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Optimal Design of a Damped Input Filter Based on a Genetic Algorithm for an Electrolytic Capacitor-less Converter

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ABSTRACT

In this paper an optimal damped input filter is designed based on a Genetic Algorithm (GA) for an electrolytic capacitor-less AC-AC converter. Sufficient passive damping and minimum losses in passive damping elements, minimization of the filter output impedance at the filter cut-off frequency, minimization of the DC-link voltage and input current fluctuations, and minimization of the filter costs are the main objectives in the multi-objective optimization of the input filter. The proposed filter has been validated experimentally using an induction motor drive system employing an electrolytic capacitor-less AC-AC converter.

Keywords: Optimization Methods, Genetic Algorithms, Filters, AC-AC Power Conversion

1. Introduction

The need for damping in the L-C input filters of switching AC-AC and DC-DC power converters is well appreciated within the power electronics field [1-11]. In electrical drive systems, which include static converters, the converters deform loads for the power system network and, at the same time, deform energy sources for the electric motor. So, the main reason for employing damped input filters for Pulse Width Modulation (PWM) converter systems is to ensure sinusoidal shaped input currents at a high power factor by filtering the harmonics of the pulse-shaped rectifier input currents In addition to this, the other reasons for employing damped input filters are to prevent electromagnetic interference of the considered power electronic converter with electronic systems present in the neighboring environment and to avoid disturbance of the power converter operation by sources of electromagnetic noise from the surroundings [1], [2].

The performance and stability of input filters for DC–DC and AC-AC converters have been investigated in numerous publications. A general derivation for optimal design of single-resistor damping networks, based on Middlebrook's extra element theorem, is discussed in [3-5]. In [6], a differential mode input filter design for a three-phase buck-type PWM rectifier based on modeling of the Electromagnetic Compatibility (EMC) was presented. Optimal single resistor damping of input filters was discussed in [7]. The objective of [7] is to extend the optimization and design procedure of [4] to other basic

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input filter configurations. So, in [7] a general derivation for optimal design of single-resistor damping networks, based on Middlebrook's extra element theorem,[5] is presented. Also, an approach to design higher-order filters consisting of cascaded L-C filter sections is contained in this paper. Application of a Genetic Algorithm (GA) for optimal design of the active damping for a LCL-filter is considered in [8]. The aim of [8] is to find the best individual (i.e. the best set of coefficients for the active damping filter and the best proportional constant of the PI current controller) in order to have the desired damping of the high frequency poles and the desired bandwidth of the current loop. Input filter damping designs for DC-DC and AC-AC converters are introduced in [9-11]. In [9], the instability problem of DC-DC converters with input filter is elaborated on using a control-to-output transfer function. For this purpose a parallel Rd-Cd damped input filter is considered and designed based on an open loop transfer function. Based on the damping circuit parameters, two conditions of stability are derived for buck converters and, thus, a region of stability is found which provides minimum and maximum limits on the damping resistance which must be added if the natural parasitic resistance of the input filter is not sufficient. In [10] a low-pass filter is designed for the control circuit of DC-DC converters. The second order Butterwoth case and Chebyshev active low-pass filters are considered for this purpose. Therefore, a second-order active low-pass filter is designed in this paper for occasions that need a large time constant in practice. . In [11], a $L_F - C_F$ line input filter with a series damping resistance is used. In this paper each inductance is divided into two parts: aL_F , and $(1-a)L_F$ and this second one is bypassed by a damping resistor R_F. The filter consists of the transverse impedance of the capacitors and of the longitudinal impedance of the inductors and the resistors. The maximum damping is found based on the vector diagram of the parallel impedance ($Z_P = j\omega(1-a)L_F \big| \big| R_F$) and the longitudinal impedance of series filter branch ($Z_L = j\omega \, aL_F + Z_P$). The highest point of the circle diagram occurs with the value of the optimum damping resistor. For the sake of practical interest, two inductors are considered of the same size ($a = 0.5$) in [11].

