RESEARCH ARTICLE

NEW METHOD OF SIZING A FILTER (RL-C) FOR AN INVERTER WITH SPWM CONTROL IN MEDIUM VOLTAGE ALTERNATING

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Manuscript Info

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Abstract

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The need to use SPWM controlled voltage inverters in MV, led us to examine how to filter alternative signals with filters (L-C) and (RL-C). This allowed us to decide on the use of certain formulas for calculating the elements of these filters. Likewise, we have proposed a method of calculating the resistance R by mathematical iterations without using the quality factor Q, in order to obtain a low error rate between the RMS values and the fundamental effective values and THDs respecting the standard 519 IEEE - 2014. The results of these studies obtained using the MATLAB-SIMULINK software are presented in the penultimate session of this article.

Nomenclature

SPWM	Sinusoidal Pulse-Width-Modulation
THD	Total Harmonic distortion
S_N	Apparent power of the alternating load
MV	Medium voltage alternating voltage (1 kV -- - 50 kV)
Uph	phase-to-phase voltage at the ac load
RMS	Root Mean Squared
R L C	Resistance Inductance Capacitor
MVDC	Medium voltage direct current
VSI	Voltage Source Inverter

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Introduction:-

Africa is one of the great reservoirs of renewable energies. There is wind for wind power, the sun for photovoltaic power and solar power for heat, and rivers for hydroelectric power.

Photovoltaic energy has exploded in recent years in some countries in sub-Saharan Africa with the construction of photovoltaic power plants with peak powers of around tens of megawatts [1-2]. These photovoltaic plants are built to increase the energy resources of these countries.

However, the problem of transport and distribution in HTA in localities far from the national grid, of this energy produced in these photovoltaic plants remains unresolved because of its very high cost [3].

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It is to help meet this challenge that we propose to design and size a filter (RL-C) for an inverter with SPWM control. Because the energy sources from photovoltaic power plants are continuous, and require inverters to convert them into alternative energy. The voltage and current signals supplied by the inverters are not sinusoidal [4]. These signals contain harmonics generated by semiconductors. These harmonics hamper the proper functioning of electrical equipment [5].

According to the 519 IEEE - 2014 standard, the quality of voltage and current signals is quantified by the THD parameter. The lower the THD, the better the quality of the signal strength [5].

In order to have a better efficiency of the filter (RL-C) in MV during the operation of the inverter with SPWM control, the main contribution proposed revolves around two axes in this research article:
- discuss the applicability in HTA of the existing formulas in articles [6], [7], and [8] and, in article [9] on the one hand;
- and on the other hand, present a method of calculating the resistance R without using the quality factor Q, which gives a low error rate between the RMS values and the fundamental RMS values, and THDs respecting the 519 IEEE standard - 2014.

The document is presented as follows: in section II, the model of the system and the formulation of the problem; in section III, the filter (L-C) and the applicability of its formulas of the filter (L-C) of the three-phase inverter with SPWM control in MV; in section VI, the traditional method of calculating the filter (RL-C); in section V, the inverter with SPWM control; in section VI, the new method of calculating the resistance R of the filter (RL-C). Finally, section VII concludes the article.

II / System model and problem formulation
The contribution of this article focuses on a medium voltage direct current (MVDC) electrical energy transmission and distribution system to supply localities with low variation in energy loads.

Therefore, the improvement of the quality of the voltage and current MV signals on the AC side of the SPWM-controlled inverter must be done in accordance with the 519 IEEE-2014 standard. Also the error rates between the RMS values and the fundamental RMS values of the signals must be very low to avoid overvoltage and overcurrent.

So the first problem is the applicability of the formulas found in scientific papers to a filter (L-C) of an SPWM inverter connected to a MV grid. The second problem is the damping of the resonance of the filter (L-C) by a resistor R placed in series with the inductor L. A new method is proposed for this purpose.

