A SIMULATION COMPUTER PROGRAM FOR FULL WAVE BRIDGE RECTIFIER

برنامج حاسوب لتمثيل المغزيات المركبة والقطرية التكوين

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Abstract:

The ready availability of inexpensive and reliable silicon controlled rectifiers has enabled system designer to utilize rectifier bridge circuit in an ever increasing number of applications. This has led to the development of complex circuit-configurations consisting of multiple six pulse bridge converters.

This paper establishes a digital computer simulation of the widely used three phase full- wave controlled rectifier bridges. The program is intended to simulate multiple six – pulse bridges connected in series. The proposed method is based on the mathematical description of converter electromagnetic processes, using step – by – step numerical calculation.

The currents flow in the rectifying elements, in the DC and AC side of the bridge are determined, also the output DC voltage is evaluated. The analysis considered for a group of rectifiers supplying an inverter. The program permits evaluation of the voltage and current for various variations in the system parameters.

KEY WORDS
High voltage Dc, transmission, converters, rectifiers, computer simulation

Introduction:

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The circuit of three phase six-pulse bridge converter is the most frequently type employed in industrial applications. For high power conversion systems, there is a complex circuit configuration consisting of multiple six pulse bridge converters connected in various series and parallel arrangement. Such systems utilize multi-winding transformers which effect phase shifts between the six pulse bridges to reduce the AC and DC side harmonic content.

Mathematical simulation permits us to achieve without particular difficulty immediate numerical solutions to problems using differential equations which describe the behaviour of converters. In this simulation we can use either a digital computer which has almost unlimited algorithmic possibilities and high accuracy solutions, or analog computer in these respects.

An analog computer simulation of full wave controlled rectifier bridges has been reported in references [1-3]. Another method is proposed for valve converter simulation by an analog model which practically eliminates the short circuit occurrence due to dissimilarity of power and low-power valves, and a cascade-bridge valve converter model developed on this basis is shown in reference [4]. A new calculation approach with typical results obtained from a computer program is presented in reference [5]. This approach depends on the formulation of a periodically variable network topology with an appropriate computation efficiency for complex converter arrangements. The High Voltage DC. 12-pulse converter can be treated as a piece-wise linear configuration, this permits to have a computer program with a flexible and rapid convergence – characteristics of calculations [6].

The addition of an external commutating inductor and two clamp diodes to the phase shifted PWM (pulse width modulation) full-bridge DC/DC converter substantially reduces the switching losses of the transistors and the rectifier diodes, under all loading conditions [7]. Another paper introduce special modifications to the basic Dommel algorithm to expedite simulation of systems including arbitrary configurations of individual power-electronic switching devices. The techniques have been implemented in a prototype transients simulation program.[8]

A new type of AC/AC power converter is proposed. In contrast to the matrix converter, which requires bidirectional switches, the proposed converter consists of only unidirectional switches such as insulated gate bipolar transistors. The converter has a unity input displacement power factor, and its input line current waveform is similar to that of a diode rectifier with a DC-link inductor [9]. Another paper proposes a new digital multiple feedback control scheme for uninterruptible power supplies (UPS) using single-phase half-bridge inverter. The control scheme, which simple and can be designed easily, offers improved performance over the traditional deadbeat control, especially with non-linear load [10].

An attractive approach for realizing high-frequency power conversion at power levels greater than 100 KW have been introduced with a full-bridge DC-DC converters with one soft-switched leg and one hard-switched leg. A new variable-frequency multimodal control strategy for these converters for obtaining optimal operating characteristics was presented [11]. It appears that of all the proposed resonant techniques the well-known phase-shifted full bridge converter remains one of the most attractive because it offers an easy way of achieving ZVS with a minimum of extra components added, which is essential for the high power work [12].

In a recent paper a family of algorithms are described, with varying levels of computational complexity, for accounting such switching events in digital simulations. The proposed algorithms are applicable for both off-line and real-time simulations[13].
In this paper, the simulation of the three–phase full–wave bridge rectifiers is developed on a digital computer. The program permits the study of currents and voltages on both AC and DC sides, for a converter unit consisting of five six-pulse rectifier bridges. The effect of different values of the system components and parameters on the voltage and current can also be evaluated using this program. The converter unit supplies an inverter which is represented by an electromotive force.

