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Averaged Value Analysis of 18-Pulse Rectifiers for Aerospace Applications

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Abstract— **This paper describes the non-linear averaged value models for different configurations of an 18-pulse rectifier. The models allow rectifier and drive system interactions to be examined analytically, or through rapid simulation. The models are validated by comparison with a detailed circuit simulation.**

I. Introduction

Power electronic based power systems are increasingly being used in applications such as aircraft, spacecraft, hybrid-electric and electric vehicles and many more. In these multi converter power electronic systems, different converters are integrated together to form a complex and comprehensively interconnected system. The replacement of hydraulic and pneumatic systems in aircraft with electrical systems is known as the "More Electric Aircraft (MEA)". This concept is being used increasingly in the aerospace industry and is resulting in the growing and widespread use of electrical power and power electronic components and systems. More electric components and systems are expected to enhance reliability, fault-tolerance, power density and performance of aircraft systems. For example, many of the main pumps associated with fuel and lubrication are currently coupled directly to the engine. In the MEA approach these are likely to be driven by variable speed electrical drives with associated power electronic converters. Also, the use of new converter topologies with advanced power components as the power switches are predicted to increase system efficiency.

The MEA concept offers many advantages and benefits, however, increasing the number of power electronic loads will produce more complex electrical systems and consequently the possibility of interaction between loads and source, instability and the presence of harmonics will increase.

Due to their internal control functions, power electronic converters present 'constant power' characteristics to their supply. These types of loads are known as Constant Power Loads (CPLs). Since CPLs have negative incremental input impedance, there is a possibility of interaction, lightly damped oscillations and instability between the supply and the CPL, or between different CPLs sinking energy from one supply. This instability issue has led to the need for more thorough analysis of systems which are composed of multi-CPLs.

Over the past few years, there has been a significant amount of research on DC power distribution systems which contain tightly regulated converters. However, there are only a few papers published about AC systems which consist of rectifiers and constant power loads [2]. Using standard circuit simulation techniques to study the dynamic interaction between a single rectifier, DC link and CPL can be very demanding computationally due to the large number of diode commutations that must be calculated in a typical transient. As an alternative, averaged-value, DC-side models of the rectifier may be used. The dynamics of the resultant equivalent circuit may be either studied analytically, or used in a circuit simulator to reduce simulation times substantially. While the literature shows that averaged models of 6-pulse bridge rectifiers have been developed which are suitable for small signal analysis, ([3], [4], [5]) there is little information on the averaged models of multi-pulse rectifiers [6].

Integration of small systems to form large and complicated systems is vital for many applications. When two stable subsystems like two rectifiers with their CPLs are combined or integrated together, there is no guarantee that the combined system will be stable. There may be an interaction between the interconnected sub-systems which can result in instability, even when the sub-systems may be well designed for stand-alone operation. Another part of this research is concerned with the average modelling of different types of rectifiers with different pulse number and the interaction between them in an AC power system.

The literature survey begins with a general description of the averaged model of a general 18-pulse rectifier in section II. Section III describes the averaged value model of alternative 18-pulse rectifiers [1]. Comparison of models is in section IV. Modelling of multiple 18-pulse rectifiers are presented in section V and the paper concludes in section VI.

II. Averaged value model of a general 18-pulse rectifier

In this section we will describe the average value model of a generic 18- pulse rectifier. Figure 1 shows the schematic diagram of a general 18-pulse rectifier. The AC power supply is assumed to consist of three ideal, balanced voltage sources with 120° phase difference and three line inductors. The line-to-neutral voltages are expressed by the vector of v_s:

$$v_s = \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = V_m \cdot \begin{bmatrix} cos(\omega t) \\ cos(\omega t - 2\pi/3) \\ cos(\omega t + 2\pi/3) \end{bmatrix} \quad (1)$$

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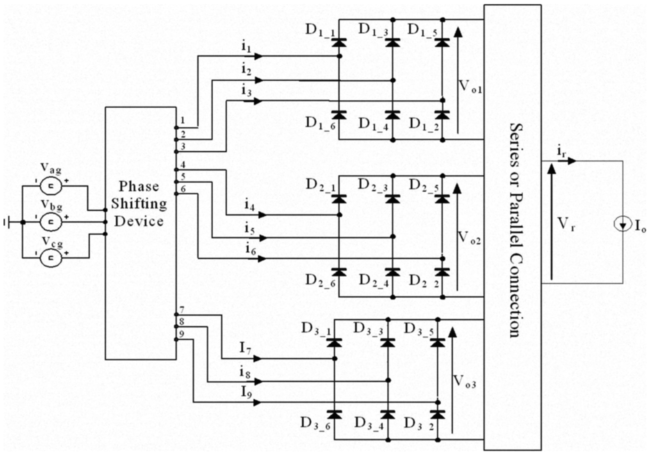

