ITM Web of Conferences **48**, 04003 (2022) https://doi.org/10.1051/itmconf/20224804003
ICCWCS 2022

A Novel Method for DC Bus Voltage Sags Estimation Using the Switching Function Approach and ADALINE Method

Mounir Bensaid***,** *Abdellfattah* Ba-Razzouk, *Mustapha* Elharoussi

Hassan First University of Settat, FST, Mathematics, Computer and Engineering Sciences Laboratory (MISI), Team: Systems Analysis and Information Processing (ASTI). Morocco.

Abstract. In this study, a functional model for diode bridge rectifiers (DB) is developed based on the concept of switching functions. The developed model is suitable for the estimation of the average voltage at the rectifier terminals from the fundamental three-phase voltage estimation based on the Adaline method and a DC bus estimator based on the switching function method, The performance of the detection estimator was validated in simulation using Matlab software under normal, unbalanced and line fault conditions. The high accuracy and efficiency of the developed estimator were demonstrated by comparison with rectifier models from SPS (SimPowerSystems), PSIM, and a reel rectifier from the pedagogical model (THREE-PHASE EDUCATIONAL INVERTER SEMITEACH 08753450BB)

1 Introduction

The conversion of energy between an alternating network and a medium or high-power electronic equipment passes more and more by a diode rectifier. However, in the context of electrical networks where it is increasingly considered, harmonic disturbances, voltage dips appear before and after the static converters [1][2]. These electrical disturbances, not very desirable, must respect standards. To analyse these electrical disturbances, models of the operation of static converters are necessary.
A voltage sag is defined as a momentary decrease in the RMS value of the nominal voltage for a duration ranging from 0.5 cycles to 1 minute [3][4]. Short circuits and the starting of large induction motors are the main causes of voltage sags. Voltage sags are the major cause of disturbances in variable speed drives, computers, and industrial process controllers [5].
A voltage dip is defined by two major parameters [15]. These parameters are as follows: the amplitude of the dip or depth, which defines the decrease in RMS voltage, and the duration, which defines the time the dip occurs [6].

The number and unit power of diode and thyristor rectifiers in electrical networks is constantly increasing. Static converters are expected to process 60% of the electrical energy produced in the future. These converters are widely used in variable speed drives, welding, electrolysis, and other applications. They are used in a wide range of applications and are required wherever AC/DC power conversion is required Variable speed drives (VSDs) appear to be more sensitive to voltage sags than data processing equipment (computers) [7].

* Bensaid mounir: bensaidmounir.eae@gmail.com

Voltage sags in (VSDs) are primarily manifested by a decrease in the voltage in the DC link [8]. In this paper, we will be interested in the variation of the average value of the rectified voltage as a function of the power supply conditions.

The difficulty in detecting voltage sags is in estimating the voltage amplitude. ADALINE, having been used to estimate the amplitude and phase of a signal's fundamental and harmonics, becomes an interesting avenue to investigate. Only the amplitude and phase of the fundamental are of interest in the case of voltage dips. The concept of function switching will be used. This concept was used to calculate the average voltage of a diode rectifier, and the accuracy of the results obtained is demonstrated.

This paper is organized as follows. The Analysis of a three-phase diode rectifier is discussed in Section 2. The algorithm of the ADALINE method and DC Bus Voltage estimation are presented in Section 3. Comparison and simulation results are presented in section 4. Finally, Section 5 concludes the paper.

2 Analysis of a three-phase diode rectifier

Consider the three-phase diode rectifier shown in Figure 1 connected to the three voltages source (v_a , v_b, v_c). The source has the internal resistance R_s and inductance

L_S. They include the values describing the connection lead. The bridge is loaded by a resistance R_d.

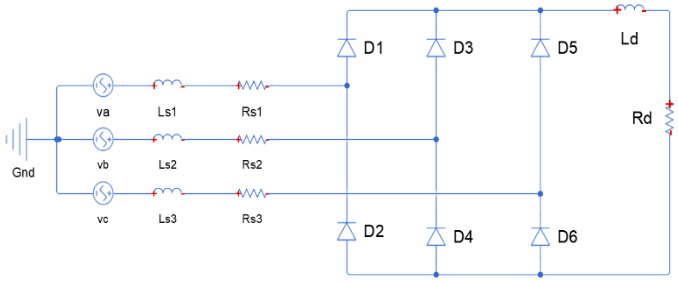

Fig. 1. Three-phase diode rectifier

Using the switching functions, we will calculate the average value of the rectified voltage. This rectifier will be analysed in both the balanced and unbalanced regimes.

