Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **680**, *3*, pp. 289–294, Bucarest, 2023

DYNAMIC RELAXATION IN THE ITERATIVE METHODS FOR SOLVING NONLINEAR THREE-PHASE CIRCUITS

CLAUDIU TUFAN [1], MIHAI EUGEN MARIN [1,2], GEORGE MARIAN VASILESCU [1], RADU MIRCEA CIUCEANU [1], MIHAI MARICARU [1]

Keywords: Nonlinear three-phase circuits; Picard-Banach iterative solution; Hănțilă method; Convergence acceleration; Dynamic overrelaxation.

The Hănțilă method has proven its effectiveness in solving non-linear three-phase circuits. It is the only effective method for analyzing non-linear three-phase circuits containing machines with different sequence reactances. Since solving a system of equations is unnecessary, the computational effort is reduced, and a large number of harmonics can be considered. The convergence of the method is certain - demonstrated mathematically and allows the use of overrelaxation. To develop the method, we analyze the efficiency of computing a dynamic overrelaxation factor for accelerating the computational algorithm.

1. INTRODUCTION

Power electronics allow equipment development with better reliability and the efficient use of electrical energy [1–3]. A consequence of these technical solutions is the increase of non-linear elements in the electrical networks that affect the power quality. The availability of efficient computation methods for solving non-linear three-phase circuits allows for modeling the distorted non-sinusoidal signal, estimating the losses, and evaluating the effectiveness of corrective measures.

A method successfully used for solving electrotechnical problems with nonlinearities is the iterative solution based on the Picard Banach procedure – the Hănțilă method [4–11]. The method [4] was successfully developed for solving resistive circuits containing non-linear elements in a periodic regime, both in the frequency and time domains [12–15]. The use of the method is proved mathematically: the construction of a Picard-Banach sequence associated with a contraction, therefore convergent and whose limit is the solution of the circuit. The method is based on an iterative procedure, it is not necessary to solve a system of equations (as in the case of the Harmonic Balance method), the calculation effort is reduced, and many harmonics can be considered, a fact practically impossible in the case of other methods.

The method was also developed for solving three-phase circuits with non-linear elements and demonstrated its efficiency in all cases analyzed [16–20]. It also allowed the solution of three-phase circuits with non-linear elements, controlled switching (thyristors), or different sequence reactances. It presents several advantages [17,8]: the convergence is certain, the possibility of solving on a single phase, the easy highlight of the power transfer on harmonics, and the option to mitigate the Gibbs phenomenon.

According to our knowledge, it is the only effective method for analyzing nonlinear three-phase circuits containing machines with different sequence reactances. The method can also be useful for studying the operation of equipment designed to mitigate harmonics weights in three-phase circuits.

Non-linearity is treated by generating an iterative algorithm that is always convergent, the method allows convergence acceleration procedures [7,21,23]. They can be very useful when the contraction factors have values close to 1 and when many harmonics are considered.

One of the acceleration procedures analyzed in [19] is overrelaxation. Following the simulations performed in [19] using a fixed value for the overrelaxation factor, we noticed that in the case where the contraction factor of the algorithm is very close to 1, high value overrelaxation factors (30 and even more) can be used and the computation time decreases significantly (even to 30 %). In [7], the mathematical solution for the dynamic calculation of an optimal overrelaxation factor was proposed for the case of solving non-linear three-phase circuits. The case of the diode with piecewise linearized characteristics was analyzed theoretically without presenting numerical examples. The dynamic overrelaxation procedure has already been developed to solve field problems in nonlinear media using the Hănțilă method [7–11].

In the present paper, we analyze the dynamic overrelaxation proposed in [7] for a three-phase circuit with thyristors and compare its efficiency with the acceleration procedures previously analyzed in [19–20].

2. DYNAMIC OVERRELAXATION

We briefly present the dynamic calculation method of an optimal overrelaxation factor from [7]. The Hănțilă method is a fixed-point method and treats nonlinearity by generating a convergent Picard-Banach sequence. The method consists in "linearizing" the circuit by replacing the non-linear elements with generators with controlled sources and internal resistances. The iterative correction is done for the time domain values of the non-linear sources. The value of the internal resistances of the generators is chosen to ensure the algorithm's convergence. The analysis of the linear circuit connected to the terminals of the nonlinear element is done in the frequency domain. The method has two variants: voltage correction of the controlled source or current correction [16–20]. For simplicity, we analyze only the voltage correction, the other variant being its dual. Briefly, for voltage correction, the solution algorithm (detailed in [19]) is:

$$e^{(n)} \xrightarrow{F} \underline{E}^{(n)} \xrightarrow{h} \underline{U}^{(n)} \xrightarrow{F^{-1}} u^{(n)} \xrightarrow{g} e^{(n+1)}, \tag{1}$$

where e is the value of the controlled source in the time domain (it can be initially 0), $\underline{E}$ is the vector of the complex images of the Fourier harmonics of the controlled source, $\underline{U}$ is the voltage on the nonlinear element in the frequency domain, u the voltage on the nonlinear element in the time domain, F and F^{-1} represent the direct and inverse Fourier transforms, (n) the iteration number, h is the diagonal operator and performs in the frequency domain the connection with the rest of the circuit and is non-expansive, and g provides the correction with the nonlinear characteristic in the time domain and is contraction.