Fig. 1. A Generic 18-pulse rectifier

The transformer is a three-phase transformer with three three-phase output voltages, which have the same amplitude, and there is a 20 phase shift between them. The three six-pulse rectifiers are connected in series or parallel to feed a constant power load via a second-order DC link filter. The three equal inductors $L_{p1} = L_{p2} = L_{p3} = L_p$ represent the primary leakage inductances and the inductance of the supply lines. The inductors $L_{s1} = L_{s2} = L_{s3} = L_s$ represent the transformer secondary leakage serie's inductances. The forward resistance of the diodes and the resistance of the DC link inductor are included. The model is derived by averaging the state variables across each 20° portion of the supply waveform. Each 20° portion begins with an overlap transient as the DC link current commutates between diodes, whilst in the second part of the 20° interval only two diodes in each bridge are in conduction. A straight line is assumed between initial and final values of every phase current.
The output voltages of the 6 pulse rectifiers are V_1 and V_2 and V_3. The matrix equations of them are:

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = A_1 v_s - B_1 \frac{d}{dt}(i_1) - C_1 \frac{d}{dt}(i_2) - D_1 \frac{d}{dt}(i_3) \tag{2}$$

Where i_1, i_2 ,i_3 are vectors of the line currents of each rectifier.

$$i_1 = [I_1,\ I_2,\ I_3]^T \tag{3}$$

$$i_2 = [I_4,\ I_5,\ I_6]^T \tag{4}$$

$$i_3 = [I_7,\ I_8,\ I_9]^T \tag{5}$$

The matrixes A_1, B_1, C_1, and D_1, are coefficient matrixes and the values of them depend on the type of three-phase transformer and the system analysis interval and can be easily obtained as described in [11].

The rectifier output voltage equation is obtained by summation of V_1, V_2, and V_3 for serial configuration. However, for parallel configuration, because of the interphase reactor(s), the output voltage is average of V_1, V_2, and V_3, and the effect of interphase reactor leakage inductance(s) will appear as an inductance in series with the rest of the circuit. Therefore a general equation for V_r is:

$$V_r = A \cdot v_s - B\frac{d}{dt}(i_1) - C\frac{d}{dt}(i_2) - D\frac{d}{dt}(i_3) - E\frac{d}{dt}(i_L) \tag{6}$$

Where i_L is the DC load current. The matrixes A, B, C, and D are also the coefficient matrixes, and as it is mentioned before the values of them depend on the three-phase transformer and the system analysis interval and value of E depends on the connection type of bridges outputs and the number of interphase reactors.

The average output voltage of $\overline{V_r}$ is determined by integrating 6 over one of its switching intervals, which is 20° and it is between $\theta_1 < t < \theta_2$.

$$\begin{aligned} \overline{V_r} &= \frac{1}{\pi/9}\int_{\theta_1}^{\theta_2}(Av_s)d\theta - B\frac{[i_1(\theta_2) - i_1(\theta_1)]}{\Delta t} - C\frac{[i_2(\theta_2) - i_2(\theta_1)]}{\Delta t} \\ &- D\frac{[i_3(\theta_2) - i_3(\theta_1)]}{\Delta t} - E\frac{d}{dt}(i_L) \end{aligned} \tag{7}$$

$$\begin{aligned} \overline{V_r} &= \frac{1}{\pi/9}\int_{\theta_1}^{\theta_2}(Av_s)d\theta - \frac{9\omega}{\pi}B\begin{bmatrix} i+\Delta i \\ -i \\ -\Delta i \end{bmatrix} - \frac{9\omega}{\pi}C\begin{bmatrix} -\Delta i \\ 0 \\ \Delta i \end{bmatrix} \\ &- \frac{9\omega}{\pi}D\begin{bmatrix} -i \\ -\Delta i \\ i+\Delta i \end{bmatrix} - E\frac{d}{dt}(i_L) \end{aligned} \tag{8}$$

Where $\Delta t = \frac{\pi}{9\omega}$ and $\frac{d}{dt}(i_L)$ is the local rate of change of the DC-link current. It is assumed the DC load current is i_L at the beginning of this time interval and there is a small linear Δi change at the end of it. Δi denotes the change in average current over $\frac{\pi}{9}$ period and is approximated as $\Delta i \approx \frac{di}{dt} \cdot \Delta t = \frac{\pi}{9\omega}\frac{di}{dt}$. The current values of the bridge lines at this interval are the same for every configuration if the conducting interval is chosen in that manner which it starts at θ_1 when a current transfer is started from $D1-1$ to $D1-3$, and finishes at θ_2 when a current transfer is started from $D3-2$ to $D3-6$.