The proposed method is based on the mathematical description of converter electromagnetic processes by formulation of a periodically variable network topology and using step-by-step numerical calculation. This method improves the computation efficiency and produces satisfactory results at a modest computer cost for complex convector arrangements.

**Basic circuit model:**

The converter arrangement shown in Figure (1) is a complex converter system. This type of circuit incorporates the feature of high voltage system, namely multiple series bridges.

![Figure (1): Complex converter system](image)

This converter unit supplies a load consisting of an electromotive force in series with a resistance and an inductance. The electromotive force represents a naturally commutated inverter unit, while the $R_d$-$L_d$ parameters ($R_d$-$L_d$ represents Equivalent resistance of the DC side in ohm, and Equivalent inductance of the DC side in henry) represent the smoothing reactor and the DC transmission line.

A simplified diagram of the basic three phase six-pulse full wave fully controlled bridge rectifier considered in this paper, is given in figure (2). This system consisted of a strong three phase power source, a rectifier transformer, a full wave fully controlled bridge rectifier, a smoothing reactor, a line resistance and a back – electromotive force.
In the analysis, the following assumptions are made:

1. The magnetizing current component in the rectifier transformer can be neglected, only leakage inductances are taken into account.
2. Thyristors are represented by a series of logic statement which control an ideal switch. Conduction occurs with the presence of positive forward voltage and firing pulse and/or when the forward current exceeds the thyristor latching current.
3. The triggering of the thyristor also initiates the commutation of second thyristor which is already conducting on the same side of the same bridge. But the extinction of this second thyristor occurs only after the current, passing through it, has fallen to a value less than the holding current (approximately zero value and tends to reverse in direction).
4. During normal operating modes (overlap angle $\mu < 60^\circ$), current is conducted in different positive and negative legs of the bridge. With $\mu > 60^\circ$, both arms of the same leg may conduct simultaneously and the output voltage during these intervals should be zero.
5. The firing pulses may be considered equidistant pulses or nonsymmetrically spaced pulses.
6. The power source may be considered as a set of balanced or unbalanced sinusoidal three phase voltages.
7. Phase shift between the AC voltages applied to the bridges is considered.
8. The thyristors firing sequence is 4-3-5-1-6-2.

**System equations:**

Each bridge has six valves and each valve contains N thyristors in series. In the simulation, the valve is represented by an equivalent thyristor which is defined by:

1. Its residual voltage, this is the voltage across the valve terminals during the conduction stage, $V_{th}$.
2. Its holding current $i_h$ (i.e. the minimum value to flow).
3. The firing angle of the thyristors $\alpha$ (degree)
4. The conduction period of the valve.

The theory of superposition is applied to represent the load connected to the bridge. The total value of the inductance and the resistance on the DC side are considered, while the back-electromotive force is divided by the number of bridges connected in series.
The problems and their solutions are best explained in the context of a specific two six-pulse Greatz bridges connected together in series. The transformer connection of the first bridge is star-star, while it is star-delta connection for the second bridge. This ensures that there is a 30 degrees phase shift between the line AC voltages across the two bridges.

The equations which describe the electromagnetic processes shown in figure (2) may be expressed in the following sections

1. Bridge applied AC voltages:

The secondary line voltage of the star connected transformer is given by:

\[
\begin{align*}
  v_i(1) & = U_i \sin(wt + \theta_i) \\
  v_i(2) & = U_i \sin(wt + \theta_i - 2\pi/3) \\
  v_i(3) & = U_i \sin(wt + \theta_i - 2\pi/3)
\end{align*}
\]

Where \( \omega \) is supply voltage angular frequency; \( \theta_i \) is the voltage phase shift referred to the origin.(degree)

The phase shift between the secondary voltages of the two bridges is defined by :

\[
\Psi(1) = 0, \quad \Psi(2) = \frac{\pi}{6}
\]

Then, the secondary voltages applied to the Jth bridge can be determined by:

\[
\begin{align*}
  v_{i(J)} & = -Y.v_i(m) + X.v_i(m+2) \quad \text{for } m = 1 \\
  v_{i(J)} & = -Y.v_i(m) + X.v_i(m-1) \quad \text{for } m = 2,3
\end{align*}
\]

Where \( X = \frac{\sin \Psi(J)}{\sin \pi/3} \), \( Y = \cos \Psi(J) - \frac{X}{2} \)

And m\textsuperscript{th} subscript means the phase number.