The analysis hypotheses are:

- ✓ The source and power switches are perfect;
- ✓ The rectifier operates in continuous conduction mode;
- ✓ The voltages are sinusoidal in nature.
- ✓ The inductances and line resistors are identical.

2.1 Analysis of the diode rectifier in balanced regime

This is analysis under normal operating conditions in the absence of voltage dips or in the case of type A dips.

We will use the switching functions T_a, T_b, and T_c to calculate the average output value of a three-phase diode rectifier. T_a, T_b, and T_c are switching functions related to the conduction and blocking states of the diodes of each supply phase of the rectifier [9][10].

These switching functions are shown in Figure 2.

In the case of a balanced three phase source, the switching times are defined as follows:

$$\theta_1 = \frac{\pi}{6} \qquad \theta_2 = \theta_1 + \alpha$$
$$\theta_3 = \frac{\pi}{2} \qquad \theta_4 = \theta_3 + \alpha$$
$$\theta_5 = \frac{5\pi}{6} \qquad \theta_6 = \theta_5 + \alpha$$
$$\theta_7 = \frac{7\pi}{6} \qquad \theta_8 = \theta_7 + \alpha$$
$$\theta_9 = \frac{3\pi}{2} \qquad \theta_{10} = \theta_9 + \alpha$$
$$\theta_{11} = \frac{11\pi}{6} \qquad \theta_{12} = \theta_{11} + \alpha$$

α is the overlap angle

The switching functions are defined as follows:

$$T_a = \begin{cases} -1, & if \quad \theta_8 \le \theta \le \theta_{11} \\ -0{,}5, & if \quad \theta_7 \le \theta \le \theta_8 \quad and \quad \theta_{11} \le \theta \le \theta_{12} \\ 0, & if \quad 0 \le \theta \le \theta_1 \quad and \quad \theta_6 \le \theta \le \theta_7 \\ & \quad and \quad \theta_{12} \le \theta \le 2\pi \\ 0{,}5, & if \quad \theta_1 \le \theta \le \theta_2 \quad and \quad \theta_5 \le \theta \le \theta_6 \\ 1, & if \quad \theta_2 \le \theta \le \theta_5 \end{cases}$$