III / Filter (L-C)
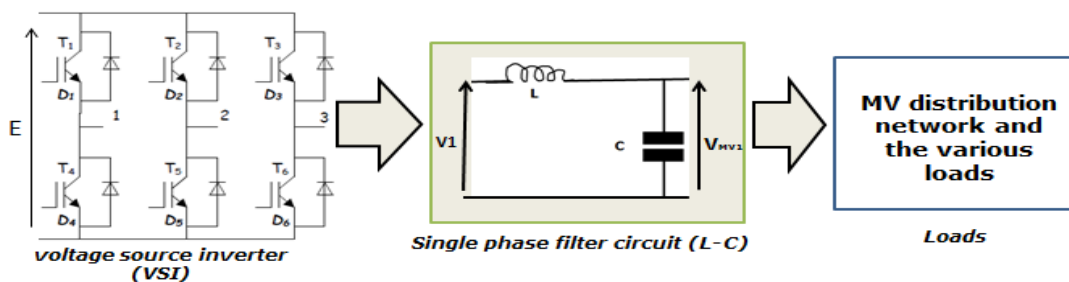Consider Figure No. 1 where the filter (L-C) is illustrated:

Figure No. 1: Equivalent diagram of a three-phase VSI connected to the network with output LC filter

The diagram of the filter (L-C) in figure N ° 1 makes it possible to obtain the transfer function H (P):

$$H\,(P) = \frac{V_{MV\,1}(P)}{V_1(P)} = \frac{1}{LC\,P^2 + 1} \quad (1)$$

The filter (L-C) attenuates signals by 40 (dB) / decade.

The articles [6], [7] and [8] reviewed, noted the formulas for calculating L and C of the filter (L-C) for a three-phase inverter with SPWM control as follows:

$$I_N = \frac{S_N}{\sqrt{3}*U_{ph}} \text{ and } \Delta V_L \leq \frac{U_{ph}}{10*\sqrt{3}}$$

$$C \leq C_{maxi2} = \frac{0{,}05*S_N}{3*\omega*U_{ph}{}^2} \quad \text{and} \quad L \leq L_{maxi2} = \frac{3*U_{ph}{}^2}{10*\omega*S_N}(2)$$

These formulas given by equation (2) were obtained while respecting two constraints: the reactive power of the capacitor C (limited to 5% of the reactive power of the alternating load) and the voltage drop across the terminals of the inductance L (limited to 10% of the phase-to-neutral voltage supplying the alternating charge).

On the other hand in the paper [9]; the calculation of L and C of the filter (L-C) for a three-phase inverter with SPWM control is done as follows:

$$L \leq \frac{0.03*U_{ph}}{2\pi*f*I_N} \; ; \; f_c < \frac{1}{10}*f_{sw} \text{ and } C = \frac{1}{(2\pi f_c)^2 L} \qquad (3)$$

These formulas given by equation (3) were obtained by limiting the voltage drop across inductance L (limited to 3% of the voltage of the alternating load) and the cut-off frequency fc of the filter (L-C) (limited to 1/10 of the semiconductor switching frequency f_{sw}).

Applicability of these formulas of the filter (L-C) of the three-phase inverter SPWM in MV
The calculation of the capacitance of the capacitor and the inductance according to first the approach No. 1 described in articles [6], [7] and [8], then then the approach No. 2 given by the article [9] for an inverter with SPWM control delivering medium voltage alternating voltage (MV). We performed a voltage and current simulation of the SPWM controlled inverter via Matlab using the following parameters.
Load data:
S_N = 30MVA; Cosφ = 0.86; U_{ph} = 30000V

DC power source E $= \frac{2\sqrt{2}}{M_a*\sqrt{3}} * U_{ph}$ = 61237.244 V; with a modulation index M_a = 0.8

The simulation results, given in Figure No. 2, show the voltage and current waveforms of the two approaches.

LOAD VOLTAGE

LOAD CURRENT

obtained by the method of [6], [7] and [8]
Voltage THD = 230,48% and Current THD = 23,28%