2: Valve terminal voltage:

For the negative side of the bridge rectifier, the voltages across valves (1,2,3) can be determined from the matrix equations.

\[
[A][v_i] = [SM] \quad \text{.........................................................(3)}
\]

Where

\[
[A] = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}, \quad [v_i] = \begin{bmatrix} v_i(1) \\ v_i(2) \\ v_i(3) \end{bmatrix}
\]
\[ SM \] = 
\[
\begin{bmatrix}
    v_{(3)} - v_{(i)} - \left\{ L_3 \left( i_c (6) - i_c (3) \right) + L_1 \left( i_c (1) - i_c (4) \right) / \Delta t \right\} \\
    v_{(i)} - v_{(2)} - \left\{ L_1 \left( i_c (4) - i_c (1) \right) + L_2 \left( i_c (2) - i_c (5) \right) / \Delta t \right\} \\
    v_{(2)} - v_{(3)} - \left\{ L_2 \left( i_c (5) - i_c (2) \right) + L_3 \left( i_c (3) - i_c (6) \right) / \Delta t \right\}
\end{bmatrix}
\]

Where \( v \) is instantaneous value of bridge secondary voltage (V), and \( L_1, L_2, L_3 \) are Leakage inductances of the transformer (H).

These equations are available for one bridge. Therefore the subscript \( J \) (which represents the bridge number) is omitted.

There is a sequence of valves firing, which permits to modify the elements of the matrices \([A]\) and \([SM]\), corresponding to the conducted valves. This matrix equation permits to evaluate the voltages \( v_{(i(1))}, v_{(i(3))}, \) (where \( v_i \) is the instantaneous value of the voltage across the valve) i.e. the potential difference across valves (1:3) of the negative side. Therefore the voltages across the valves of the positive leg can be determined from the equation:

\[
v_{(i)} = -v_{(i-3)} - Rd \sum_{r=1}^{3} i_{d(r)} - \frac{L_d}{\Delta t} \sum_{r=1}^{3} i_{r(r)} - E_b \]

\[
\text{.........................(4)}
\]

Where \( i^{th} \) is a subscript means the valve number and it is equal to 4,5 or 6. When the calculation procedure is started the voltage \( v_{(i(i))} \) is not determined by equations (3,4). But it is evaluated as follows:

\[
v_{(i(i))} = -v_{(m)} \quad ; \quad v_{(i(i+3))} = v_{(m)}
\]

\[
\text{for} (m = i) \leq 3
\]

3: Valve current:

The current flowing in each valve of the \( J^{th} \) bridge is determined by the equation

\[
i_{d(i,j)} \bigg|_{t = T} = i_{d(i,j)} \bigg|_{t = T - \Delta t} + i_{c(i,j)} \bigg|_{t = T - \Delta t} \]

\[
\text{.........................(5)}
\]

Where \( i_d \) is the instantaneous value of current flowing in the valve (A), and \( i_c \) is the instantaneous current in the valve during commutation (A). The subscript \( i \) varies from 1 to 6.

4: Current in the AC side :

The phase shift due to the connection of the transformer secondary windings must be taken into account.

\[
\Psi_{(a)} = -(X + 2Y) / 3 \quad , \quad a = 1, 5 \ or \ 9
\]

\[
\Psi_{(b)} = (2X + Y) / 3 \quad , \quad b = 3, 4 \ or \ 8
\]

\[
\Psi_{(c)} = -(X + Y) / 3 \quad , \quad c = 2, 6 \ or \ 7
\]

where \( \Psi \) is the phase shift between the bridges secondary voltages (degree)
The phase currents which flow in the AC side of the Jth bridge is given by

\[
i(m, J) = \frac{1}{2} \left( i_d(1, J) - i_d(4, J) \right) \frac{\Psi}{(m)} + \frac{1}{2} \left( i_d(2, J) - i_d(5, J) \right) \frac{\Psi}{(m+3)} + \frac{1}{2} \left( i_d(3, J) - i_d(6, J) \right) \frac{\Psi}{(m+3)} \]  

(6)

Where \( i \) is the instantaneous value of phase current (A) and subscript \( m \) equal 1,2 or 3.

