THE IMPLEMENTATION OF THE FREQUENCY ANALYZER PRINCIPLE FOR THE ESTIMATION OF THE ELECTRONICALLY SWITCHED CAPACITOR'S CAPACITANCE

Adrian DĂNILĂ, Radu CÂMPEANU
Transilvania University from Brasov, Romania

Abstract. In this work, the authors investigated the implementation of the frequency analyzer principle to produce real-time estimates of the equivalent capacitance of the electronically switched capacitor for the two-phase induction servo-motor. The on-line estimation of the capacitance of the start-up switched capacitor for the auxiliary phase of the two phased induction motor is subjected to disturbances due to the large commutation voltages. The correlation frequency analyzer is mainly used in systems identification to estimate the dynamic models within the frequency and correlation identification methods. In comparison with the direct data averaging, the frequency analyzer implementation is less noise sensitive, more accurate and subjected to the embedded implementations. The experimental results of this investigation proved that the embedded implementation of the frequency analyzer principle is possible within the same microcontroller that produces the control law for the switched capacitor.

Keywords: electronically switched capacitor, frequency analyzer, two-phase induction servo-motor

1. Introduction

The electronically switched capacitor is used for the frequency or phase-angle control within a wide range of applications such as the power factor optimization and the electronically controlled oscillators and receivers [5, 6, 7]. In electrical drives, the electronically switched capacitor is used for the optimization of the two-phase induction servo motor in two directions (1) the maximization of the start-up torque and (2) the optimization of the machine's efficiency at steady-state operation, [3, 4].

The two-phase induction servo motor is widely used in the industrial automations as execution element within the remote control of the hydraulic valves, for fans and small pumps. In the domestic appliances the two-phase induction motor is mainly used as execution element for the washing machines. The rated power of the motor is in the range of some watts up to two kilowatts.

Several contributions to the optimization of the two-phase induction servo motor are presented in the literature. Liu, [3], and Muljadi, [4], proposed a two direction electronic switch parallel connected with the capacitor. This structure is simple but the range of the controlled capacitance is reduced. The full controlled bridge structure of the switched capacitor, proposed by Lettenmaier [8] and Suciu [2] produce larger range for the controlled capacitance. In previous works, the authors of this work emphasized the main characteristics of two-phase induction motor controlled with the electronically switched capacitor from both the mathematical modelling and optimization points of view, [9, 10, 11, 13, 14]. The quoted investigations lead to the idea of the feedback control of the capacitance for the drive. In this perspective, the on-line estimation of the capacitance from the measurements of voltages and currents within the drive is mandatory. This problem raises difficulties due to the high commutation noise produced by the switching capacitor.

In this work, the authors investigated the implementation of the frequency analyzer for the estimation of the equivalent capacitance from measurements. The paper's organization is as follows: in the second section are presented the theoretical aspects of the frequency analyzer and the operation principle of the electronically switched capacitor; the experiment organization and the additional software are described in the third section of the paper; the results of the study and the associated interpretations and conclusions are presented within the fourth part of the paper.

2. Prerequisites and means for the problem solution

2.1. The frequency analyzer principle

The frequency analyzer is used in System Identification to produce estimated values of a system frequency function from input / output sinusoidal signals, into the frequency analysis method [1, 12]. The signals are eventually corrupted by measurements and system's noise.

The frequency analyzer principle, Figure 1 consists in the multiplication of the output sinusoidal signal with two other sine and cosine probe signals. The signal under investigation and the probe signals feature the same angular frequency. In sequel, the results are integrated over an integer number of periods.

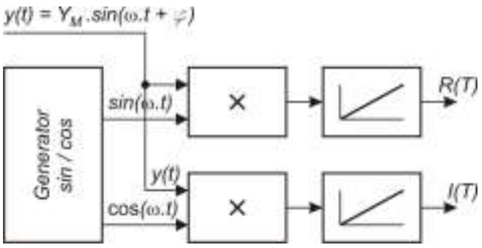

Figure 1. The schematic of the frequency analyzer principle

In this work is proposed a slight modification of the analyzer for the estimation of the amplitude and the phase angle of the noise corrupted sinusoidal input signal instead of the magnitude and argument of the frequency transfer function.

In this approach, the principle of the frequency analyzer is given in the followings.

