Abstract: This paper proposes the use of simulation techniques to solve specific problems encountered in the use of three phase rectifiers to control the switching of A.C. drives with an induction motor. The solution proposed in the paper is based on the PRACED simulator and is applicable to pulse rectifiers of A.C. electric drives. The PRACED simulator is shown to be especially useful in the design and in the development of various A.C. electric drives. Experimental results demonstrate the high performance of the simulator in application to the dynamic simulation of power generation systems.

Keywords: Pulse rectifier, control circuits, modulation, simulation, power factor and harmonic content.

1. INTRODUCTION

Simulation is a powerful technique that can be used for several stages of any system development process; e.g. simulation of power systems using special purpose tools is now a well established area. The power system of Toolbox [Chow et al., 1992] set of Mathlab program files is capable of dynamical simulation of power systems. Dual Foil is an electromechanical model that solves partial differential equations in FORTRAN while B-Sharp is a programmable power supply that emulates the behavior of a battery [Liu et al., 1994]. The main objective of this paper is to find a suitable solution for some selected problems of a three-phase pulse rectifier “PR” used for supplying a 1000-kW electric drive with an induction motor through a voltage inverter. With the PWM control [Raun, 2001; Dewan et al.,1990; Iwaji, 1992; Boost et al., 1988; Ziogas, 1981], which is most commonly used for generating the switching signals for the devices of the pulse rectifier, the performance of the rectifier suffers from drawbacks as: low fundamental output voltage, high harmonic content and less improvement of input power factor [Rashid, 2004]. This paper provides a new way of modulation and control for improving the performance and the principle of operation of the pulse rectifier. Also, in this paper, PRACED simulator is developed for controlling the switching of devices to obtain a unity power factor and achieving a minimum harmonic content losses of pulse rectifier.

2. OPERATION PRINCIPLE OF THE PULSE BRIDGE RECTIFIER

Figure 1 shows a pulse rectifier with a capacitive filter at the output. It is used for supplying an a.c. electric drives with induction motors through a voltage inverter. The switching actions of the devices can be performed by GTO or IGBT. The characteristics of GTO are such that a GTO can be turned ON by applying a short positive pulse to its gate as in the case of normal thyristors and can be turned OFF by applying a short negative pulse to its gate. An IGBT remains on as long as a gate voltage is applied to its gate terminal.
Depending on the control strategy, a forced-commutated can be operated as either an inverter or a rectifier [Rashid 2004, Boys et al. 1989], therefore it is often referred to as a converter.

The principle of operation of the pulse bridge rectifier can be explained as shown in figure 1. The rectifier is supplied by an alternating voltage $V_a$. By using a suitable switching method of the transistors, it is possible to obtain nearly a sinusoidal current $I_a$ and in phase with the input voltage, thereby having an input PF of approximately equal to unity ($\cos \phi = 1$) as follows:

- If switches 1, 3 OFF and 2, 4 are ON, then the terminals of voltage $V_v$ are short-circuited and the absolute value of current $I_a$ increases;
- If switches 1, 2 are ON; then voltage $V_v = V_d$ and the positive current $I_a$ decreases;
- But if switches 3, 4 are ON, then voltage $V_v = -V_d$ and the negative current $I_a$ absolutely decreases (its absolute value decreases).

The input current of the converter is controlled to follow the full-rectified waveform of the sinusoidal input voltage by PWM control. The PWM control signals can be generated by using the bang-bang hysteresis technique (BBH). The switching of the transistors is always changed as soon as the current $I_a$ reaches the reference boundary value of the hysteresis window. This technique is shown in figure 1 which has the advantage of yielding instantaneous current control, resulting in a fast response where the switching frequency is not constant and varies over a wide range during each half-cycle of their ac input voltage. The frequency is also sensitive to the values of the circuit components. It is evident clear that the d.c. current $I_d$ has an a.c. component of 100 Hz. In order to reduce the harmonic content (ripple) in the voltage $V_d$ across the output capacitor, an LC filter can be used.