The convergence of the iterative procedure is certain and

[1] University Politehnica of Bucharest, Faculty of Electrical Enginering
[2] INFINEON Technologies Romania & CO. SCS
E-mails: claudiu.tufan@upb.ro, mihai.marin@upb.ro, marian.vasilescu@upb.ro radu.ciuceanu@upb.ro, mihai.maricaru@upb.ro

DOI: 10.59277/RRST-EE.2023.68.3.7

allows the use of overrelaxation [6, 7, 19, 20]:

$$e'^{(n)}=e^{(n-1)}+s\left(e^{(n)}-e^{(n-1)}\right) \text{ with } s>1, \tag{2}$$

where s is the overrelaxation factor. Using overrelaxation, the solution algorithm in (1) becomes (Fig.1):

$$e^{(n)} \xrightarrow{s} e'^{(n)} \xrightarrow{F} \underline{E}'^{(n)} \xrightarrow{h} \underline{U}^{(n)} \xrightarrow{F^{-1}} u'^{(n)} \xrightarrow{g} e'^{(n+1)}. \tag{3}$$

The efficiency of using overrelaxation at iteration (n) is evaluated at iteration (n+1) by the distance $\varepsilon'^{(n+1)}$ (Fig. 1).

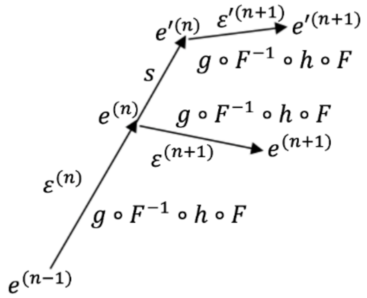


Fig. 1 – The efficiency of using overrelaxation at iteration n is evaluated at iteration n+1.

The use of overrelaxation is effective if:

$$\varepsilon'^{(n+1)}<\varepsilon^{(n+1)}, \tag{4}$$

where

$$\varepsilon^{(n)} \stackrel{\text{def}}{=} \left\| e^{(n)}-e^{(n-1)} \right\| = \left\| \Delta e^{(n)} \right\|, \tag{5}$$

with

$$\|e\|=\sqrt{\langle e,e\rangle_{\frac{1}{R}}}=\sqrt{\int_0^T \frac{e^2}{R}\,dt} \tag{6}$$

The procedure can be used with a fixed value for s as exemplified in [19], by testing relation (4) for a fixed value of s and applying overrelaxation when the inequality is satisfied. Or one can use an algorithm to find optimal values for s [7] for which ε' has the minimum value at the next iteration. This provides the minimum distance $e'^{(n+1)}$ from the fixed point e^* of the Picard Banach sequence, given that:

$$\| e^* - e'^{(n+1)} \| \leqslant \frac{\theta}{1-\theta} \| e'^{(n+1)} - e'^{(n)} \| \tag{7}$$

where θ is the contraction factor of the algorithm.

For this the minimum of the function $\Gamma(s)$ must be calculated:

$$\Gamma(s)=\left\| e'^{(n+1)}-e'^{(n)} \right\|^2 \tag{8}$$

$\Gamma(s)$ can be written only as a function of s and vectors that do not depend on s, such as: $e^{(n-1)}$, $\Delta e^{(n)}$, $u^{(n)}$, $\Delta u^{(n+1)}$:

$$\Gamma(s)=\left\| g(F^{-1}(h(F(e'^{(n)}))))-e'^{(n)} \right\|^2 \tag{9}$$

$$\Gamma(s)=\left\| g(u^{(n-1)}+s\Delta u^{(n)})-(e^{(n-1)}+s\Delta e^{(n)}) \right\|^2 \tag{10}$$

To find the minimum, we calculate the derivative of the function $\Gamma(s)$ and condition it to be zero:

$$\frac{d\Gamma(s)}{ds}=0 \tag{11}$$

$$\left\langle \left(\left.\frac{dg(u)}{du}\right|_{u^{(n-1)}+s\Delta u^{(n)}} \Delta u^{(n)}-\Delta e^{(n)} \right), \left(g(u^{(n-1)}+s\Delta u^{(n)})-(e^{(n-1)}+s\Delta e^{(n)}) \right) \right\rangle = 0 \tag{12}$$

Equation (12) is solved numerically having in view that the function g is nonlinear. A simple solution is the Secant Method. To determine whether the obtained value is minimum and not maximum, we must check how the derivative changes sign around the value where the derivative cancels. Calculating a 2nd derivative to determine concavity can be difficult.