Consider the sinusoidal signal with the *rms* value *Y*, the angular frequency ω, and the phase angle φ:

$$y(t)=\sqrt{2}\cdot Y\cdot\sin(\omega\cdot t+\varphi)=\sqrt{2}\cdot\mathrm{Im}\{\underline{Y}\}. \quad (1)$$

The signal at the output sine channel of the analyzer is given by the following expressions:

$$\begin{aligned} R(T)&=\frac{1}{T}\cdot\int_0^T y(t)\cdot\sin(\omega\cdot t)dt=\\ &=\sqrt{2}\cdot Y\cdot\frac{1}{T}\cdot\int_0^T\sin(\omega\cdot t)\cdot\sin(\omega\cdot t+\varphi)dt=\\ &=\sqrt{2}\cdot Y\cdot\frac{1}{2\cdot T}\cdot\int_0^T[\cos(\varphi)-\cos(2\cdot\omega\cdot t+\varphi)]dt=\\ &=\sqrt{2}\cdot Y\cdot\frac{1}{2\cdot T}\cdot\left[T\cdot\cos\varphi+\frac{1}{2\cdot\omega}\cdot\sin\varphi-\right. \\ &\left.-\frac{1}{2\cdot\omega}\cdot\underbrace{\sin(2\cdot\omega\cdot T+\varphi)}_{T=\frac{N\cdot\pi}{\omega}\Rightarrow\sin\varphi}\right]=\sqrt{2}\cdot Y\cdot\frac{1}{2\cdot T}\cdot T\cdot\cos\varphi=\\ &=\frac{\sqrt{2}}{2}\cdot Y\cdot\cos\varphi=\frac{\sqrt{2}}{2}\cdot\mathrm{Re}\{\underline{Y}\}. \end{aligned} \quad (2)$$

Similarly, the output signal at the cosine channel of the frequency analyzer will be as follows:

$$\begin{aligned} I(T)&=\sqrt{2}\cdot Y\cdot\frac{1}{2\cdot T}\cdot T\cdot\sin\varphi=\\ &=\frac{\sqrt{2}}{2}\cdot Y\cdot\sin\varphi=\frac{\sqrt{2}}{2}\cdot\mathrm{Im}\{\underline{Y}\}. \end{aligned} \quad (3)$$

The frequency analyzer is high selective in frequency acting as a band pass filter with the centre frequency ω, (the frequency analyser's frequency). This is the feature that allows the use of the frequency analyzer for the analysis of the voltages and currents at the electronically switched capacitor.

2.2. The electronically switched capacitor

The schematic of the full controlled bridged electronically switched capacitor [2] is depicted in Figure 2.

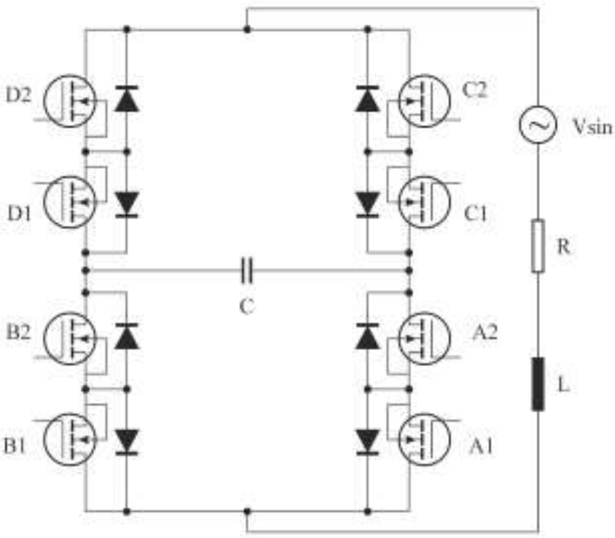

Figure 2. The electrical diagram of the proposed electronically switched capacitor, [2]

A commutation cycle consists of two steps. For the positive polarity of at the lower terminal of the bridge, in the first commutation step the transistors A_1, D_1 and the free wheeling diodes A_2, D_2 are switched on. In the second commutation step the transistors C_1, B_1 and the free wheeling diodes C_2, B_2 are switched on. For the negative polarity of at the lower terminal of the bridge, in the first commutation step the transistors A_2, D_2 and the free wheeling diodes A_1, D_1 are switched on. In the second commutation step the transistors C_2, B_2 and the free wheeling diodes C_1, B_1 are switched on.

The duty cycle is the ratio between the time interval of the first commutation step and the switching period.

Comprehensive studies of the electronically switched capacitor are presented in [6] and [2].