3. CONTROL ALGORITHMS FOR PULSE RECTIFIERS

Good control of the pulse rectifier must result in a sinusoidal current $I_a$, a very small content of high harmonics, very low switching losses and zero phase shift between the input current and voltage. The response of control circuits must also be very fast to obtain a stable system. With respect to the above mentioned facts, there is a testing for the following two possible variants of control and modulation:

- Bang-bang technique (BBH) or Hysteresis control of current $I_a$ as shown in figure (1): In bang-bang technique, a triangular wave is allowed to oscillate within a defined window above and below a reference sine wave. The switching function is generated from the vertices of a triangular wave. This way of control is very simple since without any troubles, we can obtain a unity PF ($\cos \phi = 1$). Despite of all these facts, the above mentioned way of control will not be taken into consideration. It requires a very fast microprocessor and it is not suitable for in parallel operating pulse rectifiers [Chow, 1992].
• Modulation of voltage $V_v$: This way of control yields a sinusoidal current $I_a$ with a unity PF ($\cos \phi = 1$). The required harmonic component of voltage $V_v$ can be obtained by using a suitable way of control of voltage $V_d$ and $\cos \phi$ or by using a suitable mathematical operation and analysis.

Advanced Modulation Techniques of $V_v$

◊ Optimal modulation
For a given frequency of modulation, it results in a minimum a.c. component of the current $I_a$. With respect to the power electronic circuit, it is considered to be the best possible modulation. The optimal instants for switching the transistors must be estimated for the whole half-cycle of voltage $V_v$. This way of switching causes a delay in the control circuit which consequently affect the stability of control circuits.

◊ Delta modulation
It is usually used for inverters with IGBT transistors. With respect to the minimum ripple of current $I_a$, it is not optimal, but it causes a very small delay to the function of control circuits which is given as a function of the sampling period of signals. It is also easy to use the parallel connection of pulse rectifiers which operate out of phase. According to the obtained simulation and with respect to the required quality of control circuits, we have decided to use the "delta" modulation technique. The basic principle of delta modulation is shown in figure 2 where some symbols will be explained in figure 4. Gating signals for transistors are determined by the control system at the points of coincidence of two waveforms by comparing the control signal $V_r$ with the given saw-tooth signal which is shifted by a certain angle. The amplitude of $V_r$, $(V_r)_m$ is estimated in a manner shown in figure 2. Dividing $V_{vm}$ by $V_d$ results in an equality (a coincidence) of the given estimated voltage $V_v$ with the 1st harmonic component of the actual voltage $V_v$. It is valid even for a variable $V_d$. The non-linearity $N_2$ is used for achieving a continuous transition into a single-pulse modulation.

Where:-

$V_{vm}^{(1)}$: Desired peak value (amplitude) of a 1st harmonic component of voltage $V_v$

$\varepsilon$: Desired phase shift $V_{vm}^{(1)}$

$V_d$: Voltage of the capacitor

4. THEORETICAL PROBLEMS OF CONTROL CIRCUITS
The characteristics and the dynamic properties of the electric drive essentially affect the quality of the control circuits of voltage $V_d$. With respect to the control circuits, the control of $\phi$ is not problematic, since the control loop of $\phi$ is considered to correct the desired value of $V_{vm}^{(1)}$ to obtain a unity power factor, i.e. $\cos \phi = 1$. The characteristics of the control loop of $V_d$ may be reviewed according to block diagram in figure 3. The block diagram is obtained by using the following analysis (figure 3):

$$\frac{X I_m^{(1)} V_{vm}^{(1)}}{V_{vm}} = \tan(\varepsilon) \approx \varepsilon, X = \omega L \Rightarrow I_m^{(1)} \approx \varepsilon \frac{V_{vm}}{X} \quad (1)$$

Figure 2: Delta modulation technique of $V_v$
These expressions are valid only for \( \cos \phi = 1 \)
\[ I_c + I_{cl} = I_d - I_z \]  (3) The positive polarities of the quantities are valid for motoring regime.

Block diagram illustrated in figure 3 shows the dynamic behavior of the pulse rectifier with respect to using a block Fekv.

Figure 3: Block diagram of the control circuit of \( V_d \)

Where:-

\[
F_c(p) = \frac{1}{p(C + C_1)} \left( \frac{1}{\omega_1} + \frac{1}{\omega_2^2} + 1 \right) \]  (5)

\[
\omega_1 = \frac{1}{\sqrt{L_1 C_1}}, \quad \omega_2 = \frac{C + C_1}{\sqrt{L_1 C_1 C_1}}, \quad \tau_1 = \frac{L_1}{R_1} \]  (6)

Note: Circuit Impedances \( C, C_1, L_1 \ldots Z_c(j \omega_1) \rightarrow 0, Z_c(j \omega_2) \rightarrow \infty, \quad \omega_1 = 2 \pi 100 \)
\( \Rightarrow \omega_1, \omega_2 \) must be sufficiently different \( \Rightarrow C_1 \cong C \).