LOAD VOLTAGE

LOAD CURRENT

obtained by the method of [9]
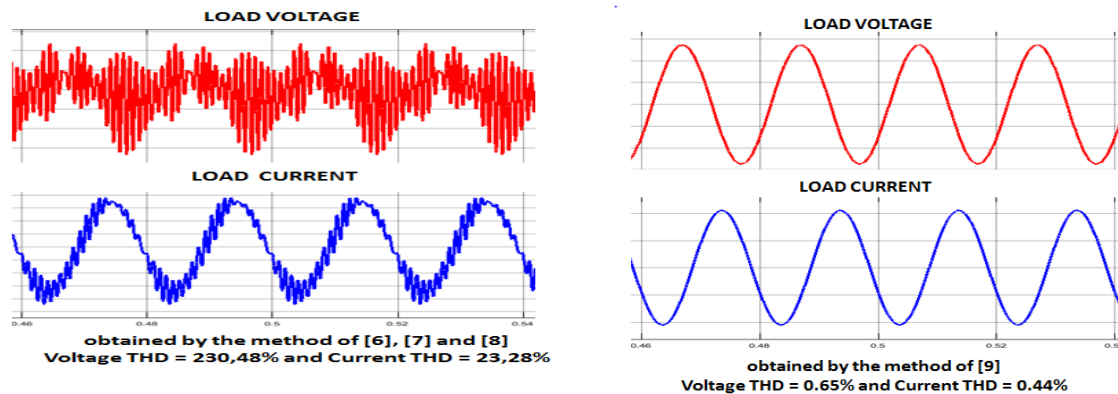Voltage THD = 0.65% and Current THD = 0.44%

Figure No. 2:- Voltage and current waveforms of the two approaches.

Analytically, through equation (3), we have:

$$L_{max1} = \frac{0{,}052*U_{ph}{}^2}{2\pi f*S_N} \text{ and } C_{max1} = \frac{2\pi f*\frac{S_N}{0{,}052}}{(4\pi f)(4\pi f)*U_{ph}{}^2} = \frac{\frac{S_N}{4*0{,}052}}{(2\pi f)*U_{ph}{}^2} = \frac{4{,}81*S_N}{(2\pi f)*U_{ph}{}^2} \quad (4)$$

Where $f_c = 2*f$; f: frequency of the fundamental; f_c: cut-off frequency
Via equations (2) and (4), we have:

$$L_{max2} = \frac{0{,}3*U_{ph}{}^2}{2\pi f*S_N} > L_{max1} \text{ and } C_{max2} = \frac{0{,}05*S_N}{3*\omega*U_{ph}{}^2} < C_{max1} \quad (5)$$

We note that for L_{max1} and C_{max1}, the THD% of voltage and current are respectively 0.65% and 0.44% (***Standard***

519 IEEE-2014 is respected).

We find that for L_{max2} and C_{max2}; the voltage and current THD% are 230.48% and 23.28% respectively (***The IEEE-2014 519 standard is not met for the voltage THD which should be less than 8% in MV***).

In conclusion for this part, from equation (5), we note that the filter (L-C) needs a large capacitor capacity and a small inductance.

The quantities $C = C_{max1}$ and $L = L_{max1}$ of approach No. 2 [9], are the formulas of the filter (L-C) of the three-phase inverter with SPWM control in MV which give voltage and current THDs complying with the standard 519 IEEE-2014.

For the rest of this article, the method given in article [9] is considered.

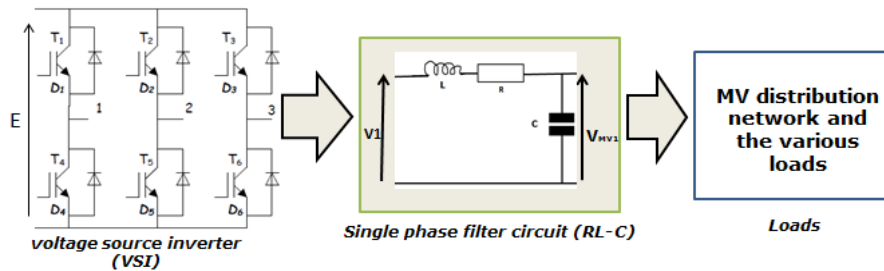## IV / Traditional filter calculation method (RL-C)

Figure No. 3: Equivalent diagram of a three-phase VSI connected to the network with output (RL-C) filter

This involves taking into account a resistor R which acts as a filter damper (L-C) to obtain the filter (RL-C) shown in figure No. 3.