The relation between the equivalent capacitance, C_e of the electronically commutated capacitor and duty cycle is given by the following expression [2]:

$$C_e = \frac{C}{(2 \cdot a - 1)^2}, \tag{4}$$

where C is the capacitance of the capacitor and a is the commutations' duty cycle.

3. The experiment organization and the additional software

3.1. The experiment setup

The objective of the experiment was the experimental determination of the equivalent capacitance of the electronically switched capacitor by means of the described principle. The experimental setup, Figure 3 consisted of four snubber circuits grouped within one block – (A), one signal conditioner with eight outputs – (B), one control unit based on the ATmega32u4 micro-controller – (C), and one capacitors block – (E), the equivalent capacitance of this block was set to 10.5 μF. The load of the switched capacitor was a resistor; the equivalent resistance of the resistor was 100 Ω.

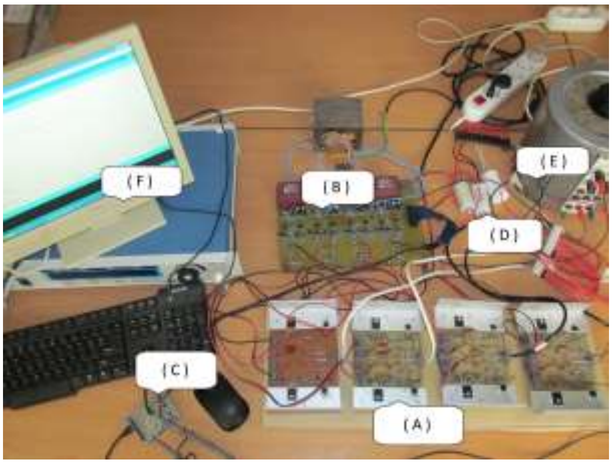

Figure 3. The experimental setup

The electrical variables (voltages and currents) were observed by means of a Metrix OX 6152 featured with serial and Internet connections.

The data acquisition and computations were made by means of two dedicated software applications. The first software application was implemented into the embedded microcontroller for the snubber's control pulses. The second software application was made for the data acquisition and computations. This software was written into the MathLab software environment and connected with the scope by means of the serial interface.

The graphical interface of the mentioned application, Figure 4 is provided with several software objects that allow the basic commands and monitoring.

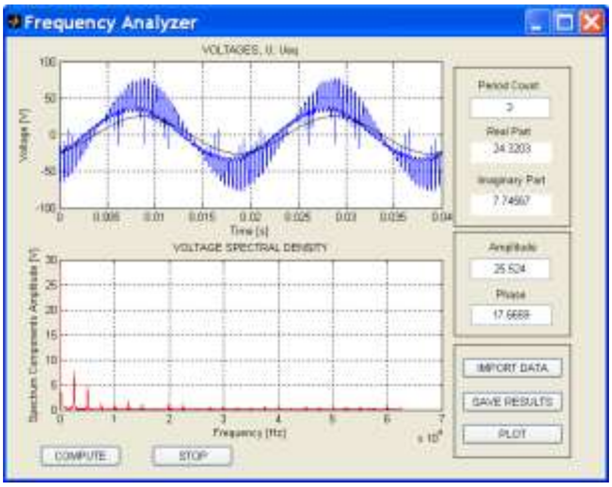

Figure 4. The graphical interface of the second software application

The main features of the application were (1) the implementation of the frequency analyzer for the noisy input data, (2) the computation of the amplitude and phase angle of the equivalent signal and (3) the computation of the amplitude spectral density of the signal and (4) the computation of the equivalent capacitance of the electronically switched capacitor.

3.1. The experiment procedure

The duty cycle of the electronically switched capacitor was set to values within the range (0.5… 1) by means of the control unit. The voltage and current through the resistive load were measured and acquired. The supply voltage at the input terminals was maintained constant at 40 V.

The acquired, measured data (voltages and currents) were loaded into the second software and interpreted.

An additional database application was used to the final interpretation and conclusions.

4. Results and discussion

The voltages and currents wave forms as well as the corresponding amplitude spectral densities are depicted in Figures 5 to 7.

The wave forms are corrupted by the capacitor's commutation noise as seen in Figures 5 and 6. The frequencies of the signal's high order harmonics correspond to the commutation frequency and its multiples, Figure 7.

The amplitude spectral density for the load current features the same harmonics as the voltage.

The magnitude and the phase angle of the estimated signals at the output of the frequency analyzer are modified by the corrupting commutation noise.