Based on the above discussion of the previously research [1-11], the following design targets can be considered for the damped input filter design:

- Minimization of the physical size/energy stored in the filter components;
- Sufficient passive damping in order to avoid oscillations for no-load operation;
- Minimum losses in passive damping elements;
-Avoidance of filter resonances at multiples of the switching frequency;
- Minimization of the filter output impedance in order to ensure system stability and minimize control design restrictions;
- Fulfillment of international EMC regulations in differential mode that translates into minimum filter attenuation requirement at given frequencies;

In this paper, based on these design targets, a multi-objective optimal damped input filter design procedure for an electrolytic capacitor-less AC-AC converter is presented. In the electrolytic capacitor-less inverter, the high frequency currents caused by the switching current of the inverter are mostly transferred directly to the input side due to the small capacitance in the DC-link. Hence, an input filter should be installed to reduce the switching current ripple to the AC source. In many power converter applications, an L-C filter with a damping resistor is widely used for an input filter due to its robustness and simplicity.

In this paper an L-C damped input filter is designed by using a multi-objective optimization method based on a Genetic Algorithm (GA). Therefore, for optimal input filter design, the following design targets can be formulated:

-Sufficient passive damping and minimum losses in passive damping elements;
- Avoidance of filter resonances;
- Minimization of the filter output impedance at the filter cut-off frequency (based on Middlebrook's extra element theorem) in order to ensure system stability and to minimize control design restrictions;
- Minimization of DC-link voltage fluctuations;
- Minimization of input current oscillations; and
- Minimization of the filter costs.

Also, limitation of the physical size/energy stored in the filter components should be considered.

The advantages of the proposed method are:

- The proposed method could be used as a fast systematic algorithm for multi-objective optimization of the damped input filter for AC-DC-AC converters.

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- The proposed method is a derivative free optimization and does not need functional derivative information to search for a set of parameters that optimize the given objective functions. A derivative free optimization also relieves the requirement for differentiable functions, so an objective function can be used that, despite being complex, avoids sacrificing too much computation time in extra coding.

- The importance degree weight for the objective functions can be considered based on the multi-objective optimal filter design.

This paper is organized as follows: in section 2.1, 2.2, and 2.3, the AC-AC power electrolytic capacitor-less converter [12], damped input filter, and conventional design of the damped input filter based on trial and error are explained, respectively. In section 3.1, multi-objective optimization based on a GA [13] is discussed, and a multi-objective optimization of the damped input filter based on a GA is formulated in section 3.2. In section 4, experimental results using the designed input filter are compared with the results utilizing a conventional filter for a 14 kW vector controlled AC drive system.

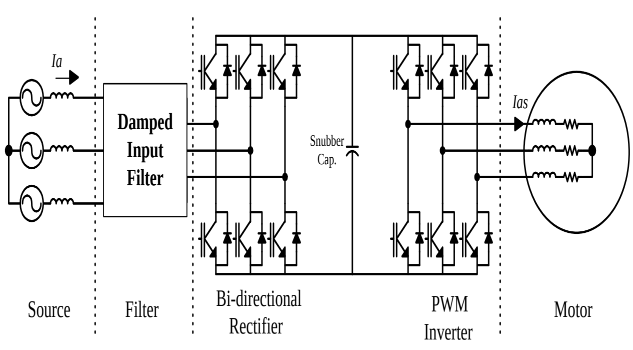


Fig. 1. Drive system with AC-AC power electrolytic capacitor-less converter.