The diagram of the filter (RL-C) in Figure No. 3 provides the transfer function H (P):

$$H(P) = \frac{V_s(P)}{V_e(P)} = \frac{\frac{1}{LC}}{P^2 + \frac{R}{L}P + \frac{1}{LC}} \quad (6)$$

By identifying equation (6) of a low-pass filter of order 2 of the canonical form, we have:

$$\omega_n = \frac{1}{\sqrt{LC}} ; \zeta = \frac{R}{2*L*\omega_n} \quad \text{and} \quad Q = \frac{1}{2*\zeta} \quad (7)$$

Where ω_n is the proper pulsation; ζ the damping factor and Q the quality factor. To calculate R of the filter (RL-C) for the three-phase inverter with SPWM control, article [10] proceeded as follows from (7):

1. by setting that $\omega_n = \omega_{Res}$ (resonance pulsation) and fixing its value through f_{Res} its resonant frequency;
2. by fixing the quality factor Q knowing that $0 \leq \zeta \leq \frac{\sqrt{2}}{2}$ (because of the resonance) which clearly indicates that Q must be greater than or equal to $\frac{\sqrt{2}}{2}$;
3. fixing L or C to infer one or the other.

The problem posed by the method of article [10] is as follows:

By this method, the calculated capacitance C, inductance L and resistance R do not allow obtaining RMS values of voltage and current close to the fundamental RMS values of voltage and current. Because the choice of the resonant frequency f_{Res}; the quality factor and inductance L or capacitor C is hazardous.

V / PWM control inverter

Consider the diagram of a three-phase inverter below (Figure No. 4)
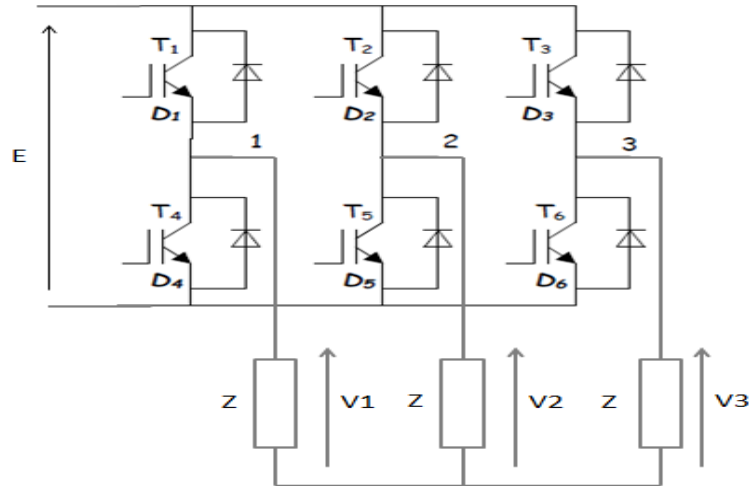
Figure No. 4 : Three-phase inverter

In the three-phase two-level inverter (Figure No. 4), we have three arms. Each arm has two controllable switches K_i ($i = 1, 2, 3\ldots, 6$). Each controllable switch consists of:
- Bipolar power transistor or IGBT or thyristor (controllable component);
- Diode mounted head-to-tail (antiparallel) on each controllable component.
The inverter is supplied by a DC source E.

SPWM (Sinusoidal Pulse Width Modulation) control
In SPWM control for a three-phase two-level inverter (Figure No. 4), a high-frequency saw tooth wave is created: this is the carrier. It is compared to the image of the three-phase network coming out of the inverter. This comparison generates three signals shifted from each other by 120 °. They are of logic levels: 1 or 0. Thus the logic signal obtained by the image of V1 (Θ) will control the IGBT in the upper part of the 1st arm of the three-phase inverter; the one obtained by the image of V2 (Θ) will control the IGBT in the upper part of the 2nd arm of the three-phase inverter and the logic signal obtained by the image of V3 (Θ) will control the IGBT in the upper part of the 3rd arm of the three-phase inverter. For the IGBTs in the lower part of the arms, it is the complementary signals that will control them.