5: Rectified current and voltage:

The rectified current flowing in the bridge is defined by:

\[
I_{d(J)} = i_{d(1, J)} + i_{d(2, J)} + i_{d(3, J)}
\]

While, the rectified voltage of the Jth bridge is

\[
V_{d(J)} = \left[ v_{i(1, J)} + v_{i(4, J)} \right]
\]

(7)

6: Commutation current:

The currents in the valves of bridge J, during the overlap period, can be calculated using a matrix equation similar to that for the valve terminal voltage evaluation (section 3.2)

\[
\begin{bmatrix} A_e \end{bmatrix} \begin{bmatrix} i_c \end{bmatrix} = [SN] \Delta t \]  

(8)

Where \( [A_e] = \)

\[
\begin{bmatrix}
  L_1 + L_d & -L_2 + L_d & L_d & -L_1 & L_2 & 0 \\
  L_d & L_2 + L_d & -L_3 + L_d & 0 & -L_2 & L_3 \\
  -L_1 + L_d & L_d & L_3 + L_d & L_1 & 0 & -L_3 \\
  -L_1 & L_2 & 0 & L_1 + L_d & -L_1 + L_d & L_d \\
  0 & -L_2 & L_3 & L_d & L_2 + L_d & -L_3 + L_d \\
  L_1 & 0 & -L_3 & -L_1 + L_d & L_d & L_3 + L_d
\end{bmatrix}
\]

\[
\begin{bmatrix} i_c(1) \\ i_c(2) \\ i_c(3) \\ i_c(4) \\ i_c(5) \\ i_c(6) \end{bmatrix} = [SN]^{-1} \begin{bmatrix} v(2) - v(1) \\ v(3) - v(2) \\ v(1) - v(3) \\ v(1) - v(2) \\ v(2) - v(3) \\ v(3) - v(1) \end{bmatrix}
\]

\[
[CD] = \left\{ 2V_{th} - E_h - I_{d(J)}R_{d(J)} \right\} [U]
\]
Where: \( U = \) Matrix defining the conduction state of the valves, and \( \Delta t \) is time increment (sec).

These equations, which are determined initially, will be modified for each step of calculation, according to the state of conduction of the valves. As an application example, if valves 2, 3 and 4 are in the conduction state, then some of the matrices elements will be modified to:

\[
\begin{align*}
A(2,1) &= A(2,2) = A(2,3) = 1 \\
A(2,4) &= A(2,5) = A(2,6) = -1 \\
\text{SM}(2) &= 0
\end{align*}
\]

Taking the suffix (y) to define a nonconducting valve, then

\[
\begin{align*}
A(y,b) &= 0 \quad \text{for } y \neq b \\
A(y,y) &= 1 \quad \text{and } \text{SN}(y) = 0
\end{align*}
\]

With these modifications in the matrices elements, and solving equation (8) numerically, the commutation currents can be determined.

**7: Valves firing sequence:**

For each step of calculation, the phase angle is defined by

\[
\Phi(J) = \omega t + \theta(J) + \Pi \Psi(J) \tag{9}
\]

While the thyristors firing pulses are given by

\[
\delta(i,J) = (9 - 2i) \frac{\Pi}{6} + \alpha(i,J) \tag{10}
\]

Initially, the valves are in the off-state; at each calculation step, the thyristors conduction state is examined as follows:

a) If the thyristor is already in the conduction state, then

\[
i_{d(i,J)} > i_{h(i,J)} ; \quad v_{i(i,J)} \geq v_{ih} \tag{11}
\]

b) If the thyristor conducts at this instant, then

\[
0 \leq 2\Pi \left| \Phi(J) - \delta(i,J) \right| < \rho_{(i,J)} \quad \text{and} \quad v_{i(i,J)} \geq v_{ih} \tag{12}
\]

Where is the interval of thyristor conduction. When the calculation procedure is started, i.e at \( t < t_s \) (where \( t_s \) is starting time needed for the thyristor firing in sec). the state of thyristors conduction is not determined as mentioned in equations (11,12). But, it is determined by applying the condition:

\[
\begin{align*}
v_{i(i,J)} &\geq v_{ih} \\
i_d(i,J) &> i_{h(i,J)} \text{ or } i_{c(i,J)} \geq 0
\end{align*}
\]

**Results:**
A flow chart of the computation process is given in figure (3), while the input data needed to run the program are: \( n, t_m, \theta_1, \psi_{th}, \rho_{(i,j)}, R_d, L_d, \theta_{hi(j)}, n_p, t_s, E_b, L_1, L_2, L_3, U_1, U_2, U_3, \alpha_{(i,j)} \) and \( \psi_{(j)} \), where \( n \) is the number of bridges connected in series; and \( t_m \) is maximum permitted time of calculation (sec); \( n_p \) is the number of calculation intervals during one half period; \( E_b \) is Load counter-electromotive force (V); while \( U_1, U_2, U_3 \) are maximum values per phase of the star connected secondary voltage (V).