2. AC-AC Power Electrolytic Capacitor -Less Converter and Input Filter

2.1 AC-AC power electrolytic capacitor-less converter

An AC-AC power electrolytic capacitor-less converter used in a high-performance drive systems is shown in Fig. 1. As shown in Fig. 1, it is divided into a bi-directional rectifier, a PWM boost converter and a PWM inverter with DC voltage link. In the conventional AC-AC converter widely used in drive systems, an energy storage component employing a large electrolytic capacitor bank and heavy AC or DC inductors for power factor improvement are required. The DC-link capacitor bank can be a critical component, especially in high-power or high-voltage applications, since it is bulky and expensive, and its life expectancy is shorter than any other power components. Also, the large AC or DC inductors are a burden to the system with regard to both cost and volume.

The objective of using less reactive components can be achieved by using a matrix converter. The electrolytic capacitor-less AC-AC converter in this paper is a hybrid of a matrix converter and a conventional PWM boost converter [12]. Like a conventional PWM boost converter, it uses only unidirectional switches and consists of two converter stages. However, it does not need a large DC-link capacitor or input inductor for energy storage.

The electrolytic capacitor-less inverter shown in Fig. 1 is a good candidate to reduce the reactive components. The proposed electrolytic capacitor-less inverter can operate both in motoring mode and regenerating mode due to the bi-directional rectifier whose switching instance of the active switch is synchronized with the parallel diode. Due to the low switching frequency of a bi-directional rectifier, an additional heat sink is not needed. Also, a small film capacitor, whose value is only several μF and whose life expectancy is almost ten times that of the electrolytic capacitor, is installed instead of the large electrolytic capacitor in the DC-link. The Total Harmonics Distortion (THD) of input currents can be improved remarkably due to the small capacitance in the DC-link. However, the rectifier bridge's output, which is the DC-link voltage, is a rippled voltage waveform that traces the top of the absolute value of the line-to-line input voltages. The AC output voltage of the inverter bridge is synthesized based on the DC-link voltage by a Space-Vector PWM (SVPWM) [14], [15].

2.1.1 Input filter

Fig. 2 shows the addition of an input filter to a switching voltage regulator system. The input filter elements affect all transfer functions of the converter, including the control-to-output transfer function, the line-to-output transfer function, and the converter output impedance. Moreover, the influence of the input filter on these transfer functions can be quite severe. The control-to-output transfer function is defined as follows [3]:

$$G_{vd}(s)=\frac{\hat{v}(s)}{\hat{d}(s)}\bigg|_{\hat{v}_g(s)=0} \tag{1}$$

Middlebrook's extra element theorem is employed to determine how the addition of the input filter modifies the control-to-output transfer function. It is determined that the modified control-to-output transfer function can be expressed as follows [3]:

$$G_{vd}(s)=\left(G_{vd}(s)\big|_{Zo(s)=0}\right)\left(\frac{1+\dfrac{Z_o(s)}{Z_N(s)}}{1+\dfrac{Z_o(s)}{Z_D(s)}}\right) \tag{2}$$

From Fig. 2 and (2), the quantity $Z_D(s)$ is equal to the converter input impedance, $Z_i(s)$, under the condition that the controller output, $\hat{d}(s)$, is equal to zero and the quantity $Z_N(s)$, is equal to the converter input impedance $Z_i(s)$, under the condition that the feedback controller of Fig. 2 operates ideally. In other words, the controller varies $\hat{d}(s)$ as necessary to maintain $\hat{v}(s)$ equal to zero and $Z_O(s)$ is the output impedance of the input filter. Equation (2) reveals that the addition of the input filter causes the control-to-output transfer function to be modified by the last term of the right side in (2)[3].

When the following inequalities are satisfied, the correction factor has a magnitude of approximately unity, and the input filter does not substantially alter the control-to-output transfer function [3], [4].

$$|Z_O| << |Z_N| \quad and \quad |Z_O| << |Z_D| \tag{3}$$

These inequalities limit the maximum allowable output impedance of the input filter, and constitute the useful filter design criteria.

2.1.2 Damping the input filter

To damp the resonance of the input filter, impedance inequalities by (3) should be satisfied over all frequencies.