Figure No. 5 gives the IGBT control signals then figure No. 6 represents the voltage signals V1 (Θ), V2 (Θ) and V3 (Θ).
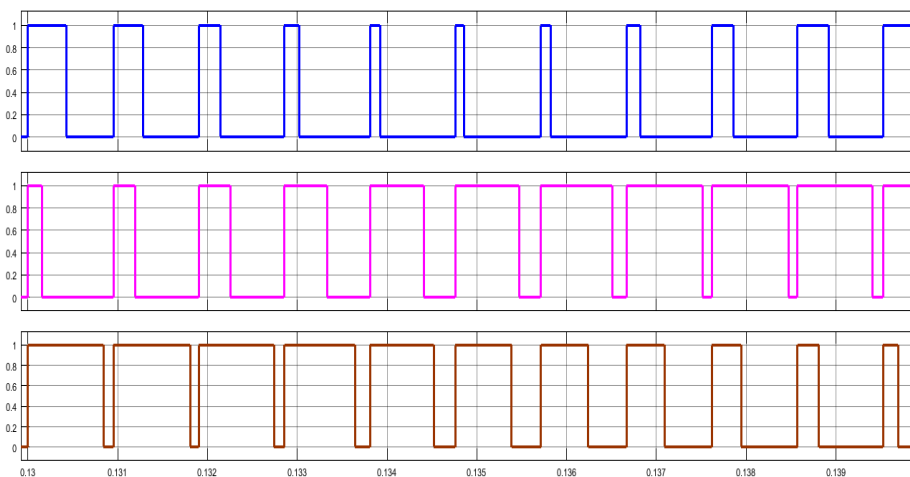

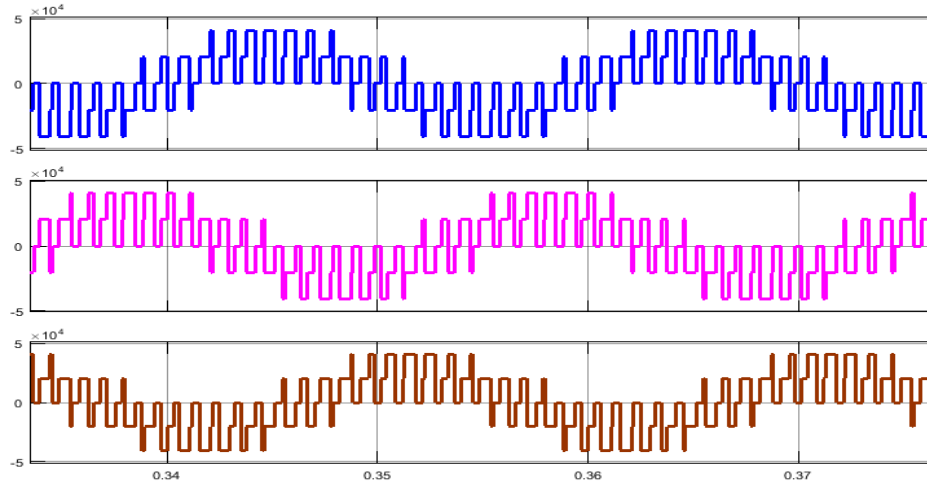*Figure No. 5:- Control signals of IGBT T1, T2, and T3.*

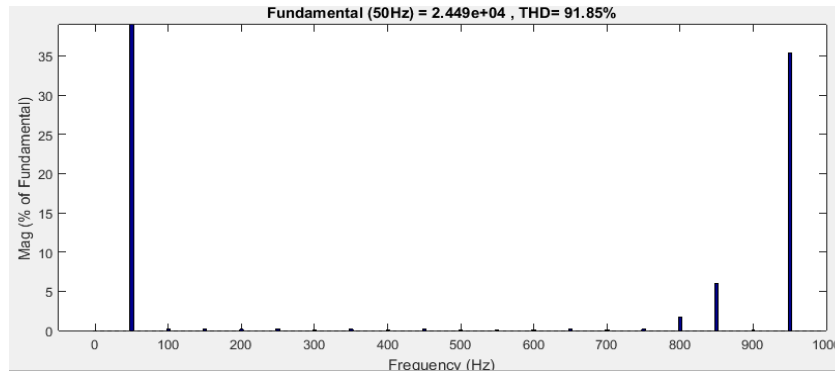***Figure No. 6**:- Curves of V1 (Ɵ), V2 (Ɵ) and V3 (Ɵ).*

Figure No. 7:- The spectral analysis of V1 (Ɵ).

It is clearly seen in figure No. 7 that the harmonics which pollute the phase-to-neutral voltage signals are of ranks: 16; 17; 19.

The effective fundamentals of voltage and current are:

$$V_{11eff} = \frac{M_a * E}{2\sqrt{2}} \ ; \ I_{11eff} = \frac{V_{11eff}}{|Z|} = \frac{M_a * E}{2\sqrt{2}|Z|} \ \text{ and } Z = r + j_* x \tag{8}$$

Remember that without the filter (L-C), the harmonic distortion rate (THD = 91.85%). This does not comply with the 519 IEEE [9] standard, which requires that in MV, this THD be 8%.