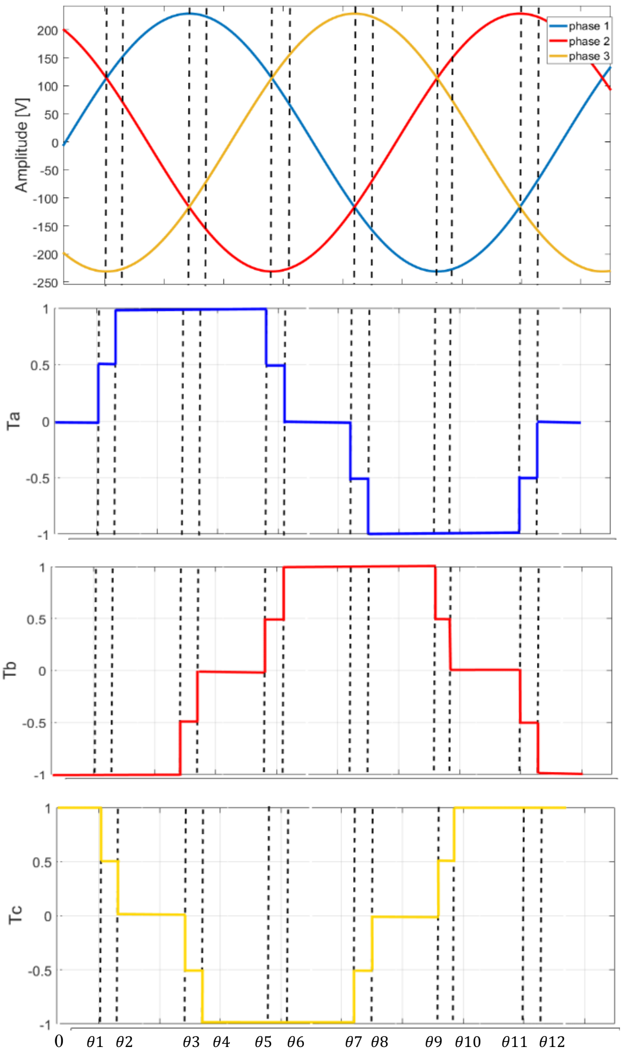

Fig. 2. Switching functions

$$T_b = \begin{cases} -1, & if \quad 0 \le \theta \le \theta_3 \quad and \quad \theta_{12} \le \theta \le 2\pi \\ -0{,}5, & if \quad \theta_3 \le \theta \le \theta_4 \quad and \quad \theta_{11} \le \theta \le \theta_{12} \\ 0, & if \quad \theta_4 \le \theta \le \theta_5 \quad and \quad \theta_{10} \le \theta \le \theta_{11} \\ 0{,}5, & if \quad \theta_5 \le \theta \le \theta_6 \quad and \quad \theta_9 \le \theta \le \theta_{10} \\ 1, & if \quad \theta_6 \le \theta \le \theta_9 \end{cases}$$

$$T_c = \begin{cases} -1, & if \quad \theta_4 \le \theta \le \theta_7 \\ -0{,}5, & if \quad \theta_3 \le \theta \le \theta_4 \quad and \quad \theta_7 \le \theta \le \theta_8 \\ 0, & if \quad \theta_2 \le \theta \le \theta_3 \quad and \quad \theta_8 \le \theta \le \theta_9 \\ 0{,}5, & if \quad \theta_1 \le \theta \le \theta_2 \quad and \quad \theta_9 \le \theta \le \theta_{10} \\ 1, & if \quad 0 \le \theta \le \theta_1 \quad and \quad \theta_{10} \le \theta \le 2\pi \end{cases}$$

The voltage at the output of the rectifier is defined as follows

$$V_d = T_a v_a + T_b v_b + T_c v_c - (T_a^2 + T_b^2 + T_c^2) I_d R_s \qquad (1)$$

Where v_a , v_b and v_c represent the three-phase voltage source and are given by:

$$\begin{aligned} v_a &= V_a sin(\theta) \\ v_b &= V_b sin(\theta - \tfrac{2\pi}{3}) \\ v_c &= V_c sin(\theta - \tfrac{4\pi}{3}) \end{aligned} \qquad (2)$$

As an analysis assumption, we consider Rs, the resistance of the source impedance negligible, and equation (1) becomes:

 https://doi.org/10.1051/itmconf/20224804003

$$V_d = T_a v_a + T_b v_b + T_c v_c \tag{3}$$

The Fourier series development of the rectified voltage is given by:

$$V_d = U_{d0} + \sum_{m=6}^{\infty} (A_{dm} cosm\theta + B_{dm} sinm\theta) \tag{4}$$

Where U_{d0} is the average value of the voltageV_d
And A_{dm}, B_{dm} are the Fourier coefficients of the rectified voltage's harmonic components.
We are only interested in the average value of the redressed tension in this analysis, so:

$$U_{d0} = \frac{1}{2\pi} \int_0^{2\pi} [T_a v_a + T_b v_b + T_c v_c] d\theta \tag{5}$$

equation 5 gives:

$$U_{d0} = \frac{1}{2\pi} \left[\int_0^{2\pi} [T_a v_a] d\theta + \int_0^{2\pi} [T_b v_b] d\theta + \int_0^{2\pi} [T_c v_c] d\theta \right]$$

let's put:

$$U_{d0A} = \int_0^{2\pi} [T_a v_a] d\theta$$

$$U_{d0B} = \int_0^{2\pi} [T_b v_b] d\theta$$

$$U_{d0c} = \int_0^{2\pi} [T_c v_c] d\theta$$

After development, we obtain:

$$U_{d0A} = \sqrt{3} V_a (1 + \cos(\alpha))$$
$$U_{d0B} = \sqrt{3} V_b (1 + \cos(\alpha))$$
$$U_{d0C} = \sqrt{3} V_c (1 + \cos(\alpha))$$

therefore,

$$U_{d0} = \frac{1}{2\pi} [U_{d0A} + U_{d0B} + U_{d0C}] = \frac{\sqrt{3}}{2\pi} (1 + \cos(\alpha) [V_a + V_b + V_c]$$