Contrary to [19], the overrelaxation is applied in the time domain and not in the frequency domain. In the present situation, because the derivative $\Gamma(s)$ is easier to calculate in the time domain. Dynamic overrelaxation was calculated on harmonics to solve electromagnetic field problems in nonlinear media [5–11]. In the numerical examples, acceleration was applied only on the fundamental, a larger number of harmonics implying a very high computational effort.

In the case of solving nonlinear circuits in the time domain and treating the nonlinearity with the Newton-Raphson Method, the convergence of the nonlinear procedure is controlled with under- or overrelaxation without rigorous arguments regarding the choice of relaxation factor values. On the other hand, for the Hănțilă method, the convergence is certain – mathematically demonstrated, and the method allows a rigorously substantiated computation of the optimal overrelaxation factor during the iterations.

3. ILLUSTRATIVE EXAMPLE

To be able to compare the efficiency of using dynamic overrelaxation with the other acceleration procedures presented in [19,20], we analyze the same circuit from [19,20], which is shown in Fig. 2, and keep the same computation values: three-phase sinusoidal generator with symmetrical sources with amplitude 325 V and frequency 50 Hz, $R_l = 1\ \Omega$, $R_1 = 2\ \Omega$, $R_s = 10\ \Omega$, $L_l = 5 \times 10^{-4}$ H, $L_1 = 5 \times 10^{-2}$ H. For thyristors Tr we use the piecewise linearized characteristic described in [18-21] with the blocking resistance $R_b = 1/G_b = 10^4 \Omega$, conduction resistance $R_c = 1/G_c = 0{,}05\ \Omega$, $V_f = 5V$ și $\alpha = \pi/5\ (t_\alpha = T/10)$. We note that we have analyzed the use of dynamic overrelaxation in other circuits as well and the conclusions hold.

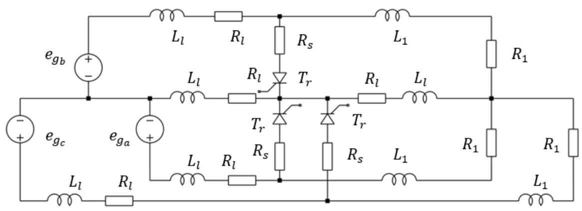


Fig. 2 Three-phase circuit used for simulation.

From [18], if we use voltage correction, the value of the function g(u) is:

$$e=g(u)=\begin{cases} u\left(1-\frac{R}{R_c}\right)+\frac{RV_f(R_b-R_c)}{R_bR_c} \text{ for } u \geq V_f \ \& \ t\in \begin{cases} [t_\alpha, t_b),\ t_b<T \\ [0,t_b)\cup[t_\alpha, T],\ t_\alpha>t_b \end{cases} \\ \\ u\left(1-\frac{R}{R_b}\right) \text{ for the rest of period T.} \end{cases} \tag{13}$$

where t_b is the blocking time at which the condition $u < V_f$ it is fulfilled for the first time after the moment of disappearance of the control signal from the gate. Inequality $t_\alpha > t_b$ occurs when the conduction started in the previous period and is maintained in the current period until the condition $u < V_f$ is met.

For $g(u)$ to be a contraction, the computation resistance must be chosen with $R \in (0{,}2R_{min})$ [12–20]. In the present example $R_{min} = R_c$.

By derivation we get:

$$\left.\frac{dg(u)}{du}\right|_{u^{(n)}+s\Delta u^{(n+1)}} =$$

$$= \begin{cases} (R_c\text{-}R)/R_c \quad \text{for } u^{(n)}+s\Delta u^{(n+1)} \geq V_f \ \& \ t\in \begin{cases} [t_\alpha, t_b),\ t_b < T \\ [0,t_b)\cup[t_\alpha, T],\ \ t_\alpha > t_b \end{cases} \\ (R_b\text{-}R)/R_b \qquad \text{for the rest of period T} \end{cases} \quad (14)$$

provided for t_b as $u^{(n)}+s\Delta u^{(n+1)} < V_f$.