There are many types of damped input filters [9-11], and one simple and low cost approach to damping the filter is to add a resistor, R_f in parallel with the capacitor as illustrated in Fig. 3(a). The maximum value of the output impedance occurs at the resonant frequency and is equal to the value of the resistance, R_f. Hence, to satisfy impedance inequalities in (3), R_f should be set to be much less than the $|Z_N|$ and $|Z_D|$ asymptotes. Unfortunately, this raises a new problem: the enormous power dissipation in R_f. If the input voltage, v_g, is applied across resistor, R_f, the power loss across the resistor is equal to v_g^2/R_f. This power loss may be greater than the load power. Therefore, the circuit of Fig. 3(a) is not a practical solution. One solution to the above mentioned loss problem is to place R_f in parallel with L_f as illustrated in Fig.3 (b). Since the average DC voltage across inductor L_f is zero, there is no DC power loss in resistor R_f as long as DC current flows through the inductor.

In this paper, an optimal and a conventional damped

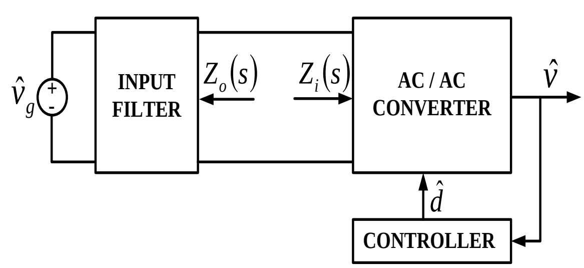


Fig. 2. Addition of an input filter to a switching voltage regulator system [3], [4].

input filter, based on Fig.3(b), are designed and their performance is compared for the electrolytic capacitor-less converter in Fig. 1. The conventional method for designing the damped input filter is disscused in the next section.

2.2 Conventional design of the damped input filter based on trial and error

In this section, to analyze the performance of the optimal damped input filter, an input filter design strategy based on the conventional method of trial and error is introduced. For this purpose, the damped input filter shown in Fig. 3(b) is considered. In the electrolytic capacitor-less inverter, the high frequency currents caused by the switching current of the PWM inverter shown in Fig. 1 are transferred directly to the input side due to the small capacitance in the DC-link. Hence, a damped input filter should be installed to reduce the switching current ripple to the AC source. On the basis of the method in [11], reasonable input filter parameters are designed using trial and error. The cut-off frequency of the input filter and the filter resistance to maximize the damping effect is given as (4-a) when the feasible region is in (4-b).

$$f_n = \frac{1}{2\pi\sqrt{3L_f C_f}}$$
$$R_f = 2\pi f_n L_f \tag{4-a}$$

Subject to;

$$1:\ 0.1 f_s \le f_n \le 0.2 f_s$$
$$2: C_f < C_{f\max}$$
$$3: L_f < L_{f\max} \tag{4-b}$$

where, f_s is the switching frequency of the inverter and f_n is the input filter cut-off frequency.

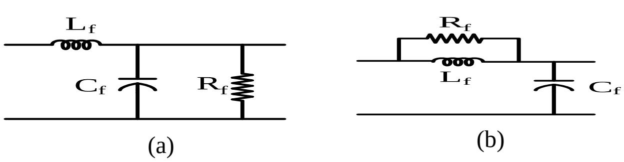


Fig. 3. Two attempts to damp the input filter a) damping resistance R_f across C_f b) damping resistance R_f across L_f.

In (4.a), the cut-off frequency of the input filter can be set by considering the switching frequency of the PWM inverter shown in Fig. 1 and the filter volume. High frequency currents are generated by the PWM inverter to regulate the currents, and their frequency is twice the switching frequency of the PWM inverter. Hence, in order to have a sufficient filtering effect, the cut-off frequency of the input filter should be set to $0.1 \sim 0.2$ of the switching frequency of the PWM inverter depending on the size of the input filter.