If $V_a = V_b = V_c = V_{LN}$ then the amplitude of the line-to-neutral voltage

$$U_{d0} = \frac{3\sqrt{3}}{2\pi} V_{LN} (1 + \cos(\alpha))$$

Or again,

$$U_{d0} = \frac{3}{2\pi} V_{LL} (1 + \cos(\alpha))$$

Where V_{LL} is the amplitude of the line-to-line voltage.
Forgetting the overlap effect, we obtain:

$$U_{d0C} = \frac{3\sqrt{3}}{\pi} V_{LN} = \frac{3}{\pi} V_{LL} \tag{6}$$

2.2 Analysis of the diode rectifier in unbalanced regime

In the presence of unbalanced voltage dips, the intervals of the switching functions change, because the terminals of these intervals represent the zero crossings of the switching voltages (v_{ac} , v_{ba}, v_{cb} , v_{ab} et v_{bc} .

For example, θ_1 and θ_7 will be found for v_a = v_c (i.e. v_{ac} = 0); by substituting v_a and v_c by their expression we have:

$$\begin{cases} V_a sin(\theta_1) = V_c sin\left(\theta_1 + \frac{2\pi}{3}\right) \\ V_a sin(\theta_7) = V_c sin\left(\theta_7 + \frac{2\pi}{3}\right) \end{cases} \tag{7}$$

We get two angles after trigonometric development: θ_1 and θ_7:

$$\theta_1 = tan^{-1}\left(\frac{\sqrt{3}V_c}{2V_a + V_c}\right)$$
$$\theta_7 = tan^{-1}\left(\frac{\sqrt{3}V_c}{2V_a + V_c}\right) + \pi \tag{8}$$

θ_3 and θ_9 will be found for v_c = v_b (i.e. v_{bc} = 0) and we obtain:

$$\theta_3 = tan^{-1}\left(\frac{\sqrt{3}(V_c + V_b)}{(V_c - V_b)}\right)$$
$$\theta_9 = tan^{-1}\left(\frac{\sqrt{3(V_c + V_b)}}{(V_c - V_b)}\right) + \pi \tag{9}$$

θ_5 and θ_{11} will be found for v_a = v_b (i.e. v_{ba} = 0) and we obtain:

$$\theta_5 = tan^{-1}\left(\frac{-\sqrt{3}V_b}{2V_a + V_b}\right)$$
$$\theta_{11} = tan^{-1}\left(\frac{-\sqrt{3}V_b}{2V_a + V_b}\right) + \pi \tag{10}$$

After development, we get:

$$U_{d0A} = \frac{1}{2} V_a \{(1 + \cos(\alpha))(cos(\theta_1) - cos(\theta_5) - cos(\theta_7) + cos(\theta_{11})) - s\,in(\alpha)(sin(\theta_1) - sin(\theta_5) - sin(\theta_7) + sin(\theta_{11}))\}$$

$$U_{d0B} = \frac{-1}{2} V_b \{(1 + \cos(\alpha) - \sqrt{3}\sin(\alpha))(cos(\theta_3) + cos(\theta_5) - cos(\theta_9) - cos(\theta_{11})) - (\sqrt{3}\,(1 + \cos(\alpha)) + s\,in(\alpha))(sin(\theta_3) + sin(\theta_5) - sin(\theta_9) - sin(\theta_{11}))\}$$

$$U_{d0C} = \frac{1}{4} V_c \{(1 + \cos(\alpha) + \sqrt{3}\sin(\alpha))(cos(\theta_1) + cos(\theta_3) - cos(\theta_7) - cos(\theta_9)) + (\sqrt{3}\,(1 + \cos(\alpha)) - s\,in(\alpha))(sin(\theta_1) + sin(\theta_3) - sin(\theta_7) - sin(\theta_9))\}$$

