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Energy consumption reduction of a center-pivot with the use of a variable-frequency drive

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Abstract

Pressure demand of a center-pivot can be controlled by variable frequency drives during irrigation system operations, leading to a rational use of electrical energy. However, numerous studies encountered problems due to the lack of field data to perform the simulations. The objective of this study was to simulate the reduction of the average value of the active electrical power required to drive the pumping unit of a center-pivot irrigation system by controlling the rotational speed through a frequency inverter. The simulation was conducted considering a complete rotation of the lateral line of a central pivot, installed in an area of 70-ha, in the municipality of Formiga-MG. The simulation demonstrated the possibility of reducing the active electrical power required for the pivot pump by 18%, from an average of 131 to 107 kW. For 1300 pumping hours per year, the investment's payback time would be two and four years for the highest (R$ 0.48 kWh-1) and lowest energy cost (R$ 0.32 kWh-1), respectively. Results suggest that irrigated areas by center-pivot with variations of topographic altitude require technical-economic evaluations for using frequency inverters.

Keywords

Irrigation; Electric Power; Simulations.

Introduction

Irrigation is the largest consumer of water in agricultural production, but it is also the most efficient way to produce food, fiber, and bioenergy. 23% of the total area cultivated is irrigated, and it provides more than 40% of agricultural production (Comas et al., 2019). It is expected that irrigation and nutrient input intensification will increase global crop production volumes by up to 150% in the next few years (Gupta et al., 2020).

According to Ayrimoraes (2020), 8.2 million hectares correspond to the irrigated area in Brazil. Sprinkling is the most predominant method, subdivided into 27% for central pivots. The irrigated area by central pivots is distributed among 415, 250, 202, 211, and 125 thousand hectares for the states of Minas Gerais, Goiás, São Paulo, Bahia, and Mato Grosso, respectively. In these areas, the cost of irrigation is primarily the expense of power and equipment.

In 2015, the energy consumption of the rural segment was approximately 3.5 million MWh, corresponding to 5.9% of the total energy of the Cemig group. Compared to 2014, consumption was reduced by 0,14% for use in irrigated agriculture, which could be associated with the increase in energy tariffs (CEMIG, 2015).

One of the great challenges facing Brazil, as in other countries, is the growing demand for energy. Short-term solutions require large investments in power generation, and an agile alternative to such a challenge would be the rational use of available forms of energy (Pereira et al., 2013; Coelho et al., 2019). With frequent increases in electricity rates, water pumping has become a large part of the production cost of the irrigated agricultural sector, which makes it necessary to seek methods to reduce these costs (Almeida et al., 2016; Azevedo, 2003; Costa et al., 2017).

The variable frequency drive allows adjusting the pump rotation according to the best suitability, adjusting the energy consumption to the load requirements. In this way, center-pivot tests showed that control of the pump rotation leads to significant energy savings (Brar et al., 2017). However, due to the high costs associated with the installation of the frequency inverter, their implementation must be preceded by a technical economic study.

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The objective of this study was to simulate the reduction in the average value of electric power required by adjusting the pump rotation of a pivot irrigation system. In addition, to assess the economic feasibility, the payback period for the initial cost of using the frequency inverter was determined.

Materials and methods

The simulations were carried out for a center-pivot irrigation system installed at Farm São Pedro in Formiga, Minas Gerais state, Brazil. The center of the fixed tower is located at latitude 20°37'28.28" S and longitude 45°34'36.09" W, at an altitude of 821m. The main characteristics of this pivot are shown in Table 1.

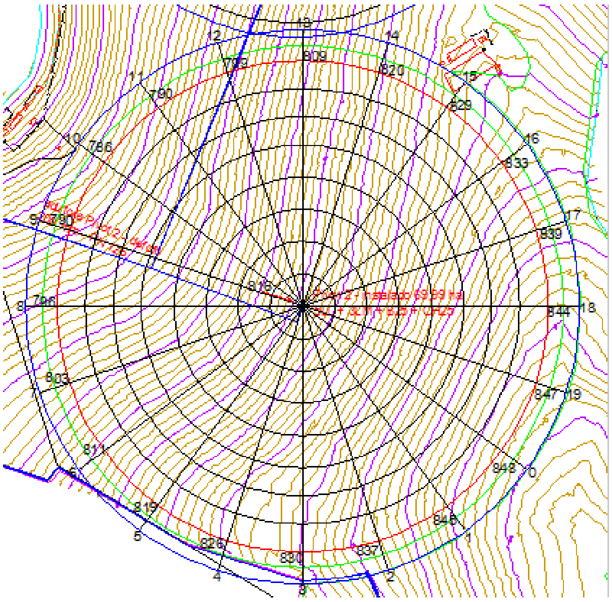
Table 1. Characteristics of the center pivot, the pipe, and the pumping unit.