VI / New method of calculating the resistance R of the filter (RL-C)
Suppose that the magnitudes of the Load are given by: S_N; U_{ph}; cos (φ).

Resistance calculation algorithm R:
Start Algorithm:
Step 1:
- Consider U_{ph} as the fundamental effective voltage;
- Calculate the direct voltage $E = \frac{2\sqrt{2} * U_{ph}}{M_a \sqrt{3}}$;   (9)
- Also calculate the effective fundamental current $I_n = \frac{S_N}{\sqrt{3} U_{ph}}$;   (10)
- Calculate the capacitance C and the inductance L:

$$C = C_{max1} = \frac{4,81 * S_N}{(2\pi f) * U_{ph}^{\ 2}} \quad et \quad L = L_{max1} = \frac{0,052 * U_{ph}^{\ 2}}{2\pi f * S_N} \; ; \qquad (11)$$

- Measure the starting RMS voltage and RMS current U_{ph0} and I_{n0} respectively without R in the filter;
- Calculate: $\Delta U_{ph0}(\%) = \frac{U_{ph0} - U_{ph}}{U_{ph}} * 100$ et $\Delta I_{n0}(\%) = \frac{I_{n0} - I_n}{I_n} * 100$ (12)

Step 2:
- Calculate the coefficient ε_0 fixing the starting point (initial point) of the iterations;

$$\boldsymbol{\varepsilon_0} = \frac{\boldsymbol{\Delta U_{ph0}(\%)}}{\boldsymbol{\Delta I_{n0}(\%)}} \quad (13)$$

Let us set as the unit basis of resistance γ = 1 ohm. **b**, **c**, and **d** are natural numbers with values less than 5 and **a** is a natural number.

- If ε_0 = **a** then the resistance R_1 = **a**$_*\gamma$
- If **a, 1** $\leq \varepsilon_0 \leq$ **a, b** then the resistance $R_1 = \varepsilon_0 * \gamma$
- If **a, b1** $\leq \varepsilon_0 \leq$ **a, bc** then the resistance $R_1 = \varepsilon_0 * \gamma$.
- If **a, bc1** $\leq \varepsilon_0 \leq$ **a, bcd** then the resistance $R_1 = \varepsilon_0 * \gamma$

The iteration steps $\boldsymbol{\Delta_i} = \boldsymbol{10^{-i}}$ for **i** (natural integer) ranging from 0 to 3. There is an incrementation of **i** as soon as condition 3, or condition 5, or condition 6 is true. $\boldsymbol{\Delta_i}$ will be denoted $\boldsymbol{\Delta}$ for the rest of the expressions.

Step 3:
- Calculate $\Delta U_{ph1}(\%)$ and $\Delta I_{n1}(\%)$
- Check condition 1: $\Delta U_{ph1}(\%) > 0.2\%$ and $\Delta I_{n1}(\%) > 0.2\%$

As long as condition 1 is true

- Carry out the iterations with $\boldsymbol{R_j = R_1 + \Delta_* \gamma_* (j-1)}$

for j = 2, 3, …; and i = 0, or 1, or 2, or 3;

- Check condition 2 at each iteration:
$$\Delta U_{phj}(\%) < 0.2\% \text{ and } \Delta I_{nj}(\%) < 0.2\%$$

If condition 2 is true then **R = R_j**;

Step 4:

If condition 2 (in Step 3) is false then

- Check condition 3: $\Delta U_{phj}(\%) < 0$ and/or $\Delta I_{nj}(\%) < 0$

If condition 3 is true then

- Carry out the iterations with $\boldsymbol{R_k = R_{j-1} + \Delta_* \gamma_* k}$

for k = 1, 2, 3,…;

- Check condition 4 at each iteration:
$$\Delta U_{phk}(\%) < 0.2\% \text{ and } \Delta I_{nk}(\%) < 0.2\%$$

If condition 4 is true then **R = R_k**;

Step 5:

If condition 1 (in Step 3) is false then

- check condition 5:
$$\Delta U_{ph1}(\%) < 0\% \text{ and/or } \Delta I_{n1}(\%) < 0\%$$

If condition 5 is true then

- Carry out the iterations $\boldsymbol{R_j = R_1 - \Delta_* \gamma_* (j-1)}$

for j = 2, 3, …;