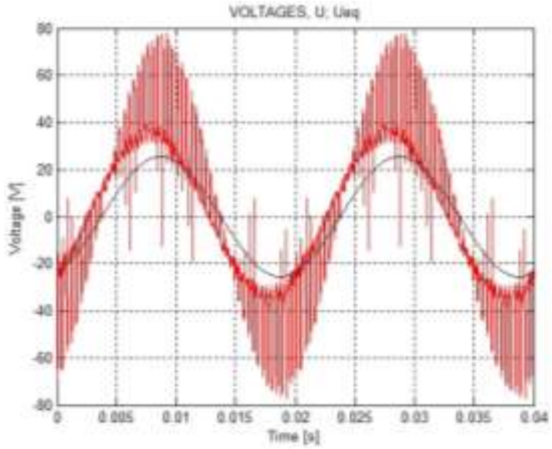

Figure 5. The load voltage (1) measured values – the thick plot, and (2) the estimated values – the thin plot. Duty cycle a = 0.6875

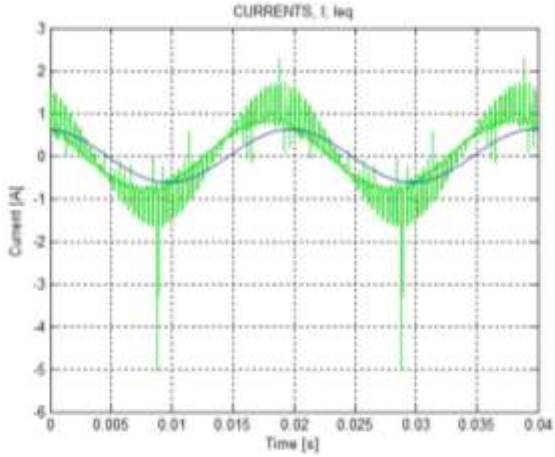

Figure 6. The plot of the load current (1) measured values – the thick plot, and (2) estimated values – the thin plot. Duty cycle a = 0.6875

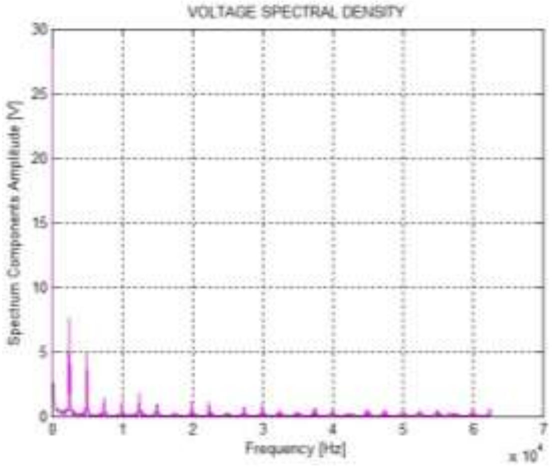

Figure 7. The amplitude spectral density of the load voltage. Duty cycle a = 0.6875

The true and estimated capacitances of the electronically switched capacitor are presented in Table 1.

Table 1. True and estimated capacitance of the switched capacitor with respect to the duty cycle

Duty cycle	True value	Estimated value	Estimation error
-	[μF]	[μF]	[%]
0.9375	22.40	28.32	26.429
0.8750	24.25	30.30	26.250
0.8125	25.85	32.46	25.571
0.7500	28.00	34.51	23.250
0.6875	30.55	39.41	29.002
0.6250	33.60	45.24	34.643

In Figure 8, the main experimental results are depicted in the graphical representation.

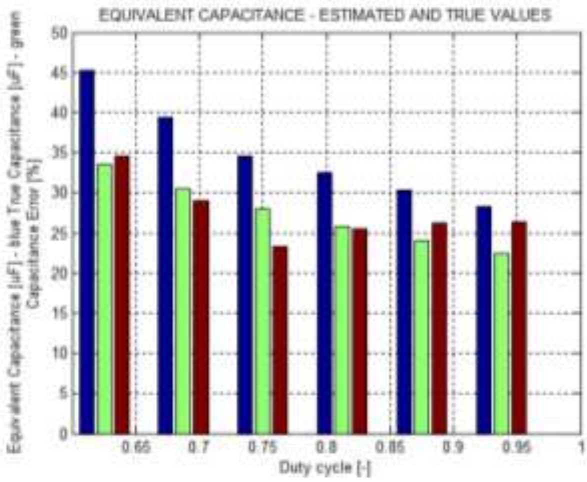

Figure 6. The equivalent capacitance vs. the true equivalent capacitance with respect to the duty cycle. The estimation errors with respect to the duty cycle

The equivalent capacitance decreases with the increase of the commutation duty cycle. The average of estimation errors is 27.524 %. The commutation frequency of the electronically switched capacitor was set to 2.5 kHz which is a multiple of the input voltage, i.e. 50 Hz. This fact increased the systematic errors of the frequency analyzer.