Characteristics of the center-pivot	
Brand / model	Valley/ 4871-8000 -VSL/8 -1.101
Length of spans	54.86m+54.86m+54.86m+54.86m+ 54.86m+48m+48m+48m+25m(Swing)+ 28m (Final Cannon) = 471.3m
Last Tower Radius / Turning Time	418.55m/ 9.39horas
Irrigated radius / irrigated area / spin	472.00m/ 69.99ha/ 360°
Total flow / gross blade per course	249.96m³/h/ 3.35mm/come back
Advancing tubulation	
Material / Diameter / Length	Pipe 1: Zinc-plated steel / 200mm/ 150m Pipe 2: PVC PN 125/ 200 mm/ 635m
Total manometric height / NPSH Available	
Pressure at the end of the pivot side	13.00mca
Rising pivot point - highest point	34.00m
Load loss on the pivot side	13.66mca
Height of the sprinklers	4.55m
Pressure at pivot point	65.21mca
Pneumatic Pump Dump - Pivot Point	55.00m
Loss of load on the pipeline	15.65mca
Maximum suction height	1.50m
Localized losses	6.87mca
Total manometric height	144.23mca
NPSH available on site	6.74mca
Pump unit	
Pump data	Engine data
Brand / model: KSB/WKL 150/3	Brand: MWM
Rotor diameter / rot.: 315mm/ 1750rpm	Engine: Diesel
Flow / pressure: 250m³/h /151 mca	Rotation / poles: 1750rpm
Yield/ NPSH req: 74%/ 3mca	
Power absorbed at the axle: 188.94 hp	

Source: Valley Irrigation (2022).

Twenty different equally spaced geometric positions adopted by the lateral line along its rotational motion around the stationary pivot point were considered in this study (Figure 1). To simplify the computational procedure, at each one of the geometrical positions, identified by an "i" index value ($0 \leq i \leq 19$), a constant value of lateral line topographic slope (S_i) was assumed. Each topographic slope value was computed based on the topographic elevation difference of each considered position of the last tower path (Z_{li} in Figure 1) to the pivot point ($Z_o = 816$ m) and the distance from the stationary pivot point up to the last tower (418.3 m). In this way, negative topographic slope means that the topographic elevation of the last tower path is greater than the topographic elevation of the stationary pivot point.

Figure 1. Twenty lateral line positions and the altitude of the irrigated area with the central pivot of the last tower dimensions.



Source: Original results.

The system was fed by a KSB / WKL 150/3 pump with 315mm rotors and a 1750 rpm rated speed. The characteristic of this pump is represented by the polynomial model described by Azevedo (2003), which allows estimating the flow pairs and the total pressure head of a pump operating under different combinations of number of rotors, rotor diameter and pump rotation shaft speed.

The required value of the pressure head at the base of the riser at the pivot point was determined for the twenty different geometric positions of the lateral line of the central pivot following the methodology proposed by Azevedo (2003).

The distance between the pivot point and the point of lowest pressure head of the pivot lateral line was calculated, as described by Azevedo (2003), considering three different situations:

a) When the value of the average slope of the lateral line (s_{α})is positive (ascending lateral) or is zero (level lateral), i.e., when the elevation of the last tower ($ZUT_{\propto}$) is greater than or equal to the elevation of the base of the pivot point (ZP), the point of minimum pressure of the lateral line is at the end, Equation (1):

$$r_{\propto} = L, \text{if } s_{\propto} \geq 0 \qquad (1)$$

where,

L: length of the lateral pivot line (m).