### 5. ALGORITHMS OF CONTROL CIRCUITS

The control circuits of PR have two main functions given by the following:

- Assuring a constant voltage across the capacitor \( V_d \) during the variations of the supply voltage \( V_s \) and the load current \( I_l \) (Keeping \( V_d \) constant is a necessary condition for good operation of the electric drive).
- Assuring \( \cos \phi = 1 \) during motoring and braking regime (It is a very important condition but breaking this demand (condition) does not affect the function of the drive).

For developing the electric drive, the following types of control circuits were taken into consideration:

1. The desired 1st harmonic of a voltage \( V_v \) is evaluated by using 2 controllers. The phase shift \( \varepsilon \) between voltage \( V_v^{(1)} \) and voltage \( V_s \) is evaluated by using the voltage controller of \( V_d \), the peak value (amplitude) of \( V_v^{(1)} \) is evaluated by using the controller of \( \phi \).

**Evaluation:** Current \( I_l \) may have in the previous states a dc component, therefore phase shift \( \phi \) cannot be evaluated from the instant of zero-crossing of current \( I_l \). The evaluation can be done as soon as the Fourier analysis of current \( I_l \) is obtained. Fourier analysis is however unworkable for fast transients.

2. The desired phase shift \( \varepsilon \) of voltage \( V_v^{(1)} \) is set by controlling the voltage \( V_d \) across the capacitor (amplitude \( V_v^{(1)} \) is estimated).
In the case of a simple PR shown in figure 1, its function may be described by using a phasor diagram (this diagram is in this case valid only for motoring regime for braking regime $\varepsilon$ is negative).

$$V_{vm}^{(1)} = \frac{V_{am}}{\cos \varepsilon}$$

In the case of a real PR the magnetization current of a transformer makes the evaluation of $V_{vm}^{1}$ more complicated (A unity power factor is desired at the primary side of the transformer, $\cos \varphi = 1$), in the case of parallel connection of PR, the leakage inductances of a transformer makes the estimation of voltage drops at the primary side complicated.

Evaluation of exact estimation of $V_{vm}^{1}$ is hardly realizable in a real time

3. The desired phase shift $\varepsilon$ of a voltage $V_{v}^{1}$ is set by the controller of voltage $V_{d}$, amplitude $V_{v}^{1}$ is estimated and it is corrected by a controller of $\varphi$. Since the phase controller is used only for the purpose of correction, complicated demands will not be put on the control circuits of $\varphi$.

Evaluation: According to the dynamic properties of the a.c. electric drive and the possibility of realizing our standard microprocessor technique, we have decided to use the last variant of the above mentioned control circuits. Principle of operation of this variant of control circuits is shown in figure 4.

**Figure 4:** Principle of operation of the selected control circuits

Where:

- **Block G** ... shown in figure 2
- **Block „Freq“** tests and evaluates the period of voltage $V_a$ ... $T_{ua}$.
- **Block „Four“**... continuously prepares Fourier analysis for current $I_a$.

Period of sampling $TV = T_{ua}/10$

$$\left(a[i+1] \rightarrow a[i]\right)_{i=0.9} \quad (7), \quad \left(b[i+1] \rightarrow b[i]\right)_{i=0.9} \quad (8), \quad \omega_a = 2\pi \frac{1}{T_{ua}} \quad (9)$$
\[ a[10] = I_{sa} \cos(\omega_a \cdot n \cdot TV) \quad \text{(10)} \]
\[ b[10] = I_{sb} \sin(\omega_a \cdot n \cdot TV) \]

\[ S_a \leftarrow S_a + a[10] - a[0] \]
\[ S_b \leftarrow S_b + b[10] - b[0] \quad \text{(11)} \]
\[ \varphi_s = \arctan \left( \frac{S_a}{S_b} \right) \quad \text{(12)} \]

6. RESULTS OF SIMULATION OF FAST CONVERSION: Motoring → Braking

The Math lap software was used to develop PRACED simulator using the proposed algorithm for solving various problems. The proposed circuits were used to implement this PRACED simulator. The request \( V_d = \text{const} \) is hardly achieved. After the conversion of the drive from motoring to braking regime, the polarity of the mean value of the current \( I_z \) which charges the capacitor changes. If the voltage of the capacitor should not increase, PR must be converted into the inverting regime. This is problematic since a very fast control circuit can cause non-stability to the system. From figure 5, the following results can be achieved:

- The simulated results show an increase of a voltage across the capacitor which is obtained under the following conditions:
  - A Filter for the 2 harmonic is not used (positive effect)
  - A feedback from the disturbance \( I_x \) is not also used (negative effect)

- The conversion of a simulated electrical drive from a rectifying mode to an inverting mode may occur during two time constants (periods). Within this time, the current will be shifted out by 180°. From the waveform of the current, it is seen that the result of the continuously prepared Fourier analysis is a non-useful signal. Therefore it is difficult to obtain a unity power factor (\( \cos \varphi = 1 \) just by controlling it). The essential evaluation of the desired value of voltage \( V_{vm}^{(1)} \) is necessary to do by normal mathematical operation (estimation).

- From the waveform of the current, it is seen that the output of the controller \( R_\varphi \) during a fast transition is a bad signal. This signal should not affect the transition in a bad way, and so the controller \( R_\varphi \) is proposed with a small gain and long time constant. Figure 5 proves the problem of obtaining a unity power factor \( \cos \varphi = 1 \) which is successfully solved. During the time of fast transition of PR from rectifying to inverting mode, \( \cos \varphi \) is not define.

![Figure 5: Waveforms during fast conversion from motoring to braking regime](image-url)
7. CONCLUSIONS
This research has developed and demonstrated a simulation approach to address specific problems encountered in the use of three phase pulse rectifiers to control the switching of A.C drives. These problems, namely, low fundamental output voltage, high harmonic content, and low input power factor, can be solved if the ripple of output voltage (Vd) is sufficiently reduced with the introduction of a capacitor (C). However, the filter may cause technical and construction problems if capacitor (C) is used for more than one converter. The internal feedback from an output voltage (Vd) is positive for the case of braking regime, which has indeed a negative effect on the stability of the system. The dynamic properties of the system can be improved by adding a feedback from the "disturbance" current Iz. This feedback is however hard to implement because the current sensor connected between capacitor (C) and the inverter gives rise to over voltages. The simulation-based solution achieves high performance in obtaining minimal harmonic content losses and a unity power factor, thus the proposed simulator can effectively support the design and management processes.

REFERENCES

AUTHOR BIOGRAPHIES
Walid Emar was born in Palestine, in 1970. He received the Dipl.-Ing. (M.Sc.) degree in industrial electronics and the Dr.-Ing. (Ph.D.) degree in power electronics and control from the University of West Bohemia, Pilsen, Czech Republic. In 2001, he joined Škoda Transportation, Škoda Company, Pilsen, Czech Republic. In 2002, he joined Birzeit University, Electrical and Computer Department. Currently, He is now teaching at Al-Isra Private University as a full-time assistant professor. He is engaged in research and development of high-power multilevel converters for industrial and traction applications, as well as dc/dc converters and regulators.

Musbah J. Aqel he obtained his B.Sc. in electronics and communication Engineering and M.Sc. in computer Engineering from Aligarh Muslim University- India and his PhD from I.T, Banaras Hindu University- India in computer Engineering. He is currently associated professor of computer engineer, and chairman of Electrical and Computer Engineering Dept. His research interest includes knowledge-base system design, image processing, computer networks, and simulation techniques.

Ibrahim M. M. El Emary received the Dr. Eng. Degree in 1998 from the Electronic and Communication Department, Faculty of Engineering, Ain shams University, Egypt. From 1998 to 2002, he was an Assistant Professor of Computer sciences in different faculties and institutes in Egypt. From 2002 and till now, he is a visiting Assistant Professor (Head of Computer Engineering Department, Faculty of Engineering) at Amman Al Ahliyya University, Amman, Jordan. His research interests include: analytic simulation techniques, performance evaluation of communication networks, application of intelligent techniques in managing computer communication network, and performing a comparative studies between various policies and strategies of routing, congestion, sub netting of computer communication networks. He published more than 60 articles in various refereed international journals and conferences covering: Computer Networks, Artificial Intelligent, Expert Systems, Software Agents, Information Retrieval, E-learning, Case Based Reasoning, Image processing and Pattern Recognition. He joined various international journals as an editor as well as joining international conference as a membership of the international editorial board. He was granted various international awards from USA and Jordan.