The parameters of the input filter can be found by the computer simulations of the system in Fig. 1 for the constant motor output power, but this technique is usually time-consuming. According to the simulation results and the Bode plot of the conventional trial and error design strategy, the reasonable region for the filter inductance to ignore the source impedance is considered as follows:

$$L_f > 5\, L_s$$

where, L_S is the line inductance.

Also, in order to avoid voltage distortion by the input filter, it is better to have the small filter inductance under the same cut-off frequency[16]. Once the filter inductance is determined, the other filter parameters such as filter capacitance and resistance can be set by using (4-a).

The performance of the conventional trial and error and the proposed optimal input filter are compared in section 4.

3. Multi-Objective Optimization of Damped Input Filter Based on a GA

3.1 Muti-objective optimization based on a GA

GAs have been successfully applied to various optimization problems. The application of GAs to multi-objective optimization has been reported in several research studies [17-22]. A GA is an evolutionary algorithm which maintains a population of candidate solutions for a given problem. Individuals are evaluated and assigned fitness values based on their relative performance. Then, they are given chances to be reproduced, i.e. replicate themselves a number of times proportional to their fitness. The offspring are modified by means of mutation and/or recombination operators before they are evaluated and subsequently reinserted in the population. In this paper, multi-objective optimization based on a GA [13] is applied to find the optimal parameters of the damped input filter for the electrolytic capacitor-less converter in Fig. 1.

The general multi-objective optimization problem can be stated as finding an n-dimensional vector, X, such that

$$\begin{aligned}&Maximize \quad [f_1(x), f_2(x),....., f_M(x)]\\&S.T. \quad x_{io} \le x_i \le x_{if} \quad i = 1,..., n\end{aligned} \tag{5}$$

Suppose that the population number, N, is fixed and each solution of the multi-objective problem is defined as a chromosome, with the length L. In a GA, a probability function has been defined to select the best fitted chromosomes for the existing population. Mutation and recombination operators are applied to create the new chromosomes for the new population.

In this paper, the probability function in the GA is defined as follows:

$$P_{L,i} = \frac{\prod_{m=1}^{M}\left[C_m(S_{L,i})\right]^{K_m}}{\sum_{L=1}^{N}\left[\prod_{m=1}^{M}\left[C_m(S_{L,i})\right]^{K_m}\right]} \tag{6}$$

where, $C_m(S_{L,i})$ is the fitness number of the m^th^ objective function for the L^th^ chromosome, M is the number of the objective functions, N is the number of the chromosomes in the population, and K_m is the weight that shows the importance degree of the m^th^ objective function.

For defined $C_m(S_{L,i})$, at first $C_m^0(S_{L,i})$ is defined as follows:

$$\begin{aligned}&C_m^o(S_{L,i}) = f_{objm}(S_{L,i}) - \mu_m\\&m = 1,2,..., M\\&L = 1,2,...., N\end{aligned} \tag{7}$$

where, $C_m^0(S_{L,i})$ is the fitness value for the m^th^ objective function and μ_m is the mean value of the m^th^ objective function in population sequences.

The Fitness value for each objective function is defined as:

$$C_m(S_{L,i}) = \begin{cases}\dfrac{C_m^o(S_{L,i})}{\gamma_m} & if \quad C_m^o(S_{L,i}) > 0\\ 0 & if \quad C_m^o(S_{L,i}) \le 0\end{cases} \tag{8}$$
$$L = 1,2,..., N$$
$$m = 1,2,..., M$$

where, γ_m, is the summation of the positive fitness values.

3.2 Multi-objective optimal design of the damped input filter based on a GA

In this section, several objective functions for the multi-objective optimal design of the damped input filter are defined.

A single phase circuit incorporating the damped input filter in Fig. 3 (b) is considered (Fig. 4).