b) When the value of the average slope of the lateral line ($s_{\propto}$) is negative (downward lateral), i.e., when the elevation of the last tower ($ZUT_{\propto}$) is lower than the elevation of the base of the pivot point (ZP) and the lateral slope modulus is lower than the modulus of the pressure head loss rate at the beginning of the lateral line; the minimum pressure point occupies an intermediate position between the end of the lateral ($r_{\alpha} = L$) and the pivot point (r_{α} =0m), Equation (2):

$$r_{\propto} = R.\sqrt{1 - \left(\frac{|s_{\propto}|}{J_{r=0}}\right)^{\frac{1}{1.852}}}\, if, s_{\propto} < 0 \quad and\ |S_{\alpha}| < J_{r=0} \qquad (2)$$

where,

$J_{r=0}$: pressure drop rate at the beginning of the pivot lateral line (m/m)

c) when the value of the average slope of the lateral line ($s_{\propto}$) is negative (downward lateral), i.e., when the elevation of the last tower (ZUT_{α}) is lower than the elevation of the base of the pivot point(ZP) and the modulus of the slope of the lateral is greater than the modulus of the pressure drop rate at the beginning of the lateral line, the point of minimum pressure is located at the pivot point, Equation (3):

$$r_{\propto} = 0 \quad \text{if, } S_{\propto} < 0 \quad and\ |s_{\propto}| \geq J_{r=0} \qquad (3)$$

The pressure head loss rate at the beginning of the lateral ($J_{r=0}$) was calculated for a head loss up to the end of the lateral line equal to the value indicated in the technical data sheet of the pivot following the Hazen-Williams approach (Allen, 1966).

For each of the twenty lateral line positions, the total pressure head required by the pump was calculated using the expression proposed by Azevedo (2003). The Newton-Raphson method was used to calculate the angular velocity of the pump, which resulted in the required manometric head ($HMT_{\propto}$) at the different positions assumed by the moving lateral (Ruggiero & Lopes, 1997). The active electrical power required to drive the pump without a frequency converter (nominal pump rotational speed), as well as the active electrical power required by the pump motor set operating with a frequency converter, was calculated using the expression of Azevedo (2003).

This study adopted the electricity prices established by CEMIG (*Companhia Energética de Minas Gerais*). The price considered for the conventional tariff for the normal rural class (with an ICMS of 18%) + Green Flag: R$0.37 kWh; normal rural class + Green Flag + Pasep/Confins Tariff: R$0.39 kWh; normal rural class + Green Flag + Pasep/Confins+Icms Tariff: R$0.48 kWh. For night irrigation, there is an incidence of only 12% ICMS, in addition to the 67% discount in the normal rural class + Green Flag tariff.

For the feasibility assessment, the annual value of the energy savings if the frequency converter is integrated was calculated. The cost of the frequency inverter was based on a market study with the company WEG (Poços de Caldas, Minas Gerais, Brazil) in which it was observed that the values of frequency inverters vary from R$4364.00 to R$30,000.00 according to power, rotation and voltage.

Results and discussion

Table 2 shows the behavior of the point of minimum lateral line manometric height ($r_{\propto}$) determined by the three conditions established in equations (1), (2) and (3). When the point of minimum required pressure head is at the tip of the pivot, it requires a greater pressure head at the pivot point at position α, consequently a greater total required pressure head for the pump at position α.

Table 2. Height Calculation Parameters total gauge in different angular positions HMT (α in m).

Profile	α	ZUT∝	Sα	rα	HMT∝
	(grades)	(m)	(m m^{-1})	(m)	(m)
0	0	848	0.0765001	443.3	144.1
1	18	845	0.0693282	443.3	140.9
2	36	837	0.0502032	443.3	132.4
3	54	830	0.0334688	443.3	125.0
4	72	826	0.0239063	443.3	120.8
5	90	819	0.0071719	443.3	113.3
6	108	811	-0.0119531	350.4	105.4
7	126	803	-0.0310782	235.9	99.9
8	144	796	-0.0478126	109.8	96.9
9	162	790	-0.0621563	0	96.5
10	180	786	-0.0717189	0	96.5
11	198	790	-0.0621563	0	96.5
12	216	799	-0.0406407	172.3	97.9
13	234	809	-0.0167344	320.9	103.9
14	252	820	0.0095625	443.3	114.4
15	270	829	0.0310782	443.3	124.9
16	288	833	0.0406407	443.3	128.2
17	306	839	0.0549845	443.3	134.6
18	324	844	0.0669376	443.3	139.9
19	342	847	0.0741095	443.3	144.0

Elevation of the last tower ($ZUT_{\propto}$), average slope of the lateral line (s_{α}), distance between the pivot point and the point of lowest pressure head ($r_{\propto}$), and required pressure head (HMT).