TABLE I

THE VALUES OF LINES CURRENT OF TWO BRIDGES AT THE $\theta_1 < \alpha < \theta_2$ INTERVAL

	θ_1	θ_2
$I(L_1)$	0	$i+\Delta i$
$I(L_2)$	i	0
$I(L_3)$	$-i$	$-i-\Delta i$
$I(L_4)$	$-i$	$-i-\Delta i$
$I(L_5)$	0	0
$I(L_6)$	i	$i+\Delta i$
$I(L_7)$	i	0
$I(L_8)$	$-i$	$-i-\Delta i$
$I(L_9)$	0	$i+\Delta i$

The averaged output voltage of every configuration is attainment by substituting the values of Table 1 into integration of (8) and simplifying.

$$\overline{V_r} = \frac{1}{\pi/9}\int_{\theta_1}^{\theta_2}(Av_s)d\theta - \frac{\pi}{9\omega}B\begin{bmatrix} i+\frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt} \\ -i \\ -\frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt}\end{bmatrix} - \frac{\pi}{9\omega}C\begin{bmatrix} -\frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt} \\ 0 \\ \frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt}\end{bmatrix} - \frac{9\omega}{\pi}D\begin{bmatrix} -i \\ -\frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt} \\ i+\frac{\pi}{9\omega}\frac{d\bar{i}_r}{dt}\end{bmatrix} - E\frac{d}{dt}(i_L) \quad (9)$$

$$\overline{V_r} = \frac{9\omega}{\pi}A\int_{\theta_1/\omega}^{\theta_2/\omega} v_s dt - \frac{9\omega}{\pi}\overline{i_r}(k_0L(B)\begin{bmatrix}1\\-1\\0\end{bmatrix} + k_0LD\begin{bmatrix}-1\\0\\1\end{bmatrix}) - (k_0L(B\begin{bmatrix}1\\0\\-1\end{bmatrix} + C\begin{bmatrix}-1\\0\\1\end{bmatrix})) + (k_0LD\begin{bmatrix}0\\-1\\1\end{bmatrix} + E)\frac{d\overline{i_r}}{dt} - (k_0r(B\begin{bmatrix}1\\0\\-1\end{bmatrix} + D\begin{bmatrix}0\\-1\\1\end{bmatrix}))\overline{i_r} \quad (10)$$

The values of A, B, C, D, and E depend on the configurations. Note that for series connections $k_0 = 1$ and for parallel connections, $k_0 = 0.33$.

III. AVERAGED VALUE MODEL OF ALTERNATIVE 18-PULSE RECTIFIERS

A. Serie Y/ZYZ connection

When a Y/ZYZ transformer is used as the phase shifting device, the values of θ_1, and θ_2 are $7\pi/18$ and $\pi/2$ respectively for the 20° interval that starts with the commutation from D1-1 to D1-3. In a series connection an inter-phase reactor is not required, so the constant $k_0 = 1$ and $D = 0$. The expressions for the terms in equation (10) are listed in table II. Substituting these values into (10) will lead us to $\overline{V_r}$:

TABLE II
REQUIRED PARAMETERS FOR SERIES Y/ZYZ CONNECTION

$k_0 = 1$	Series Y/ZYZ
A	$[\frac{0.83}{\sqrt{3}} \quad (1+\frac{2}{\sqrt{3}}) \quad -(1+\frac{0.83}{\sqrt{3}})]$
B	$[\frac{2L_p}{\sqrt{3}} \quad ((1+\frac{0.83}{\sqrt{3}})L_p+L_s) \quad -((1+\frac{1}{\sqrt{3}})L_p+L_s)]$
C	$[\frac{-2L_p}{\sqrt{3}} \quad ((1+\frac{1}{\sqrt{3}})L_p+L_s) \quad -((1+\frac{0.82}{\sqrt{3}})L_p+L_s)]$
E	$[\frac{2L_p}{\sqrt{3}} - (1+\frac{1}{\sqrt{3}})L_p \quad (1+\frac{0.83}{\sqrt{3}})L_p \quad -(1+\frac{1}{\sqrt{3}})L_p]$
θ_1, θ_2, D, i	$\frac{7\pi}{18} \quad \frac{\pi}{2} \quad 0 \quad i_L$

$$\overline{V_r} = \frac{9\sqrt{3}nV_m}{\pi} - [8(1+\frac{\sqrt{3}}{2})n^2L_p + 6L_s]\frac{d\overline{i_r}}{dt} - [\frac{9\omega n^2(L_p+L_s)}{\pi}(1+\frac{\sqrt{3}}{2}) + 6(1+\frac{\sqrt{3}}{2})n^2r_p + 6r_s]\overline{i_r} \quad (11)$$

