + L_b)p]i_c + (R_b + L_b p)i_b - R_f I_d = 0 \tag{7}$$

$$(v_b - v_a) + (R_a + L_a p)i_a - (R_b + L_b p)i_b + R_f I_d = 0 \tag{8}$$

$$(E_b + 2V_f) - [(R_d + 2R_f) + L_d p]I_d + R_f i_a + R_f i_c = 0 \tag{9}$$

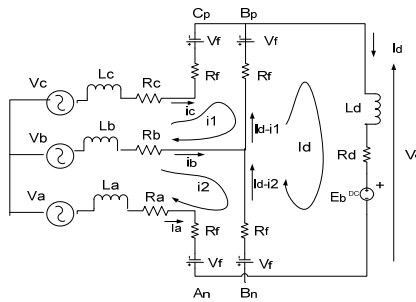


Figure-4. Effective converter circuit during conduction state 17 (mode 3 overlap).

CALCULATED WAVEFORMS

To verify the accuracy of the proposed model, calculated results obtained by the proposed model, which is written as m-file/MatLab, were compared with those obtained by using a time-domain simulation software package (MatLab/Simulink). To allow for supply unbalance, the three supply voltages are represented by the equation:

$$v_a(\omega t) = v_{s1} \cdot \sin(\omega t - \phi_a)$$

$$v_b(\omega t) = v_{s2} \cdot \sin(\omega t - 120 - \phi_b)$$

$$v_c(\omega t) = v_{s3} \cdot \sin(\omega t - 240 - \phi_c)$$

Other circuit parameters used in the calculation were as follows:

For balanced supply conditions;

$$v_{s1} = v_{s2} = v_{s3} = 50v, R_a = R_b = R_c = 0.836\Omega$$

$$E_b = 0, \phi_a = \phi_b = \phi_c = 0^\circ, L_d = 10\mu H,$$

$$R_d = 2.4\Omega,$$

$$V_f = 0.5\Omega, R_f = 0.5664\Omega, f = 50Hz$$

For unbalanced supply conditions;

$$v_{s1} = 50v, v_{s2} = 53v, v_{s3} = 48v, f = 50Hz,$$

$$R_a = R_b = R_c = 0.836\Omega, L_d = 10\mu H, \phi_a = 0^\circ,$$

$$\phi_b = 5^\circ, \phi_c = -5^\circ, E_b = 0, R_d = 2.4\Omega, V_f = 0.5\Omega,$$

$$R_f = 0.5664\Omega.$$

And for Mode-1 operation:

$$L_a = L_b = L_c = 1.6mH (\mu < 60^\circ)$$

And for Mode-2 operation: $L_a = L_b = L_c = 7.75mH$

And for Mode-3 operation: $L_a = L_b = L_c = 15mH$

Figure-5 Shows converter supply voltage and current waveforms calculated using the above analysis for mode 1 operation under balanced supply conditions. The current waveforms show very clearly the extended periods of

commutation overlap (because of the high value of supply impedance used in the calculation) and the effects of the dc current ripple on the ac current waveform. For comparison purposes, Figure-6 shows the same case calculated using Simulink. As may be seen from these figures, there is good agreement between the simulated and analytical results.

Calculated Mode 3 supply current waveforms under both balanced and unbalanced supply conditions are shown in Figures 7 and 8. During this mode of operation, the ac lines are effectively short circuited for large parts of the ac cycle because of the extended commutation process leading to the more sinusoidal looking supply current waveforms presented. Corresponding Simulink results are shown in Figures 9 and 10.

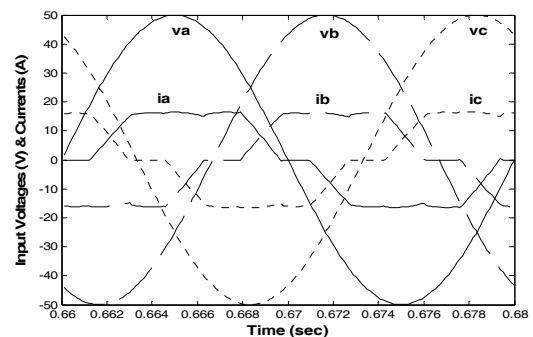


Figure-5. Calculated supply waveforms for balanced input conditions for Mode 1 operation (proposed model results).