Ignoring the overlap effect on the average voltage, we obtain:

$$U_{d0A} = V_a \{(cos(\theta_1) - cos(\theta_5) - cos(\theta_7) + cos(\theta_{11}))\}$$

$$U_{d0C} = \frac{-1}{2} V_b \{(cos(\theta_3) + cos(\theta_5) - cos(\theta_9) - cos(\theta_{11})) - \sqrt{3}(sin(\theta_3) + sin(\theta_5) - sin(\theta_9) - sin(\theta_{11}))\}$$

$$U_{d0C} = \frac{1}{2} V_c \{ (cos(\theta_1) + cos(\theta_3) - cos(\theta_7) - cos(\theta_9)) + \sqrt{3}(sin(\theta_1) + sin(\theta_3) - sin(\theta_7) - sin(\theta_9)) \}$$

With:

$$U_{d0} = \frac{1}{2\pi} [U_{d0A} + U_{d0B} + U_{d0C}] \quad (11)$$

3 DC Bus average Voltage estimation

The proposed DC Bus voltage estimation method consists of:

- ✓ ADALINE method was used in the estimation of the amplitude and phase of the fundamental of the three-phase source, with adaptation by the least squares method (LMS)
- ✓ The estimator of the average value of the diode rectifier's DC link voltage developed on the basis of the switching function theory presented in section 2.

ADALINE (Adaptive Linear Neuron or later Adaptive Linear Element), as described in [11][12], can estimate periodic signals.

$$y(t) = \sum_{n=1}^{N} ((X_n \operatorname{Cos}(n\omega t) + (Y_n \operatorname{Sin}(n\omega t)) \quad (12)$$

The structure of the ADALINE network is described in Figure 3.

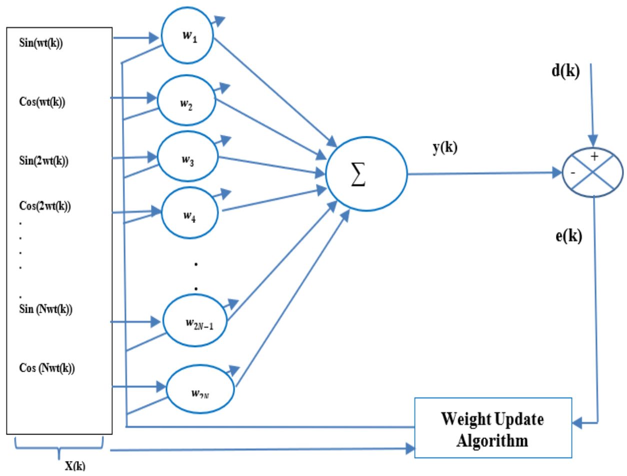

Fig. 3. ADALINE network structure

The flow chart of the ADALINE method is shown in Figure 4. This algorithm gives results with acceptable accuracies in steady-state

The three-phase detection uses three ADALINE networks to estimate the amplitude and phase of the power source voltages, and the output is used to generate the input signal of the DC bus average value estimator.