The program was written in Basic language, and it is capable of printing and plotting currents and voltages as a function of time. In addition, it calculates the average DC voltage and current.

For a time solution increment equal to \( 5 \times 10^{-5} \) second, the steady state values were reached in fifty increments.

Figures (4-7) display the currents and voltage variables for two 6-pulse converters operating with given component values. Figure (4-a) plots the current flowing through the thyristors over a full period in normal operation; while Fig. (4-b) shows the current of thyristors when \( L_1, L_2, \) and \( L_3 \) are doubled. In addition Fig. (4-c) shows the above currents when \( U_1, U_2, \) and \( U_3 \) are increased by 1.5; and Fig. (4-d) shows the currents when \( E_b \) is decreased by 50%.

Similarly the AC line current of one phase is shown in figure (5-a) in normal operation; and the effect of doubling \( L_1, L_2, \) and \( L_3 \) is shown in Fig. (5-b). Also the effect of increasing of \( U_1, U_2, \) and \( U_3 \) by 1.5 is shown in Fig. (5-c). When \( E_b \) is decreased by 50% the current waveform is shown in Fig. (5-d).

The rectified DC current is plotted in Figure (6) under the same mentioned above conditions. In Figure (7) the curves of the rectified DC voltage are shown against time also under normal operation (fig.7-a); also when \( L_1, L_2, \) and \( L_3 \) are doubled (fig.7-b); when \( U_1, U_2, \) and \( U_3 \) increases by 1.5(fig.7-c); and finally \( E_b \) is decreased by 50% (fig.7-d).
Figure (3): Program flow chart
Figure (4) A & B
Figure (4): Currents in thyristors, 1, 2 and 3
Figure 9 (a) I_L, $I_L^2$, and $I_L^3$ are doubled.

(a) Normal operation

Sec

Time

Line Current - A

Sec

Time

Line Current - A
Figure (5) current wave form in phase b, at the AC side
Figure (6) A & B
Figure: (6). Rectified DC current
Figure (7) A & B
Figure (7) Rectified DC voltage
The effect of the source inductances (i.e. the effect of the AC network configuration and its short circuit power) is illustrated in Figures (4-b: 7-b).

Comparing Fig. (6-a) with Fig (6-b) there is more ripple in currents waveforms, when these inductances are doubled. If the three phase AC supply voltage is increased, Figures (4-c: 7-c) show the influence of this increase (1.5 times the nominal values) on the voltage and currents mave forms. It is clear that the commutation period is increased, while there is a decrease in the harmonic contents of the AC phase current.

Figures (4-d: 7-d) illustrate the current and voltage waveforms when the load counter-electromotive force is decreased by 50%. The commutation period is decreased, while the DC current becomes more smooth and the AC phase current waveform is approximately a sinusoidal wave.

The program is suitable for simulation of most unbalanced operation, such as unbalanced AC supply voltages, asymmetrical firing pulses and unbalanced AC network configuration. The program is limited for five six-pulse rectifier bridges connected in series.

Conclusion

This paper dealt with a digital computer simulation of the complex converter system, i.e. multiple three phase full wave rectifier bridges connected in series on the DC side. The program study the currents and voltage waveforms on both AC and DC sides. The effect of different values of the system components and parameters is also considered. The simulation which has been developed here is well suited to studies related to the abnormal operation of the bridge such as open circuits and unbalanced source voltages. The described calculation method constitutes and effective tool for the analysis of complex converter systems. It is expected that this method of simulation will find suitable use in study of systems wherein the rectifier plays an active role in the overall system analysis.

This program can be suitably used by the centres of research and design engineering to give an idea about the operation performances of multiple bridge rectifiers without the need of an experimental simulator.

References