If it is defined that:

$$i_{line} = I_S \; ; \quad L_{line} = L_S \; ; \quad i_{DC} = I_h \; ; \quad 3C_f = C_f^*$$

then, by neglecting the effect of line resistance, the transfer function of the input filter shown in Fig. 4 can be derived as follows:

$$\frac{I_s}{I_h} = \frac{R_f + L_f s}{L_f L_s C_f^* s^3 + \left(R_f L_s C_f^* + R_f L_f C_f^*\right)s^2 + L_f s + R_f} \tag{9}$$

From the Bode plot of (9), the damping ratio (ζ) and cut-off frequency of the filter can be found to suppress the resonance in the input currents.

Fig. 5 shows a simple diagram of the first converter stage of Fig. 1, an AC-DC bi-directional power flow rectifier. The equivalent circuit for each interval when two switches are conducting in the circuit in Fig. 5 can be deduced as Fig. 6.

Based on the equivalent circuit from Fig.6, the objective functions in the multi-objective optimization of the damped input filter can be formulated as follows:

$$1) Maximize\ (Fobject\ 1) = \frac{1}{\text{Power Loss of The Input Filter}} = \frac{1}{3R_f I_{R_f}^2}$$

where, I_{R_f} is the r.m.s. value of the current flowing through the input filter resistance.

$$2)\, Maximize\ (Fobjec\ 2) = \frac{1}{\text{Maximum Peak-to-Peak Input Source Current Oscillations}}$$

$$3)\, Maximize\ (Fobject3) = \frac{1}{\text{Maximum Peak-to-Peak DC-Link Voltage Fluctuations}}$$

$$4)\, Maximize(Fobjec4) = \frac{1}{\text{Filter Cost Function}} = \frac{1}{3 \times L_f \times I_{L_f}^2 + C_f \times V_{C_f}^2}$$

where, I_{L_f} and V_{C_f} are the r.m.s. values of the filter inductance current and capacitance voltage, respectively.

$$5) = Maximize(Fobjec5) = \frac{1}{\text{Maximum Over-shoot of The Input Source Current}}$$

$$6)\, Maximize\ (Fobjec6) = \frac{1}{\text{Output Impedance Magnitude of the Filter at the Filter Cut-off Frequency}} = \left(\frac{2\pi f_c R_f L_f}{\sqrt{\left(R_f - (2\pi f_c)^2 R_f C_f^* L_f\right)^2 + (2\pi f_c)^2 L_f^2}}\right)^{-1}$$

where, (f_c) is the cut-off frequency of the input filter.

(10-a)

Subject to:

1: *Filter* damping ratio $(\zeta) \geq 0.707$

where, ζ can be found from Bode plot of (9).

2: $0.1 f_s \leq f_c \leq 0.2 f_s$

3: $C_f < C_{f\max}$

4: $L_f < L_{f\max}$ (10-b)

Based on (9) and the Bode plot, a 3dB overshoot is considered as the maximum magnitude of the filter transfer function at the filter cut-off frequency in the multi-objective optimization. To reduce the correction factor in (2) on the basis of Middlebrook's extra element theorem, the objective function (6) in (10-a) is considered for finding the minimum value of the output filter impedance at the filter cut-off frequency.

A simple flow chart for multi-objective optimal design of the damped input filter based on a GA is shown in Fig. 7. The initial population in the feasible region in (10-b) is generated at random, and a chromosome from each of the offspring is a candidate of the input filter in the optimization process. The performance of every chromosome is found by computer simulations of the system in Fig. 1 at a constant output power. Based on the Roulette wheel selection, two-point cross-over with probability functions p_c and mutation with probability function p_m, the offspring in the feasible region are generated by assuming a fixed population in GA. To find the global goal, a supervised method is used. In the offered method, if the probability function in (6) for the best chromosome in each population does not change for ten offspring, the probability functions of cross-over, (p_c) and mutation, (p_m) increased from 0.6 to 0.8 and 0.005 to 0.02, respectively, to investigate the global stability. Afterwards, these two probability functions decrease as, $p_c = 0.98 \times p_c$ and $p_m = 0.98 \times p_m$ for the next new offspring.