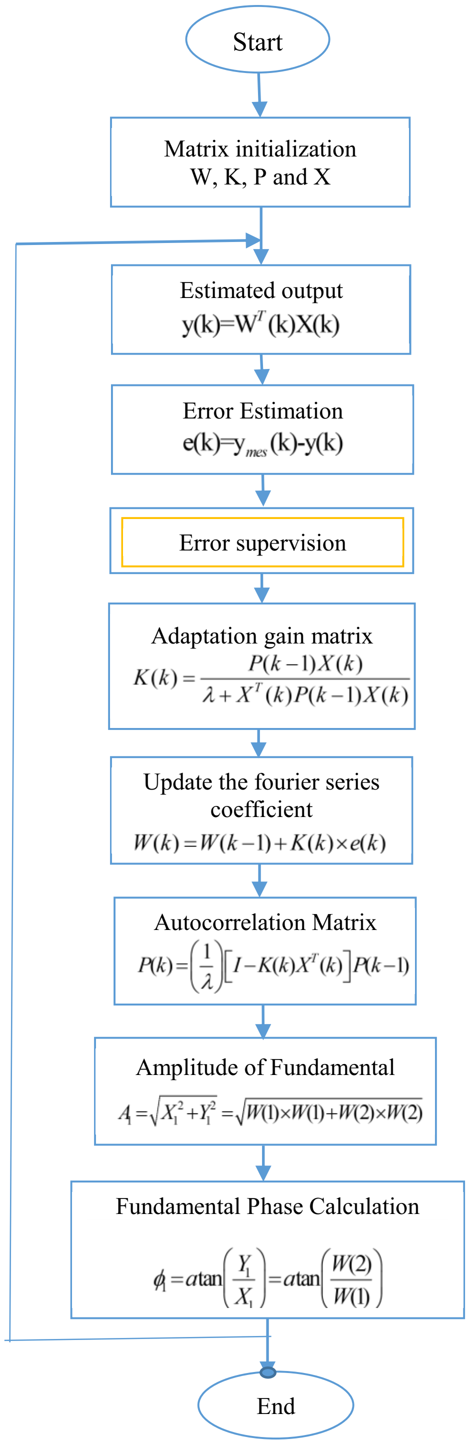

Fig. 4. Flow chart for ADALINE algorithm with Error supervision

4 Performance of DC Bus Voltage estimation

The estimator's implementation necessitates the creation of S-Functions in C. An SFunction is a programming language used to describe Simulink blocks. It can be written in the Matlab language, C, C++, Ada, or Fortran. An S-function allows you to design your own Simulink blocks. The mex command is then used to compile this program.
For the detection of the fundamental and the phase of the voltage source, three distinct estimators are

 https://doi.org/10.1051/itmconf/20224804003

implemented in the Fundamental Estimators blocks chow in figure 6. It is the same code (algorithm) with the difference is that the names assigned to them are different as well as the names of the static variables of the program

The second estimator implemented in the average DC bus voltage estimator block shown in figure 6 is that of the average value of the voltage of the dc link of the diode rectifier. This algorithm was developed on the basis of the theory of switching functions presented in section 2

The results of our estimator and the experimental results based on (THREE-PHASE EDUCATIONAL INVERTER SEMITEACH 08753450BB) shown in figure 5 available in the laboratory and the simulation results obtained using SPS (SimPowerSystems) and PSIM are shown in Table 1.

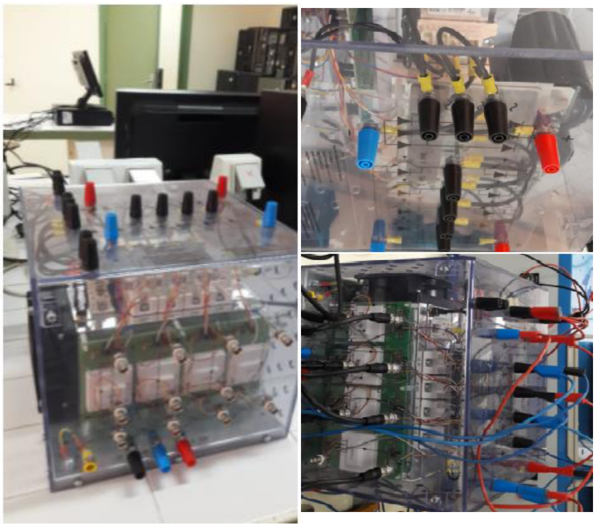

Fig. 5. ADALINE network structure

Table 1. Average values of the rectified voltage for different supply voltage conditions

		Average value [V]			
voltage type	$(V_a, V_b, V_c)[V]$	Estimator	SPS	PSIM	SEMITEACH 08753450 BB
balanced	(110,110,110)	257	255.84	257.36	263,4
	(141,141,141)	329.82	327.94	329.89	342,5
	(180,180,180)	421.04	418.65	421.14	428,3
	(200,200,200)	467.82	465.16	467.93	475,9
unbalanced	(20, 120, 120)	211,74	210,04	211,73	
	(20,20, 120)	133.67	132,07	133,80	
	(120, 60, 120)	236,48	234,88	236,58	

The accuracy of the results obtained with Estimator using the Adaline method and the switching functions is thus validated, with the small differences obtained with SPS due to differences in the switch models. For example, our analysis takes into account perfect switches, which have zero resistance for a closed switch and infinite resistance for an open switch, whereas PSIM takes into account a high resistance of 1.5 MΩ for an open switch and a low resistance of $11\mu\Omega$ for a closed switch.