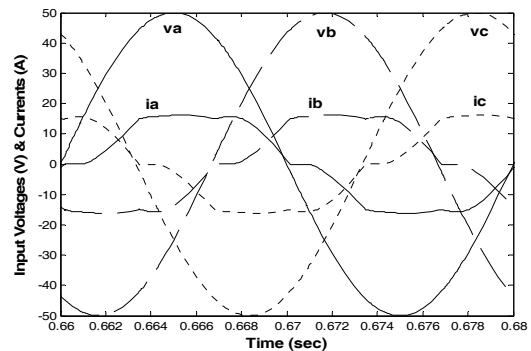


Figure-6. Simulated supply waveforms for balanced input conditions for Mode 1 operation (simulation model results).

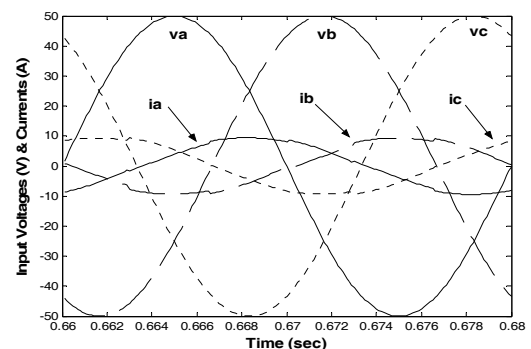


Figure-7. Calculated supply waveforms for balanced input conditions for Mode 3 operation (proposed model results).

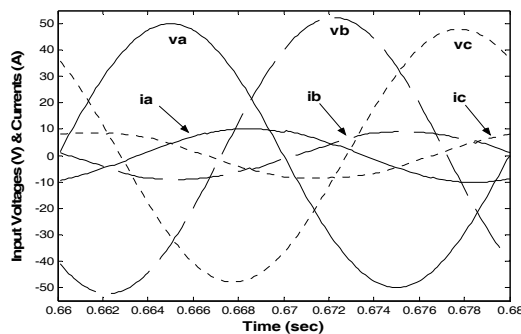


Figure-8. Calculated supply waveforms for unbalanced input conditions for Mode 3 operation (proposed model results).

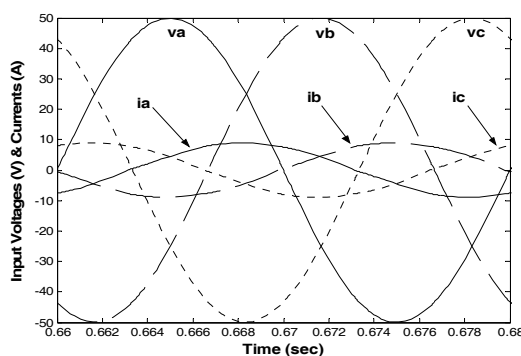


Figure-9. Simulated supply waveforms for balanced input conditions for Mode 3 operation (simulation model results).

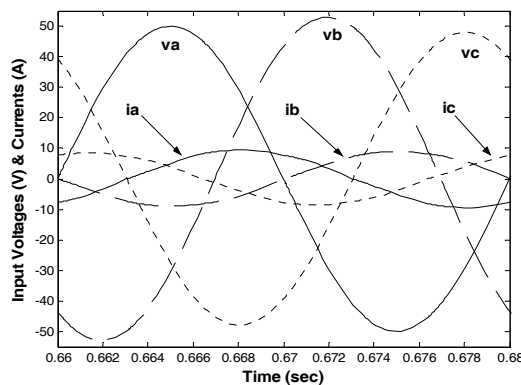


Figure-10. Simulated supply waveforms for unbalanced input conditions for Mode 3 operation (simulation model results).

CONCLUSIONS

Modeling and analysis of the converter bridge circuit, operating under practical operating conditions, when connected to an unbalanced three-phase supply is presented in this paper. The time domain model takes full account of system losses and supply impedance on circuit current and voltage waveforms, allowing for dc current ripple and the changing states of conduction of the converter devices, and is valid for all types of loads and converter conduction modes, including mode 3 overlap

when the angle of overlap extends beyond 60° and the number of conducting devices alternate between 3 and 4.

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