Table 3 shows that the variation in rotation required to change the required total pressure head implies a very small variation in pump efficiency, which ranged from a maximum of 78.7% to a minimum of 78.1%.

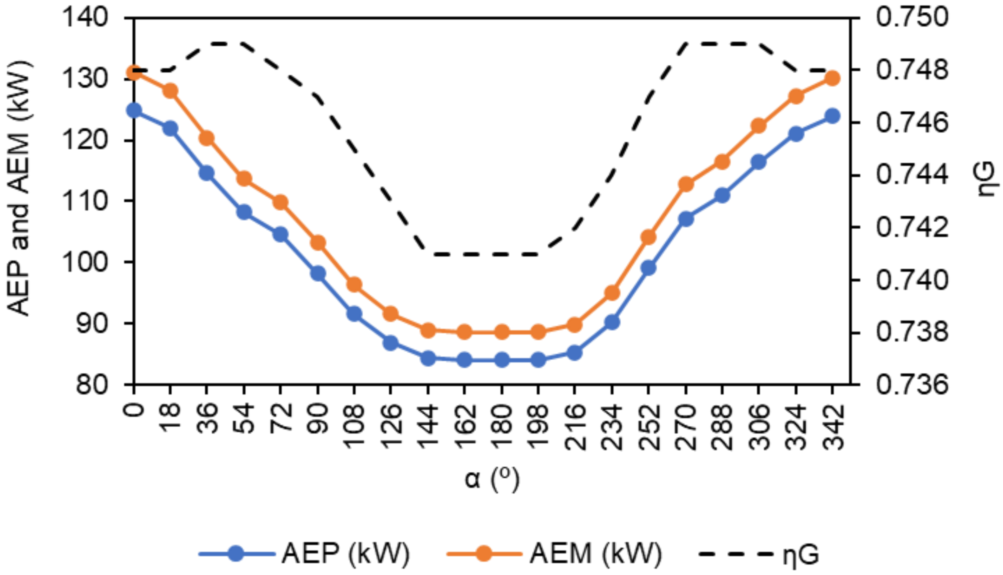
Table 3. The mechanical power calculating parameters on the pump shaft and the active power required by the inverter operating with inverter frequency.

Profile	α(°)	HMT∝(m)	rpm	nb	PME(kW)	PEA(kW)
0	0	144.1	1740.4	0.8	124.9	131.2
1	18	140.9	1724.5	0.8	122.1	128.2
2	36	132.4	1681.4	0.8	114.6	120.4
3	54	125.0	1642.7	0.8	108.2	113.7
4	72	120.8	1620.2	0.8	104.5	109.9
5	90	113.4	1580.1	0.8	98.2	103.3
6	108	105.5	1536.3	0.8	91.6	96.4
7	126	99.9	1504.4	0.8	86.9	91.6
8	144	96.9	1487.1	0.8	84.5	89.0
9	162	96.5	1484.9	0.8	84.1	88.7
10	180	96.5	1484.9	0.8	84.1	88.7
11	198	96.5	1484.9	0.8	84.1	88.7
12	216	97.9	1493.1	0.8	85.3	89.9
13	234	103.9	1527.2	0.8	90.3	95.0
14	252	114.4	1585.9	0.8	99.1	104.2
15	270	124.0	1637.2	0.8	107.3	112.7
16	288	128.2	1659.4	0.8	110.9	116.5
17	306	134.6	1692.3	0.8	116.5	122.3
18	324	139.9	1719.2	0.8	121.1	127.2
19	342	143.0	1735.1	0.8	123.9	130.2

Required pressure head (HMT), variation of rotation(rpm), pumping efficiency (nb), required mechanical energy (PME), required active electrical energy (PEA).

The variation of rotation of the pump according to the required total pressure head on the pump was between 1484.8 and 1740.3 rpm, requiring higher mechanical power from the pump shaft (Figure 2). The power demand of the system with the frequency inverter is ~107.4 kW. On the other hand, the maximum power consumption was ~131.1 kW with the pump system working without the frequency inverter. Therefore, there is an average reduction of 23.74 KW (18.1%) when using a variable-frequency drive, which is consistent with the energy savings reported by Pereira et al. (2013) in pivots of the same region when using inverters.