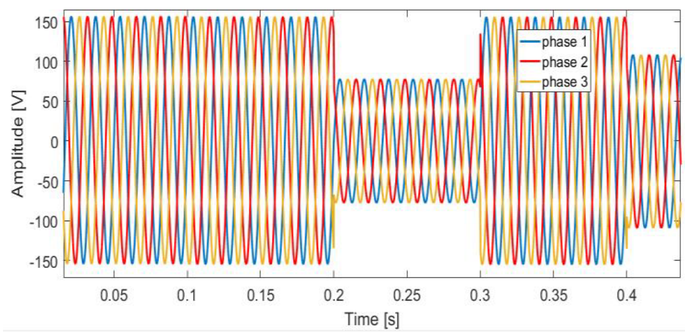

Fig. 7. Three-phase voltages for symmetrical faults, under 50% and 30%

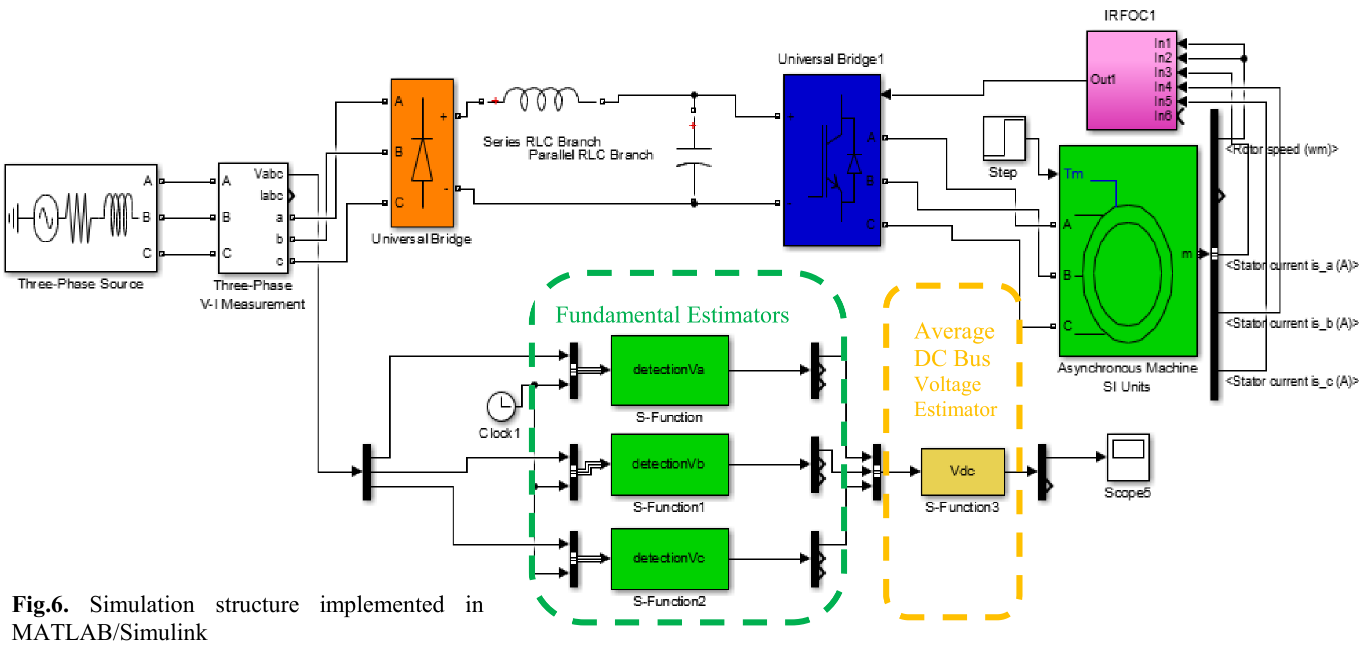

Fig.6. Simulation structure implemented in MATLAB/Simulink

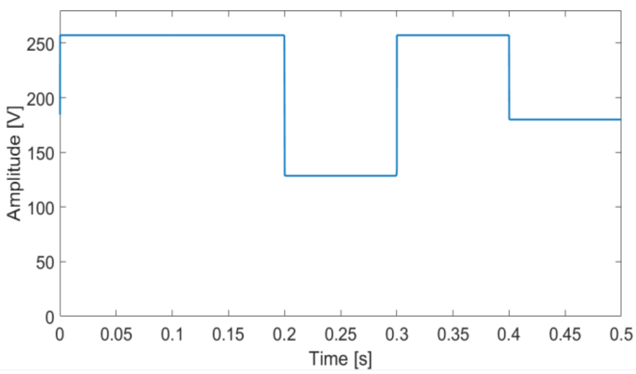

Fig. 8. Estimated DC Bus average voltage under 50% and 30%

Figure 7 represents Three-phase voltages voltage waveforms for symmetrical voltage sags from 50% between 0.2 and 0.3 s, and from 30% between 0.2 and 0.3 s respectively; Figure 8 corresponds to real data measurements estimated average voltage under symmetrical faults. The voltage sag is identified, this method can detect DC Bus average voltage in real-time, and it is very accurate in determining inception and recovery instants.

5 Conclusion

This paper presents a method to estimate the inception and recovery instants of the DC Bus average voltage sag, and the event duration, figure 8 summarizes the performance of the method. the Algorithm of the ADALINE method applied to the estimation of the fundamental and the phase of the three-phase source has been exposed, and the concept of the switching functions has allowed us to analyse and determine equations for the calculation of the average value of the rectified voltage, in the presence of balanced and unbalanced voltage dips for the different converters. Some measurements presented in Table 1 show the validity of the developed equations. These models are very useful for the development of a voltage dip management strategy for multi-motor systems.

References

1. G.Devadasu, S.Muthubalaji, S.Srinivasan, Anil Gunde “ An experimental approach of DVR for relieving voltage dip and voltage swell ” https://doi.org/10.1016/j.matpr.2021.01.056
2. A. Moreno-Munoz, J. J. G. de la Rosa, "Voltage Sag in Highly Automated Factories", Industry Applications Society Annual Meeting 2008. IAS '08. IEEE, pp. 1-6, 2008.