Figure 2 shows the NLAM of the circuit. The resistors in the model represent the overlap effects and the inductors are the coefficients of the first terms of the Taylor series of the load current.

$$\begin{aligned} V_{eq} &= \frac{9\sqrt{3}n}{\pi}V_m \\ R_{eq} &= \left[\left(\frac{9\omega n^2(L_p+L_s)}{\pi}\right)(1+\frac{\sqrt{3}}{2}) + 6(1+\frac{\sqrt{3}}{2})n^2r_p + 6r_s\right] \\ L_{eq} &= 8\left[\left(1+\frac{\sqrt{3}}{2}\right)n^2L_p + 6L_s\right] \end{aligned} \quad (12)$$

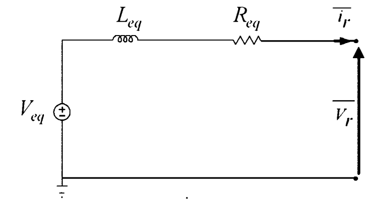

Fig. 2. Averaged value model of a series 18-pulse rectifier with Y/ZYZ transformer and constant power load

Figure 5-i shows the detailed simulation of DC-link capacitor voltage and inductor current of a 18-pulse Y/ZYZ series-connected rectifier.

B. Parallel Y/ZYZ connection

When the three rectifiers are connected in a parallel (doubly-wound, transformer-based, 18-pulse rectifier), an IPR is required to support the instantaneous voltage difference in the three outputs. Figure 4 shows the diagram of the parallel, doubly-wound transformer-based, 18-pulse rectifier. The overall transformer turns ratio is again assumed to be $1:n$.

Because of the IPR, the diode bridges will ideally, share the load current. Therefore, the constant k_0 in (10) has the value 0.33 and D in (10) is equal to L_{ipr} (The leakage inductance of the IPR). The expressions for the terms in equation (10) are listed in table III. Substituting these values into (10) will lead us to $\overline{V_r}$.

TABLE III
REQUIRED PARAMETERS FOR PARALLEL Y/ZYZ CONNECTION

$k_0 = 0.33$	Parallel Y/ZYZ
A	$[\frac{1}{0.83\sqrt{3}} \quad \frac{1}{0.82}(1+\frac{1}{\sqrt{3}}) \quad -\frac{1}{0.82}(1+\frac{2}{\sqrt{3}})]$
B	$[\frac{L_p}{\sqrt{3}} \quad ((1+\frac{1}{\sqrt{3}})\frac{L_p}{2}+\frac{L_s}{2}) \quad -((1+\frac{0.82}{\sqrt{3}})\frac{L_p}{2}+\frac{L_s}{2})]$
C	$[\frac{-L_p}{2\sqrt{3}} \quad ((1+\frac{2}{\sqrt{3}})\frac{L_p}{2}+\frac{L_s}{2}) \quad -((1+\frac{1}{\sqrt{3}})\frac{L_p}{2}+\frac{L_s}{2})]$
E	$[\frac{2L_p}{\sqrt{3}}+\frac{0.83}{\sqrt{3}} \quad (1+\frac{0.83}{\sqrt{3}}) \quad -(1+\frac{0.33}{\sqrt{3}})]$
θ_1, θ_2, D, i	$\frac{7\pi}{18} \quad \frac{\pi}{2} \quad L_{sr} \quad i_L/3$

The expression for $\overline{v_r}$ has the same form as (11) for the series connected rectifier, but with small differences. The parameters of the equivalent circuit are listed in (13).

$$\begin{aligned} V_{eq} &= \frac{9\sqrt{3}n}{2\pi}V_m \\ R_{eq} &= \frac{9\omega(n^2L_p+L_s)}{4\pi} + \left[\frac{3}{2}n^2L_p\left(1+\frac{\sqrt{3}}{2}\right) + \frac{3}{2}L_s\right] \\ L_{eq} &= \left[\frac{3}{2}n^2L_p\left(1+\frac{\sqrt{3}}{2}\right) + \frac{3}{2}L_s\right] + L_{ipr} \end{aligned} \quad (13)$$

Figure 5-ii shows the detailed simulation of DC-link capacitor voltage and inductor current of a 18-pulse Y/ZYZ parallel-connected rectifier.