- Check condition 2 at each iteration:
$$\Delta U_{phj}(\%) < 0.2\% \text{ and } \Delta I_{nj}(\%) < 0.2\%$$

If condition 2 is true then **R = R_j**;

Step 6 :
- If condition 2 (in Step 5) is false then
- check condition 3: $\Delta U_{phj}(\%) < 0$ and/or $\Delta I_{nj}(\%) < 0$
- If condition 3 is true then
- Carry out the iterations with $\boldsymbol{R_k = R_{j-1} - \Delta_* \gamma_* k}$

for k = 1, 2, 3, … ;

- Check condition 4 at each iteration:
$$\Delta U_{phk}(\%) < 0,2\% \text{ and } \Delta I_{nk}(\%) < 0,2\%$$

If condition 4 is true then **R =R$_k$**;

Step 7:

If condition 4 (in Step 4) is false then

- Check condition 6 :ΔU$_{phk}$(%) < 0% and/or ΔI$_{nk}$(%) < 0%

If condition 6 is true then

- Carry out the iterations with **R$_z$ = R$_{k-1}$ + Δ$_*$γ$_*$z**

for z = 1, 2, 3, …;

- Check condition 7 at each iteration:

ΔU$_{phz}$(%) < 0.2% and ΔI$_{nz}$(%) < 0.2%

If condition 7 is true then **R = R$_z$**;

Step 8 :
- If condition 4 (in Step 6) is false then
- Check condition 6 :ΔU$_{phk}$(%) < 0% and/or ΔI$_{nk}$(%) < 0%
- If condition6 is true then

- Carry out the iterations with **R$_z$ = R$_{k-1}$-Δ$_*$γ$_*$z**

for z = 1, 2, 3, …;

- Check condition 7 at each iteration:

ΔU$_{phz}$(%) < 0.2% and ΔI$_{nz}$(%) < 0.2%

If condition 7 is true then **R = R$_z$**;

End algorithm.

Formulas used in the algorithm:

$\Delta U_{phj}(\%) = \frac{U_{phj} - U_{ph}}{U_{ph}} * 100$ and $\Delta I_{nj}(\%) = \frac{I_{nj} - I_n}{I_n} * 100$; jϵ**N***   (14)

$\Delta U_{phk}(\%) = \frac{U_{ph\,k} - U_{ph}}{U_{ph}} * 100$ and $\Delta I_{nk}(\%) = \frac{I_{nk} - I_n}{I_n} * 100$; k $\in$**N** *(15)

$\Delta U_{phz}(\%) = \frac{U_{phz} - U_{ph}}{U_{ph}} * 100$ and $\Delta I_{nz}(\%) = \frac{I_{nz} - I_n}{I_n} * 100$; z $\in$**N** *   (16)

Simulations and Results:-

TableNo. 1:- Simulation parameters.

Parameters	Values
Apparent load power **S$_N$**	**30 MVA**
Voltage between phases at the load terminals **U$_{ph}$**	**30 000V**
Current in load**I$_n$**	**577.34 A**
SPWM inverter supply voltage **E**	**61237.24 V**
Power factor **cosφ**	**0.86**
modulation index **M$_a$**	**0.8**
Filter inductance (L-C) **L**	**$4.966e^{-3}$H**
Filter capacitor capacity (L-C) **C**	**$5.104e^{-4}$F**

Table No. 2:- Results of the simulation of the mathematical iteration method.

R in series with L	L (H)	C (F)	Uph (V)	Δuph (%)	In (A)	Δin (%)	THD C%	THD T%	ε$_0$
Without R	4,97E-03	5,10E-04	38570	28,567	741,7	28,466	0,44	0,65	
1	4,97E-03	5,10E-04	36280	20,933	697,7	20,845	0,11	0,6	
2	4,97E-03	5,10E-04	33430	11,433	642,9	11,354	0,09	0,65	
3	4,97E-03	5,10E-04	30470	1,567	585,9	1,481	0,08	0,68	
4	4,97E-03	5,10E-04	27660	-7,8	531,9	-7,872	0,08	0,77	
3,1	4,97E-03	5,10E-04	30180	0,6	580,3	0,511	0,08	0,69	
3,2	4,97E-03	5,10E-04	29890	-0,367	574,8	-0,442	0,08	0,69	1,0035
3,11	4,97E-03	5,10E-04	30150	0,5	579,8	0,424	0,08	0,71	
3,12	4,97E-03	5,10E-04	30120	0,4	579,2	0,32	0,08	0,71	
3,13	4,97E-03	5,10E-04	30090	0,3	578,6	0,217	0,08	0,71	
3,14	4,97E-03	5,10E-04	30060	0,2	578,1	0,13	0,08	0,72	
3,15	4,97E-03	5,10E-04	30030	0,1	577,5	0,026	0,08	0,72	