By using multi-objective optimization based on the flow chart in Fig. 7, the optimal values of damped input can be found.

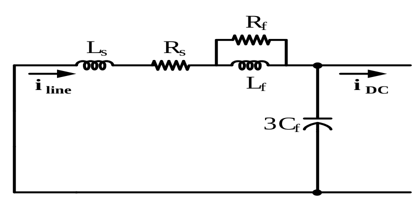


Fig. 4. Single phase circuit of the damped input.

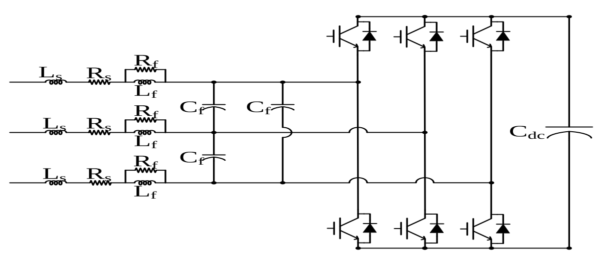


Fig. 5. Simple diagram of the first converter stage, AC-DC. bi-directional power flow rectifier, of Fig.1 with DC-link.

4. Experimental Results

In order to show the performance of the designed optimal damped input filter in the electrolytic capacitor-less converter, a prototype optimal and a conventional damped input filter were built and tested with an induction motor drive system. The converter parameters are listed in Table 1. The hardware block diagram and the induction motor with its parameters are shown in Fig. 8 and Fig. 9 where all control is carried out by a digital signal processor. By using a GA for multi-objective optimization in (10-a, b), the optimal values of the damped input filter parameters can be found. For this purpose, the physically possible region for the inductor and the capacitor of the input filter for a $220V_{r.m.s.}$ line-to-line input source power system are considered as:

$$L_{f\,\max} = 400\mu H$$
$$C_{f\,\max} = 20\mu F$$

and the similar importance degree weight for all of the objective functions are assumed for the probability function in (6). Then

$$K_m = 1$$
$$(m = 1:6)$$

The optimal parameters of the damped input filter parameters using a GA based on the flow chart in Fig. 7 and the previous explanation can be found after 30000 iterations as follows:

$$R_f = 1.02\Omega \quad L_f = 124\mu H \quad C_f = 18\mu F \tag{11}$$

Table 1 Experimental condition of the converter

Source voltage	220 V(line –to-line in r.m.s.)
Line inductance	About $16\mu H$
Line Resistance	About 0.0001Ω
Switching frequency of Inverter, (f_s)	10 KHz
Sampling frequency	20 KHz
Snubber Capacitor	$10\mu F$

In a GA, the population number (N) is fixed and equals 100.

The experimental values of the proposed optimal and the conventional damped input filter are compared in Table 2. The Bode plot of these filters based on the filter parameters in Table 2, the filter transfer function in (9) and 16μH for line inductance is shown in Fig. (10). Although the damping resistor is installed in the input filter, there is considerable overshoot around the resonance frequency of the input filter as shown in Fig. 10. In Fig. 10, the cut-off frequencies of the proposed optimal and the conventional damped input filter are 1.85kHz and 1.9kHz, respectively.

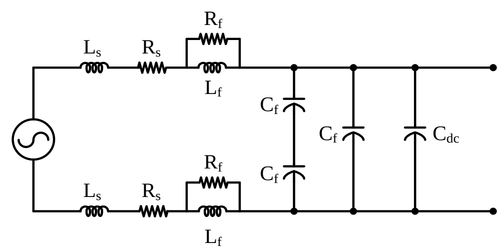


Fig. 6. Equivalent circuit of the filter including AC source when two switches are conducting.