3. M. H. J. Bollen, “Understanding Power Quality Problems - Voltage Sags and Interruptions”, 1st edition, IEEE Press, 2000.
4. M.Bensaid, A. Barazzouk, M. Elharoussi, and B. Rached “Effects of Symmetrical Voltage Sags on Two Induction Motors System Coupled with An Elastic Web”. Proceedings of the 2020 IEEE 2nd International Conference on Electronics, Control, Optimization and Computer Science (ICECOCS), pp.1-6,2020.
5. Imdadullah , Syed Muhammad Amrr , Atif Iqbal , M.S. Jamil Asghar “Comprehensive performance analysis of flexible asynchronous AC link under various unbalanced grid voltage conditions” DOI: 10.1016/j.egyr.2021.01.028
6. Alvaro Furlani Bastos; Surya Santoso; Grazia Todeschini “Comparison of Methods for Determining Inception and Recovery Points of Voltage Variation Events” DOI: 10.1109/PESGM.2018.8585977
7. Tao Yang,Serhiy Bozhko,Greg Asher “Fast functional modelling of diode-bridge rectifier using dynamic phasors” https://doi.org/10.1049/iet-pel.2014.0414
8. Surya Hardi, R. Harahap, S. Ahmad, M. Isa“Ride through testing of variable speed drive due to voltage sag types (types I, II and III) ”DOI: 10.11591/ijpeds.v10.i2.pp690-696
9. C. Marouchos, M. Darwish and M. EI-Habrouk, "New mathematical model for analyzing three-phase controlled rectifier using switching function," IET Power Electron., vol. 3, pp. 95-110, Jan. 2010
10. K. L. Lian; Brian K. Perkins; P. W. Lehn "Harmonic Analysis of a Three-Phase Diode Bridge Rectifier Based on Sampled-Data Model" DOI: 10.1109/TPWRD.2008.917671
11. Mohsen Jannati , Mohammad Mohammadi « A novel fast power swing blocking strategy for distance relay basedon ADALINE and moving window averaging technique » DOI: 10.1049/gtd2.12015,2020
12. Sarawut Janpong, Kongpol Areerak and Kongpan Areerak «Harmonic Detection for Shunt Active Power Filter Using ADALINE Neural Network» doi.org/10.3390/en14144351;,2021