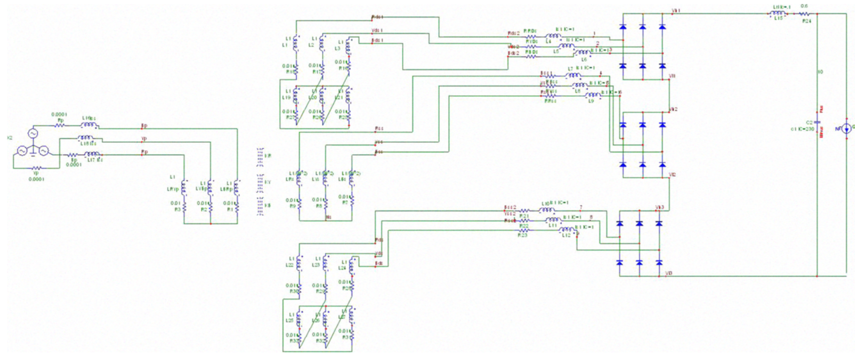

Fig. 3. A Series-connected output 18-pulse rectifier with an ideal Y/ZYZ transformer and constant power load

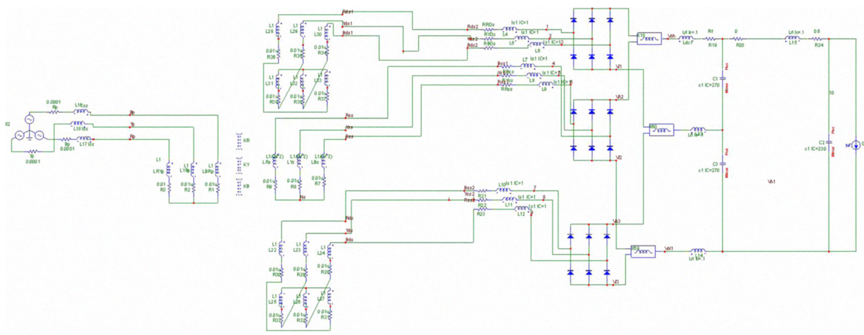

Fig. 4. A Parallel-connected output 18-pulse rectifier with an ideal Y/ZYZ transformer and constant power load

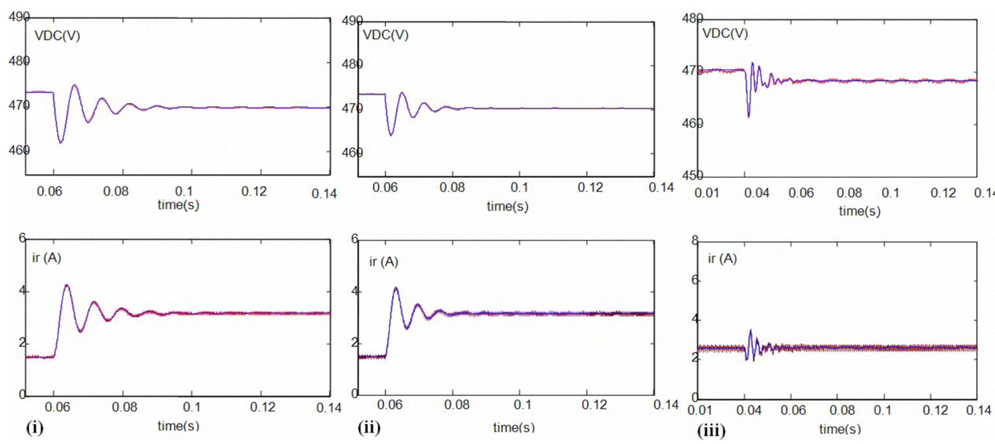

Fig. 5. Averaged value calculation and detailed simulation of DC-link capacitor voltage and inductor current of a 18-pulse (i)Y/ZYZ serie-connected rectifier(ii)Y/ZYZ parallel-connected rectifier (iii) Autotransformer-based rectifier using Micro-Cap 7 (detailed simulation (red), averaged model (blue))