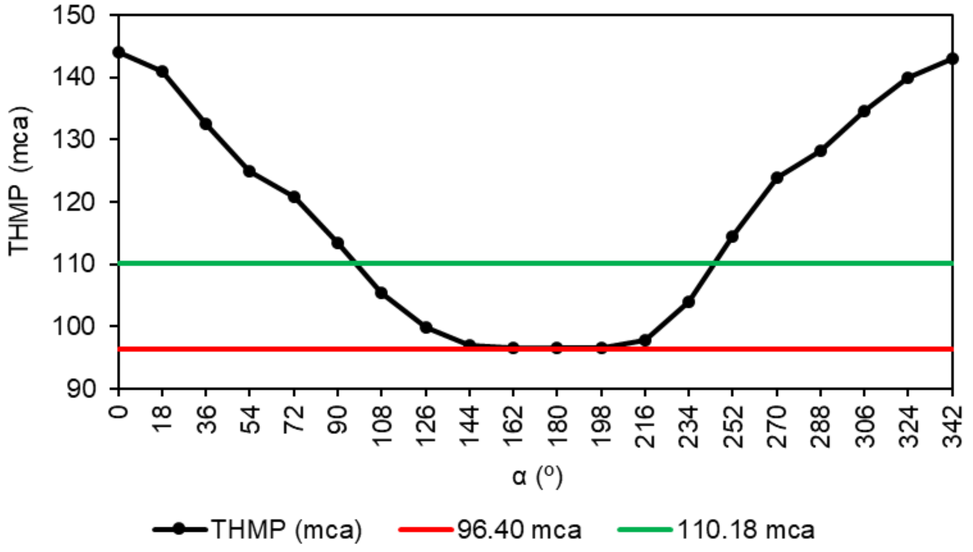
Figure 2. Mechanical power (AMP), electric power (AEP) required by the pumping unit and overall performance (ηG) at different positions of the lateral.



Moraes et al. (2014) testing an automated speed control of a center-pivot under different slope lines at 0, 10, 20 and 30% found that the energy savings were 48, 37, 26 and 16%, respectively. However, Brar et al. (2017) simulating the minimum pressure required by 100 pivots in Nebraska reported that large energy savings are associated with pivots operating at greater slopes. Overall, these inconsistencies due to topography highlight the importance of the technical-economic analysis for each project. In addition, King & Wall (2000) suggest acquiring data to evaluate the efficiency of frequency variation since higher values of energy savings could be obtained due to the inefficiency of the inverter that causes alterations in the system pressure.

The variation of the total required pressure head due to the position of the lateral line is shown in Figure 3. The difference between the total required head and the fixed part (96.52 mca) is the sum of the pressure head loss and the gap up to the minimum pressure point. A second curve of 110.18 mca fixed value has also been added which corresponds to the sum of the head loss value of 96.52 mca along the entire lateral. The intersections between the constant value line of HMT 110.18 m with the curve represent situations where the lateral is level with the center of the pivot.

Figure 3. Total pressure head (THMP) required in the α position depending on the angular position of the lateral.



The minimum number of operating hours of the pumping unit with a frequency drive for capital recovery under three scenarios is shown in Table 4. Considering these situations for an average 1300 pumping hours per year, the shortest payback period was 2 years under the highest electric tariff while the longest payback period was 4 years under the lowest electric tariff.

Table 4. Time return rate in different scenarios.

Rate Scenarios	Price	Economy	NH
	R\$ kWh^{-1}	R\$ h^{-1}	h
Normal	0.37	8.92	3361.57
Green/Daytime	0.48	11.61	2583.77
Green/Night	0.32	7.78	3856.71

The payback period was lower than that reported by Lima (2009) for a 44 ha central pivot with a frequency inverter. According to Campana et al. (2000) and Brar et al (2017), the differences in the payback period are mainly due to the hydraulic characteristics of the topography of the pivot area and the pumping unit. Furthermore, in this study, electric tariffs had an impact on the payback period. Therefore, the characteristics of each site lead to decision-making on the use of inverters.