For computation, we used GNU Octave 6.2.0 [22]. The nonlinear eq. (12) and (14) were solved using the fzero command [23].

We keep the same computation parameters from [19, 20]: we truncate the Fourier series development at the 100th harmonic inclusive and divide the period T into several 40,000 equidistant points. We used the calculation algorithm for F şi F^{-1}described in [18]. We stop the iterations when the relative distance (relative error) $\varepsilon^{(n)}/\|e_g\|$ drops below the value of 10^{-8}. The computations were done on the same MacBook Pro laptop with the configuration: Processor 2.3 GHz 8-Core Intel Core i9, Memory 16 GB 2667 MHz DDR4.

Table 1

Computations results using voltage correction for different values of $R = x\,R_{min}$ with dynamic overrelaxation computed every n iteration, fixed overrelaxation factor (s=30) and without over-relaxation (s=1)

x	Every n iterations	No. of iterations	Computation time [s]	$\theta_g \times \theta_h$	Max s	min s	Mean value of s
0.8	0	9305	1664	0.99985	1	1	
	0	2193	801		30	30	
	5	2085	448.34		139.90	2.54	18.55
	10	**1930**	**378.26**		**258.32**	**2.05**	**40.43**
	25	2225	416.39		277.61	9.64	85.65
	70	2589	478.44		347.80	44.13	220.40
1	0	7748	1361	0.99981	1	1	
	0	1767	675		30	30	
	5	**1700**	361.74		**149**	**1.81**	**19.14**
	10	**1711**	**342.71**		**178.48**	**2.35**	**37.55**
	25	1905	359.18		218.83	10.77	83.15
	70	2310	421.83		288.57	66.54	221.31
1.5	0	5534	961	0.99971	1	1	
	0	1362	506		30	30	
	5	1845	399.76		24.41	0.87	11.11
	10	**1290**	**260.38**		**118.09**	**2.075**	**35.79**
	25	1400	266.46		162.08	16.08	86.98
	70	2030	369.72		222.79	32.80	191.74
1.8	0	4750	831	0.99966	1	1	
	0	1943	730		30	30	
	5	3976	862.08		3.36	0.58	1.97
	10	3310	662.60		17.62	0.62	5.41
	25	**1276**	**243.31**		143.80	14.16	81.19
	70	1960	360.83		187.19	39.52	158.63
	100	2396	439.26		188.57	61.19	162.64
1.9	0	4539	801	0.99964	1	1	
	0	2685	1014		30	30	
	5	4140	890.26		2.51	0.54	1.48
	10	4170	823.06		11.33	0.54	1.89
	25	3500	655.45		40.7	0.93	8.75
	70	**1889**	**355.93**		176.78	46.3	153.28
R_{opt}	0	4535	809	0.99962	1	1	
	5	**3420**	742		8.15	0.51	2.37
	10	4280	845.27		9.44	0.50	1.16
	25	3761	**709**		29.57	0.50	5
	70	3989	750		29	0.5	6.27

Table 1 shows the number of iterations and the computation time for different values of the resistance R. The dynamic relaxation factor s was calculated and entered at each: 2, 5, 10, 25, 50, 70 or 100 iterations. θ_g, θ_h are the contraction factors of functions g and h, respectively [19-10]. $R_{opt}=\frac{2R_{min}R_{max}}{R_{min}+R_{max}}$ and determines the smallest contraction factor for function g [19-20].

Analyzing the results, we noticed: by calculating a dynamic overrelaxation factor, the time and the number of iterations decrease considerably in the situation where the contraction factor of the algorithm is very close to 1.

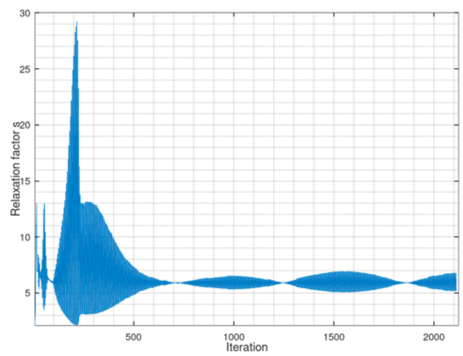
From Fig. 3a-3h, a large initial variation of the values for the optimal overrelaxation factor s is observed, after which it stabilizes and oscillates around a mean value. The average value and the maximum and minimum values obtained for s are shown in Table 1.

A smaller value of the computation resistance (and implicitly a higher contraction factor) allows the use of higher overrelaxation factors (on average). The remark remains valid also for Table 2.