4. Conclusions

In this work, the authors investigated the implementation of the frequency analyzer principle to produce real-time estimates of the equivalent capacitance of the electronically switched capacitor for the two-phase induction servo-motor. In this approach we proposed a slight modification of the frequency analyzer principle. The software implementation of the frequency analyzer algorithm to the noisy signals acquired from the electronically switched capacitor produced consistent estimates of the equivalent capacitance.

The future developments of this work will consist in the embedded implementation of the algorithm and in the integration within the automatic control of the electronically switched capacitor. This development allows the maximization of the torque and energetic efficiency of the induction servo-motor start-up.

References

1. Soderstrom, T., Stoica, P. (2001): *System Identification*. Prentice Hall International, ISBN 0-13-881236-5, New York, USA
2. Suciu, C., et al. (1996): *Phase advancing for current in R-L circuits using switched capacitors*. Electronics Letters, IEE Journal, ISSN 0013-5194, vol. 35, no. 16, p. 1296-1927
3. Liu, T.H. (1995): *A maximum torque control with a controlled capacitor for a single-phase induction motor*. IEEE Trans. on Industrial Electronics, ISSN 0278-0046, vol. 42, no. 1, p. 17-24
4. Muljadi, E, et al. (1993): *Adjustable ac capacitor for a single-phase induction motor*. IEEE Transactions on Industry Applications, ISSN 0093-9994, vol. 29, no. 3, p. 479-484
5. Laker, K.A. (1993): *Sampled-Data Signal Processing With Switched Capacitor Circuits*. Proceedings of Canadian Conference on Electrical and Computer Engineering, ISBN 0-7803-2416-1, p. 389-404, DOI: 10.1109/CCECE.1993.332338
6. Liou, M.L., Kuo, Y.-L. (1979): *Exact Analysis of Switched Capacitor Circuits with Arbitrary Inputs*. IEEE Transactions on Circuits and Systems, ISSN 0098-4094, vol. CAS-26, no. 4, p. 213-223
7. Divan, D.M. (1984): *Nondissipative switched networks for high-power applications*. Electronics Letters, ISSN 0013-5194, vol. 20, no. 7, p. 277-279
8. Dănilă, A. (2011): *The dynamic model of the capacitor-run two-phase induction motor – a variational approach*. Annals of Faculty Engineering Hunedoara – International Journal of Engineering, ISSN 1584-2665, Tome IX, fasc. 2, p. 125-128
9. Dănilă, A., Câmpeanu, R., Mera, R.M. (2010): *A Study on the Euler-Lagrange Dynamic Models of the Single/Two Phase Capacitor-Run Induction Machines*. Proc. of the 9th WSEAS Int. Conf. Recent Researches in Circuits, Systems, Electronics, Control & Signal Processing - CSECS'10, ISBN 978-960-474-262-2, p.137-142, Vouliagmeni, Greece
10. Dănilă, A., Pavel, G., Mera, R.M. (2011): *A study of the parameter estimation of the single/two-phase induction machines*. Annals of Faculty Engineering Hunedoara – International Journal of Engineering, ISSN 1584-2673, Tome IX, fasc. 4(extra), p. 19-22
11. Dănilă, A. (2013): *Modelarea şi identificarea sistemelor dinamice* (*The Dynamic Systems' Modeling and Identification*). Editura Universităţii Transilvania din Braşov, ISBN 978-606-19-0271-2, Brasov (in Romanian)
12. Dănilă, A., et al. (2008): *The optimization of the single/two phase induction motor start-up with electronically switched capacitor*. Proceedings of the 2008 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR 2008), Theta 16th Edition, vol. III, ISBN 978-1-4244-2576-1, p. 450-453, Cluj-Napoca, Romania
13. Dănilă, A., et al. (2008): *Experimental validation of the dynamic model of a single/two phase induction motor*. Proceedings of the 11th International Conference on Optimization of Electrical and Electronic Equipment, vol. II A and B, ISBN 978-973-131-030-5, p. 3-8, Brasov, Romania

Received in October 2015