C. Autotransformer-based 18-pulse rectifier

Figure (6) shows a schematic diagram of an autotransformer based 18-pulse rectifier. The source voltages are according to 1. Every L_p is sum of the source inductance and transformer primary leakage inductances and every L_s represents an autotransformer secondary leakage inductance. The interphase reactors are modelled by two L_{sr} inductors, which represent the leakage inductances and an ideal autotransformer. The turn ratio of autotransformer is $k = 9.822$ to create required voltages for three phase bridges [1]. The method of averaging of this type of rectifier is similar to a Y/ZYZ based 18-pulse rectifier. The output of every interphase reactor is the average of its input voltages. Therefore, the output voltage of the rectifier before the second order filter is according to 14.

$$\begin{aligned}\overline{V_r} &= \frac{18\sqrt{3}}{\pi} sin(\frac{\pi}{18})V_m + - \left[\frac{9\omega}{4\pi}\left(\frac{3}{2}\left(1-\frac{3}{k}\right)L_p + L_s\right)\right]\overline{i_r} \\ &- \left[3L_p + \frac{3}{2}L_s + 3L_{ipr}\right]\frac{\overline{di_r}}{dt} - \left[3r_p + \frac{3}{2}r_s\right]\overline{i_r} \qquad (14)\end{aligned}$$

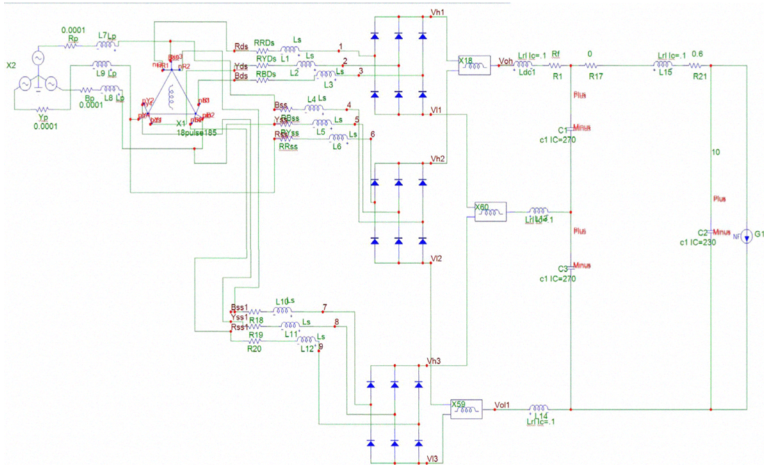

Fig. 6. Autotransformer based 18-pulse rectifier with a constant power load

TABLE IV
REQUIRED PARAMETERS FOR AUTOTRANSFORMER CONNECTION

$k_0 = 0.33$	Parallel Y/ZYZ
A	$[\frac{1}{2}\left(1+\frac{1}{0.82}\right) \quad \frac{1}{2}\left(1+\frac{1}{0.82}\right) \quad -\left(1+\frac{1}{0.82}\right)]$
B	$[\frac{2L_p}{0.82} \quad ((1+\frac{1}{0.82})L_p+\frac{L_s}{2}) \quad -((1+\frac{1}{0.82}L_p+\frac{L_s}{2})]$
C	$[\frac{-2L_p}{0.82} \quad -((1+\frac{1}{0.82})L_p+\frac{L_s}{2}) \quad ((1+\frac{1}{0.82})L_p+\frac{L_s}{2})]$
E	$[\frac{-0.33L_p}{\sqrt{3}} \quad (1+\frac{2}{\sqrt{3}})L_p+L_s \quad -((\sqrt{3}+\frac{0.82}{\sqrt{3}})L_p+L_s]$
θ_1, θ_2	$\frac{\pi}{3}-\frac{\pi}{18} \quad \frac{\pi}{2}-\frac{\pi}{18}$
D, i	$3L_{sr} \quad i_L/3$

Which means:

$$\begin{aligned} V_{eq} &= \frac{18\sqrt{3}}{\pi} sin(\frac{\pi}{18})V_m \\ R_{eq} &= -\left[\frac{9\omega}{4\pi}\left(\frac{3}{2}\left(1-\frac{3}{k}\right)L_p+L_s\right)\right]-\left[3r_p+\frac{3}{2}r_s\right] \\ L_{eq} &= -\left[3L_p+\frac{3}{2}L_s+3L_{ipr}\right] \end{aligned} \quad (15)$$

Figure 5-iii shows the detailed simulation of DC-link capacitor voltage and inductor current of an Autotransformer based 18-pulse rectifier.