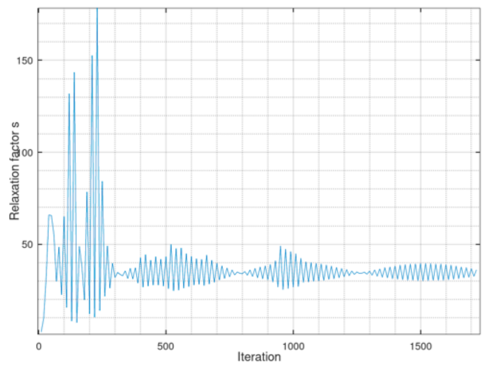
Applying the dynamic overrelaxation factor less often allows higher values for the overrelaxation factor (on average). Therefore, the smallest number of iterations and the shortest computation time were not obtained when applying the dynamic overrelaxation factor every two iterations but when applying it less often. There is a time saving due to performing the additional computations less frequently, which overlaps with increasing the value of the overrelaxation factor and decreasing the number of iterations.

In Table 1, it is observed for the cases of R= 1.8 R_{min}, 1,9 R_{min} and R_{opt}, that the use of the dynamic overrelaxation factor every 2 iterations do not bring any time savings and that the decrease of the number of iterations is quite low. For overrelaxation to be effective, the value of s must be at least greater than 2. Instead, applying a larger number of iterations determines the possibility of adopting higher value overrelaxation factors, and the number of iterations and computing time is reduced significantly.

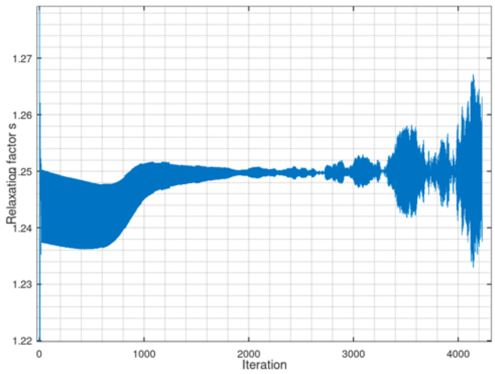
When the value of the resistance R increases and approaches the value 2 R_{min} (from which the algorithm is no longer convergent) the phenomenon of "oscillating convergence" reported in [19] appears generated by the computation errors. In this case, the proposed procedure "tries to compensate" and underrelax and (with a small exception) manages to avoid the oscillating phenomenon.



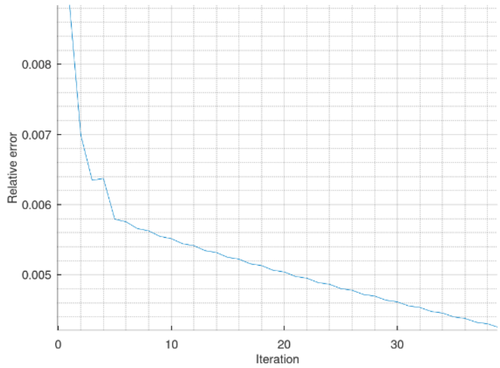
(a)



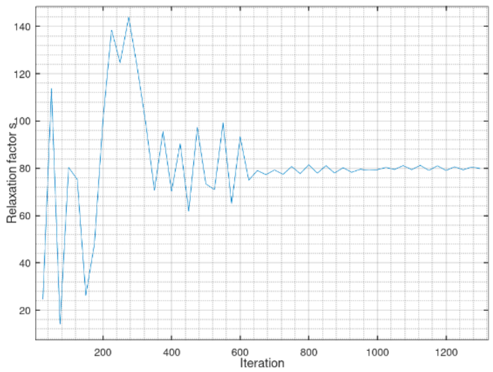
(b)



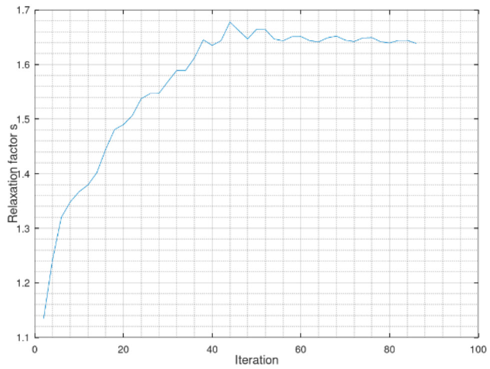
(c)



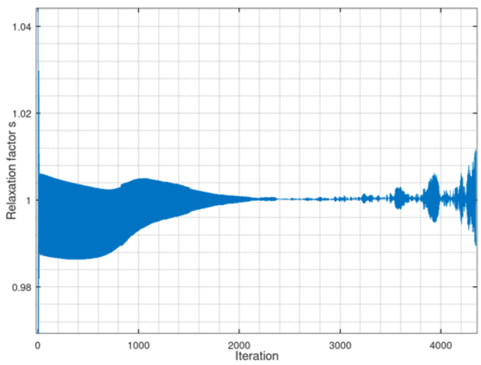
(f)