Conclusions

The implementation of a frequency inverter in the pumping unit reduces 18.1% of the power consumed by the pivot.

For 1300 pumping hours per year, the payback time for the highest tariff is 2 years, while for the lowest tariff the payback time would be extended to 4 years.

In center pivot areas with irregular topography, it is desirable to perform a technical and economic feasibility analysis before installing a variable frequency drive.

References

Allen, R. G. (1996). Relating the Hazen-Williams and Darcy-Weisbach friction loss equations for pressurized irrigation. *Applied Engineering in Agriculture*, 12(6), 685-693.

Almeida, A. N., Coelho, R. D., Farias, A. J., Monteiro, R. O., & Costa, J. O. (2016). Comparative study of energy costs in irrigation according to the new Brazilian electricity tariff model. *Engenharia Agrícola*, *36*, 902-916. https://doi.org/10.1590/1809-4430-Eng.Agric.v36n5p902-916/2016

Ayrimoraes, S. (2020). *Atlas irrigação (2nd ed.)*. Agência Nacional de Águas (ANA).

Azevedo, E. B. de. (2003). *Viabilidade do uso do inversor de freqüência em sistema de irrigação do tipo pivô central*. Universidade Federal de Lavras–UFLA.

Brar, D., Kranz, W. L., Lo, T., Irmak, S. & Martin, D. L. (2017). Energy conservation using variable-frequency drives for center-pivot irrigation: Standard systems. *Transactions of the ASABE*, *60*(1), 95–106. https://doi.org/10.13031/trans.11683

Campana, S., Oliveira Filho, D. & Soares, A. A. (2000). Inversores de freqüência: uma alternativa para racionalização do uso da energia elétrica em sistemas de irrigação pivô central. *Proceedings of the 3. Encontro de Energia No Meio Rural*.

CEMIG. (2015). *Annual sustainability report 2015-Cemig*. cemig.org.br

Coelho, R. D., Lizcano, J. V., da Silva Barros, T. H., da Silva Barbosa, F., Leal, D. P. V., da Costa Santos, L., Ribeiro, N. L., Júnior, E. F. F. & Martin, D. L. (2019). Effect of water stress on renewable energy from sugarcane biomass. *Renewable and Sustainable Energy Reviews*, *103*(January), 399–407. https://doi.org/10.1016/j.rser.2018.12.025

Comas, L. H., Trout, T. J., DeJonge, K. C., Zhang, H. & Gleason, S. M. (2019). Water productivity under strategic growth stage-based deficit irrigation in maize. *Agricultural Water Management*, *212*, 433–440. https://doi.org/10.1016/j.agwat.2018.07.015

Costa, J. O., Coelho, R. D., Almeida, A. N., Farias, A. J., & Monteiro, R. O. C. (2017). Energia elétrica e irrigação no Brasil: impacto das bandeiras tarifárias. *Item - Irrigação e Tecnologia Moderna*, 110-111-112, 52-55.

Gupta, A., Rico-Medina, A. & Caño-Delgado, A. I. (2020). The physiology of plant responses to drought. *Science*, *368*(6488), 266–269. https://doi.org/10.1126/science.aaz7614

King, B. A. & Wall, R. W. (2000). Distributed instrumentation for optimum control of variable speed electric pumping plants with center pivots. *Applied Engineering in Agriculture*, *16*(1), 45.

Lima, A. dos S. (2009). *Uso de inversor de frequência em sistema de irrigação do tipo pivô central e seu efeito na lâmina e uniformidade de distribuição de água*. Universidade Estadual Paulista (UNESP).

Moraes, M. J., Oliveira Filho, D., Mantovani, E. C., Monteiro, P., Mendes, A. L. C. & Damião, J. H. A. C. (2014). Automação em sistema de irrigação tipo pivô central para economia de energia elétrica. *Engenharia Agrícola*, *34*(6), 1075–1088.

Pereira, P. H. C., Colombo, A., Rabelo, G. F. & de Alcântara, D. (2013). O uso da engenharia de automação na redução do consume de energia elétrica em um sistema de irrigação por pivô central. *Procedings Simpósio Brasileiro de Automação Inteligente, Fortaleza, 6p*.

Ruggiero, M. A. G. & Lopes, V. L. da R. (1997). *Cálculo numérico: aspectos teóricos e computacionais*. Makron Books do Brasil.