IV. Comparison of Models

Comparing the averaged models for the three transformer coupled rectifiers (Table II and Table III) it is seen that the no load voltage is doubled in the series-connected configuration for the same transformer turn ratio n, and the effects of the primary and secondary inductances are four times larger. However, for the parallel-connected rectifier the leakage inductance of the IPR provides an additional series inductance in the equivalent circuit.

Comparing the averaged model of the three parallel connected rectifiers of Table III and Table IV; if the voltage ratio of the doubly-wound transformer n is set to unity, the no-load output voltages are slightly different, the voltage is $\frac{1}{cos(\pi/18)}$ higher for the autotransformer-based system, which is the output-to-input voltage ratio of the autotransformer. Also, in the autotransformer-based circuit the values of the series inductance and overlap resistance terms are both $\frac{1}{cos^2(\pi/18)}$ bigger than in the doubly-wound case. This suggests that the model for the autotransformer-based rectifier is a special case of parallel-connected rectifier model, with the turns ratio n set to $\frac{1}{cos(\pi/18)}$. However, in next section it will be shown that there are important differences between the two rectifiers in terms of the way they interact in multi-rectifier systems. In addition the autotransformer-based system has increased output impedance due to the requirement for three inter-phase reactors.

V. Multiple 18-pulse Rectifiers

In systems that consist of more than one rectifier, it is necessary to include in the analysis the interaction effects between rectifiers. In this section the interaction between multiple 18-pulse rectifiers of the same type is considered. The averaged model of a single 18-pulse rectifier has been analyzed in the previous section. In this part a system consisting of several autotransformer-based 18-pulse rectifiers is studied. A similar analysis may be undertaken for any other group of 18-pulse rectifiers, which are all of the same type.

A. System description

Figure 7 shows a system that consists of two autotransformer-based 18-pulse rectifiers. Each rectifier supplies a separate constant power load through a second-order DC link filter. The constant power load is realized using a tightly regulated DC-DC converter with a resistive load. Three ideal AC sources, along with three inductors and three resistors , model the supply.

B. Averaged equivalent circuit model

Figure 8 shows a simplified averaged DC model of the system that is shown in Fig 7. The expressions for the component values in the equivalent circuit are given in (16).

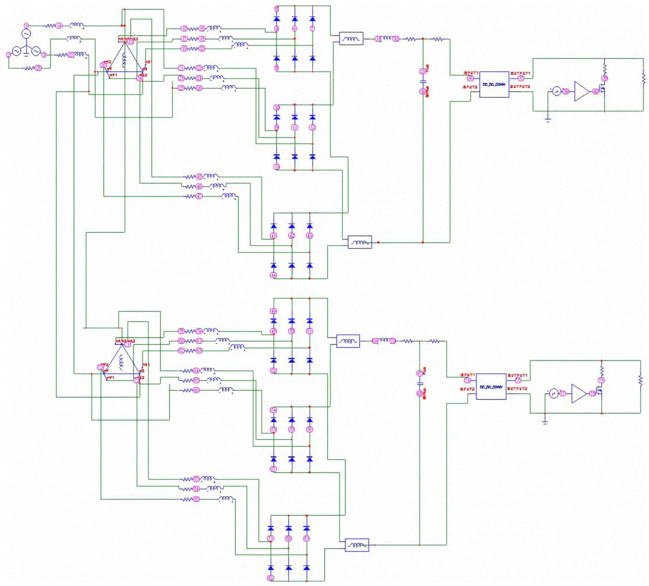

Fig. 7. A system consisting of two autotransformer-based, 18-pulse rectifiers

The equivalent circuits of the two rectifiers were combined by separating the elements in the equivalent circuit that depend on the common source impedance terms, L_p and r_p and connecting the equivalent circuits together at this point.

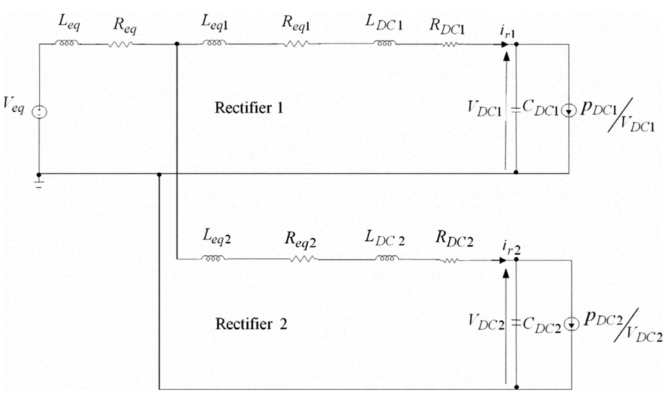

Fig. 8. Averaged value model of the system consisting of two autotransformer based 18-pulse rectifiers