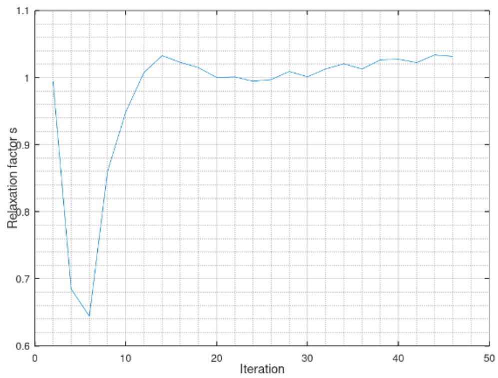
(d)



(g)



(e)



(h)

Fig. 3 – Evolution of the dynamic overrelaxation factor s for: $R = R_{min}$ with application every: (a) 2 iterations, (b) 10 iterations; $R = 1.8\,R_{min}$ with application every: (c) 2 iterations, (d) 25 iterations; $R = R_{opt}$ with application every: (e) 2 iterations and (f) detail regarding the evolution of the relative error $\varepsilon^{(n)}/\|e_g\|$; evolution of s for (g) $R^s = (R_s + R_{min})$ with application every 2 iterations and (h) $R^s = R_{opt}^S$ with application every 2 iterations

The values smaller than 1 for the relaxation factors can be noticed in Tabel 1 and the detail with the error graph in Fig. 3f, in which the oscillating phenomenon disappears compared to [19]. Due to this oscillating phenomenon that causes underrelaxation, the minimum number of iterations and computation time was not obtained near the value $R = R_{opt}$ as expected, but at $R = 1.8\,R_{min}$.

Table 2 shows the number of iterations and the computation time for the case where the characteristic of the nonlinear element is modified by including the series resistor R_s according to the acceleration procedure presented in [20]. The results obtained for other acceleration procedures analyzed in [19,20] are also presented: change in the blocking resistance or of the number of sampling points.

If the contraction factor of the algorithm is good enough, the savings of applying overrelaxation disappears. The number of iterations decreases slightly (sometimes even by zero), but the computation time increases due to the additional calculations.

The other observations are maintained: a smaller value for the new computation resistance R^s allows higher values of the overrelaxation factor, applying overrelaxation less often allows using overrelaxation factors with higher value (on average), the large variations of s values in the beginning part and then the stabilization and oscillation around an average value, the appearance of underrelaxation when R^s approaches R_{opt}^s.

We note that the application of dynamic relaxation has also been modeled for other nonlinear three-phase circuits, and the conclusions presented for the present example hold.

It would be useful to calculate an optimum number of iterations to use dynamic overrelaxation. Until then, one can imagine an algorithm to find it, not very rigorous, based on calculating average values after "stabilizing" the algorithm for a small number of iterations.

By comparing the results in Tables 1 and 2, one can notice that for the present circuit case, the acceleration effect given by the computation of a dynamic overrelaxation factor is significantly lower than the acceleration solutions presented in [20] for modifying the nonlinear characteristic by including an existing series resistance or by extracting it from the equivalent impedance. If the extractable correction resistance value is large enough and the contraction factor drops significantly from 1, dynamic overrelaxation may become ineffective. However, if the nonlinear characteristic is "very hard" and the resistance that can be extracted from the circuit is of small value, the impact on the contraction factor is not so great as in the present case. The two acceleration procedures can be used together, the shortening of the computation time being significant.

Table 2

Computations results using Voltage correction and for different values of $R^s = x(R_s + R_{\min})$ with dynamic overrelaxation computed every n iterations, fixed overrelaxation factor (s=2 / 1.5) and without over-relaxation (s=1)and other acceleration procedures