ΔU$_{phz}$(%) < 0.2% andΔI$_{nz}$(%) < 0.2% $_{nj}$(%) < 0% andΔI$_{nj}$(%) <0%; ΔU$_{phk}$(%) < 0% andΔI$_{nk}$(%) <0%.

Tables No. 1 and No. 2present the parameters and the results of the simulation.

Table No. 2shows the results of the simulation. The blue band in Table No. 2clearly shows the voltage and current THDs 0.72% and 0.08% respectively; the RMS voltage and current error rates respectively ΔU_{phj} (%) = 0.1% < 0.2% and ΔI_{nj} (%) = 0.026% < 0.2%; as well as the value of the desired resistance R = 3.15 ohms. The red lines in Table No. 2show the negative RMS voltage and current error rates. This means that we have introduced two different resistances twice: on the 1st line in red, the resistance $R_k = R_{j-1} + \Delta_* \gamma_* k$; where R_{j-1} = 3 ohms, and the iteration step goes from 1 to 0.1; at the 2nd line in red, the resistance $R_z = R_{k-1} + \Delta_* \gamma_* z$; where R_{k-1} = 3.1 ohms, and the iteration step goes from 0.1 to 0.01. This made it possible to obtain the desired resistance value R= R_5 = 3.15 ohms for   z = 5. Looking at the first column, we see that the first iteration step is 1; then 0.1; finally 0.01. There were a total of 10 iterations of which (j = 2, 3, 4); (k = 1, 2) and (z = 1, 2, 3, 4, 5).

With this value of R, we will by the traditional method calculate the quality factor Q = $\dfrac{1}{2*\zeta}$ in order to show that it is difficult that this method of calculating R in the article [5], with the quality factor Q, makes it possible to obtain a value of R for a high precision (THD <0.2%) of the RMS values of voltage and current with respect to the effective fundamentals of voltage and current.

According to the paper [5] and the values of L and C in Table No. 1, the resonance pulsation $\omega_{Res} = \dfrac{1}{\sqrt{LC}}$ = 628.12rad/s; therefore f_{Res} = 99.97 Hz; the filter damping coefficient ζ; $\zeta = \dfrac{R}{2*L*\omega_n}$ = 0.505 to get Q = $\dfrac{1}{2*\zeta}$ = 0.99.The question is: how to exactly set the resonant frequency f_{Res}; the quality factor Q and the value of C or L to obtain R in order to have fundamental RMS voltage and current values of less than 0.2% error from their RMS values? The probability is very low.

Conclusion:-
This article presents a contribution split in two:
- on the one hand, to show the applicability in MV of two groups of filter calculation formulas (L-C) obtained by two different approaches, one by the limitations of the reactive power of the capacitor C (limited to 5% of the reactive power of the alternating load) and of the voltage drop across inductance L (limited to 10% of the phase-to-neutral voltage supplying the alternating load), and on the other hand by limiting the voltage drop across the terminals of inductance L (limited to 3% of the voltage of the alternating load) and the cut-off frequency fc of the filter (L-C) (limited to 1/10 of the switching frequency f_{sw} of the semiconductors).

On this part, we note great satisfaction for the paper approach [9] which gives expected results in MV, respecting the standard in article [11].
- on the other hand, it is a question of calculating the resonance damping resistance R in series with the inductance L without using the quality factor Q, so that the error rate between the voltage RMS and the RMS fundamental voltage is low (< 0.2%), and that between RMS current and RMS fundamental current is low (< 0.2%), and that the voltage and current THDs comply with [11].

Regarding this other part of the contribution, the algorithm of the new method was applied. A simulation on the MATLAB-Simulink software allowed obtaining satisfactory and convincing results documented in Table No. 2.

Reference:-
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