$$
\begin{aligned}
V_{eq} &= \frac{18\sqrt{3}V_m}{\pi} sin(\frac{\pi}{18}),\ R_{eq} = \frac{9\omega}{2\pi}(1-\frac{3}{k})L_p + 3r_p \\
L_{eq} &= 3L_p,\ R_{eq1} = \frac{9.8\omega}{2\pi}(1-\frac{3}{k})L_{p1} + \frac{9\omega}{4\pi}L_{s1} + 3r_{p1} + 3r_{s1} \\
L_{eq1} &= 3L_{p1} + 1.5L_{s1} + 3L_{ipr1} \\
R_{eq2} &= \frac{9.8\omega}{4\pi}(1-\frac{3}{k})L_{p2} + \frac{15\omega}{4\pi}L_{s2} + 3r_{p2} + 3r_{s2} \\
L_{eq2} &= 3.7L_{p2} + 1.57L_{s2} + 3.1L_{ipr2}, k = 9.822
\end{aligned} \quad (16)
$$

VI. Conclusion

DC-side, averaged-value models have been derived for three common 18-pulse rectifiers, the autotransformer configuration being of particular interest for size/weight critical applications such as in the more-electric aircraft. The models of the three rectifiers are seen to have strong similarities, for example the model of the autotransformer-based rectifier is seen to be a special case of the parallel-connected, 18-pulse rectifier with a transformer turns ratio of $\frac{1}{cos(\pi/18)}$, however in addition a second IPR is required in the autotransformer circuit. The models have been validated by comparison with detailed simulations. It has also been seen that the individual equivalent circuit models may be straightforwardly coupled together to examine the behavior of systems that consist of multiple rectifiers of the same type.By means of this averaging method the complexity of a rectifier based system model is reduced without any serious change in state space condition of the whole system. Therefore, this method of modelling can be very useful in analysis and design of a system with a number of rectifiers with high pulse conversion.

References

[1] S. Choi, P. N. Enjeti, I. J. Pitel, *Polyphase Transformer Arrangements with Reduced KVA Capacities for Harmonic Current Reduction in Rectifier-Type Utility Interface*, IEEE Transactions in power Electronics Vol. 11, No. 5, Sep. 1996, pp. 680–690.

[2] J. T. Alt, S. D. Sudhoff, *Average Value Modelling of Finite Inertia Power System With Harmonic Distortion*, 2000 SAE Transactions , Journal of Aerospace, section 1, pp.932-946.

[3] S. D. Sudhoff, O. Wasynczuk, *Analysis and Average Value Modelling of Line-Commutated Converter Synchronous Machine System*, IEEE Tran. on Energy Conversion, Vol.8, No.1, March 1993, pp. 92-99.

[4] S. D. Sudhoff, *Waveform Reconstruction From The Average Value Model of line-Commutated Converter Synchronous Machine System*, IEEE Trans. on Energy Conversion, Vol. 8, No. 3, September 1993, pp.404-410.

[5] S. D. Sudhoff, *Analysis and Average Value Modelling of Dual Line-Commutated Converter 6-phase Synchronous Machine Systems*, IEEE Tran. on Energy Conversion, Vol.8, No.3, September 1993, pp. 411-417.

[6] A. Baghramian, A. J. Forsyth, *Averaged-value models of twelve-pulse rectifiers for aerospace applications*, PEMD 2004, Vol. 1, pp. 220–225.

[7] D. A. Paice, *Power Electronic Converter Harmonics, Multi-pulse Method for Clean Power*, IEEE press, Piscataway, NJ, 1996.

[8] K. Furmanczyk, M. Stefanich, *Demonstration of very high power airborne AC to DC converter*, SAE Power System Conference, Reno, Nevada, Nov. 2-4, 2004.

[9] F. J. Chivite-Zabalza, A. J. Forsyth, D. R. Trainer, *Analysis and practical evaluation of an 18-pulse rectifier for aerospace applications*, Proceedings of the Second International Conference on Power Electronics, Machines and Drives,2004, vol 1. pp. 338-343.

[10] K. Furmanczyk, M. Stefanich, *Demonstration of very high power airborne AC to DC converter*, SAE Power System Conference, Reno, Nevada, Nov. 2-4, 2004.

[11] A. Baghramian, *Modeling and analysis of multi-pulse rectifier systems*, PhD Thesis 2006, University of Birmingham.