x	Every n iterations	No. of iterations	Time [s]	$\theta_g \times \theta_h$	Max s	min s	Mean value of s
0.8	0	119	23.69	0.98237	1	1	
	0	105	40.64		2	2	
	0 / with R_b modification	115	22.93		1	1	
	0 / modification of no. of points	140	20.21		1	1	
	5	112	26.31		1.88	1.22	1.73
	10	109	25.18		1.85	1.44	1.75
	25	117	24.12		1.85	1.63	1.79
1	0	94	19.10	0.97548	1	1	
	0	88	34.57		2	2	
	0 / with R_b modification	91	18.77		1	1	
	0 / modification of no. of points	99	16.42		1	1	
	5	90	21.7		1.67	1.18	1.57
	10	93	20.67		1.66	1.37	1.60
	25	93	20.13		1.66	1.54	1.63
1.5	0	61	13.47	0.95453	1	1	
	0	58	23.59		1.5	1.5	
	0 / with R_b modification	59	12.99		1	1	
	0 / modification of no. of points	77	11.98		1	1	
	5	60	15.56		1.41	1.04	1.35
	10	61	14.57		1.41	1.25	1.37
	25	61	13.88		1.40	1.38	1.39
1.8	0	51	11.60	0.93976	1	1	
	0	50	21.28		1.5	1.5	
	0 / with R_b modification	48	11.01		1	1	
	0 / modification of no. of points	56	10.10		1	1	
	5	50	13.11		1.32	0.76	1.22
	10	50	12.21		1.32	0.73	1.2
	25	50	11.7		1.31	1.3	1.31
	0	**48**	11.13		1	1	
1.9	0	47	19.76	0.93452	1.2	1.2	
	0 / with R_b modification	46	10.65		1	1	
	0 /modification of no. of points	61	9.74		1	1	
	5	48	12.48		1.28	0.71	1.12
	10	48	11.89		1.29	0.62	1.12
	25	48	11.11				0.9
R_{opt}^S	0	48	11.12	0.92925	1	1	
	0 /modification of no. of points	63	**9.58**		1	1	
	5	46	**12.15**		1.06	0.66	0.94
	10	46	**11.34**		1.11	0.58	0.87
	25	**46**	**10.84**				0.58

4. CONCLUSIONS

If there is a need to consider a large number of harmonics, the volume and computation time increase significantly. Depending on the values and characteristics of the circuit elements, situations may arise where the convergence is slow due to the contraction factor of the algorithm with values very close to 1. Acceleration procedures, including overrelaxation, are very useful in such cases. If the contraction factor of the algorithm θ is good enough (significantly smaller than 1), the economy of applying overrelaxation disappears: the number of iterations decreases very little, and the computation time increases due to additional computations.

The main observations resulting from the use of a dynamic relaxation factor: a smaller value for the computation resistance R allows higher values of the overrelaxation factor, applying overrelaxation less often allows adopting overrelaxation factors of higher value (on average), the large variations of s values in the beginning part of the iterations and then stabilization and oscillation around an average value, the occurrence of under-relaxation if the calculation resistance value approaches R_{opt} that compensate for the computation errors. We specify that the observations regarding the use of dynamic overrelaxation for the illustrative example in section 3, not being mathematically demonstrated, are not necessarily valid for any other circuits. However, they suggest the validity of over-relaxation and the possibility of adopting some enforcement procedures.

It would be very useful to be able to calculate an optimum number of iterations at which to use dynamic overrelaxation.

It would be interesting to see if the conclusions and observations of this paper hold when solving field problems in nonlinear environments using the Hănțilă method. We propose to conduct such an analysis in a future article.

To be able to compare the results obtained using different acceleration procedures, as well as their efficiency, we analyzed the same circuit from [19,20]. To keep the size of the article to a limited number of pages, the analysis of other three-phase nonlinear circuits using acceleration procedures (including resonances at different frequencies and high frequencies, with different sequence reactances, with several three-phase nonlinear elements, with linear and nonlinear unbalanced elements, with other kind of nonlinear characteristics,...) will be done in a series of future papers, including the observation of power transfer on harmonics and the computation of balance of powers, as well as validation of the results with measurements obtained in the laboratory for real nonlinear circuits. Acceleration procedures allow efficient analysis - reduced computational time and volume and effective - high fidelity of calculated values through adopting many harmonics.

We believe that an important direction of development of the Hănțilă method is increasing the computation speed and developing acceleration procedures for solving non-linear three-phase circuits and field problems in non-linear media.

Received on 13 September 2023

REFERENCES

1. B. Ramachandran, N.R. Prabha, M. Jawahar. *An ultra-capacitor integrated dynamic voltage restorer for power quality enhancement in a three-phase distribution system using an adaptive neuro-fuzzy interference system controller*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **67**, *4*, pp. 383–388 (2022).
2. O. Abdessemad, A.L. Nemmour, L. Louze, *A novel control scheme implementation for a self-excited asynchronous generator*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **67**, *4*, pp. 371–376 (2022).
3. V. Rathore, K.B. Yadav, *Experimental analysis of multilevel inverter fed six-phase induction motor for high power applications*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg. **67**, *4*, pp. 389–394 (2022).
4. I.F. Hănțilă, *A method for solving nonlinear resistive networks*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **24**, pp. 217–226 (1979).
5. I.F. Hănțilă, G. Preda, M. Vasiliu, *Polarization method for static fields*, IEEE Transactions on Magnetics, **36**, *4*, pp. 672–675 (2000).
6. G.M. Vasilescu, M. Maricaru, *An efficient procedure for solving non-linear problems in electrical engineering: Hănțilă method*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **64**, pp. 187–194 (2019).
7. I.F. Hănțilă, C. Tufan, M.O. Popescu, M. Maricaru, *"Dynamic" overrelaxation in iterative methods for solving nonlinear problems in electromagnetism* (in Romanian) – Conferința Internațională Zilele Academiei de Științe Tehnice din România (ASTR), Ediția a XVII-a, Petroșani, 6–7 Octombrie 2022.
8. P.C. Andrei, M.E. Marin, S. Marinescu, C.I. Grumeza, M. Maricaru, *Assessment of static BH characteristics of electrical sheets using a dc measuring set-up*, 16th International Conference on Engineering of Modern Electric Systems (EMES), Oradea, Romania, pp. 1–4 (2021).
9. M. Codrean, M. Codrean, M.C. Novac, O.-C. Novac, C. Gordan, V.I. Farcas, *Analyzing the process of tempering a semifinished product using the FLUX2D and FEMM software*, 2019 15th International Conference on Engineering of Modern Electric Systems (EMES), Oradea, Romania, pp. 229–232 (2019).
10. M.E. Marin, V. Manescu-Paltanea, G. Paltanea, P.C. Andrei, C. Grumeza, I.F. Hantila, *Hysteresis cycle measurements using an innovative laboratory equipment*, International Symposium on Fundamentals of Electrical Engineering (ISFEE), Bucharest, Romania, pp. 1–5 (2020).
11. G. Paltanea et al., *Numerical analysis of a free rare-Earth PMaSynRM for light electric vehicle*, International Conference on Applied and Theoretical Electricity (ICATE), Craiova, Romania, pp. 1–5 (2021).
12. I.F. Hănțilă, M. Maricaru, R.M. Ciuceanu, L. Corlan, *Harmonic analysis of circuits with nonlinear resistive elements,* Rev. Roum. Sci. Techn. Électrotechn. et Énerg., 57, pp. 333–340 (2012).
13. G.M. Vasilescu, I.F. Hănțilă, M. Maricaru, I. Bârsan, V. Stanciu, *A new method for solving the periodic steady state of nonlinear circuits,* Rev. Roum. Sci. Techn. Électrotechn. et Énerg, **59**, *4*, pp. 339–349 (2014).
14. I.F. Hănțilă, F. Constantinescu, A.G. Gheorghe, M. Nițescu, M. Maricaru, *A new algorithm for frequency domain analysis of nonlinear circuits,* Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **54**, *1*, pp. 57–66 (2009).
15. I.F. Hănțilă, M. Maricaru, F. Constantinescu, R.M. Ciuceanu, *A new method for time domain computation of the steady state in nonlinear circuits*, IEEE International Conference on Microwaves, Communications, Antennas and Electronic Systems (COMCAS) (2011).
16. I.F. Hănțilă, M. Maricaru, M. Stănculescu, G.M. Vasilescu, *Method for analyzing three-phase networks with nonlinear resistive elements*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **64**, pp. 103–106 (2019).
17. C. Tufan, I.V. Nemoianu, *Method for the analysis of three-phase networks containing nonlinear circuit elements in view of an efficient power flow computation*, Electronics, **10**, 2710 (2021).
18. C. Tufan, I.V. Nemoianu, M. Maricaru, M. Stanculescu, M.E. Marin, *Efficient method of harmonic analysis of three-phase circuits with nonlinear controlled switching elements*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg, **67**, *1*, pp. 47–54 (2022).
19. C. Tufan, M. Maricaru, I.V. Nemoianu, *Procedures for accelerating the convergence of the method Hănțilă for solving three-phase circuits with nonlinear elements – part I*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg, **67**, *3*, pp. 293–300, (2022).
20. C. Tufan, M. Maricaru, I.V. Nemoianu, *Procedures for accelerating the convergence of the method Hănțilă for solving three-phase circuits with nonlinear elements – part II*, Rev. Roum. Sci. Techn. Électrotechn. et Énerg., **67**, *4*, pp. 395–401 (2022).
21. ***Mathworks https://es.mathworks.com/help/physmod/sps/ref/thyristorpiecewiselinear.html accessed: May 12, 2022].
22. J.W. Eaton, https://www.gnu.org/software/octave/ [accessed: May 12, 2022]
23. ***Mathworks, https://www.mathworks.com/help/matlab/ref/fzero.html [accessed: January 10, 2023].