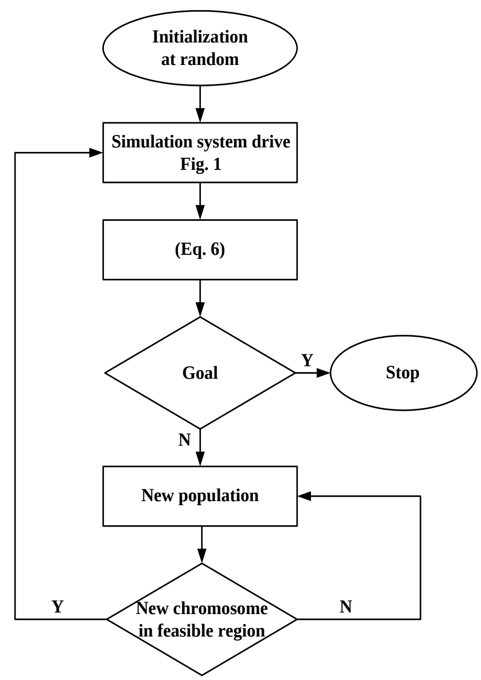


Fig. 7. Simple flow-chart for multi-objective optimal design of damped input filter based on GA.

The conventional filter parameters are found based on the trial and error method in (4-a,b) after a long time consuming process. In this paper, the source impedance is assumed to be 16μH, and the filter inductance of the conventional input filter is set to 100μH for convenience. Also, the cut-off frequency of the input filter is set to around 2 kHz in order to filter the high frequency components in the currents. Finally, the conventional input filter parameters can be determined by (4-a).

In Fig. 11, a no-load test of the motor-drive system with the optimally designed filter is shown. In Figs. 12 and 13, the motoring-mode test results using the conventional filter and the optimal filter are shown, respectively, when the induction machine is operated at 14kW and 1700 r/min. In these figures, C1 is the phase input source current, C2 is the current flowing through the input filter resistance, C3 is the line-to-line input voltage of the input filter and C4 is the DC-link voltage.

From Fig. 12 and Fig. 13, it can be concluded that the optimal filter from a GA results in a larger damping, less DC-link voltage fluctuations from the input filter, and reduced peak-to-peak input current oscillations. Although the maximum DC-link voltage fluctuation of the conventional input filter is almost 100V, it is reduced up to 70V in the proposed optimal filter. Also, the maximum peak-to-peak input current oscillation is reduced from 30A to 20A by using the proposed filter. However, the total power loss in the input filter resistance for the optimal filter is increased to 90W while the conventional filter is around 60W. The total power loss in the optimal filter is a little bit increased because of the increased filter inductance and the decreased filter resistance compared to the conventional input filter. However, compared to 14 kW output power, the loss of 30W can be neglected.

Table 2 Experimental values for the optimal and the conventional damped input filter parameters

Optimal Damped Input Filter Parameters	$R_f = 1\Omega$ $L_f = 120\,\mu H$ $C_f = 18\mu F\,(\Delta connection)$
Conventional Damped Input Filter Parameters	$R_f = 1.6\Omega$ $L_f = 100\,\mu H$ $C_f = 20\mu F\,(\Delta connection)$

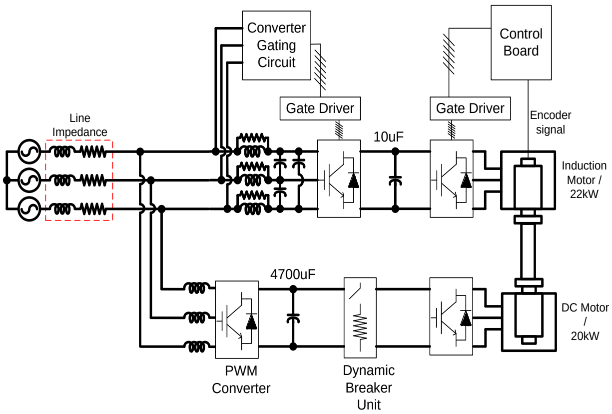
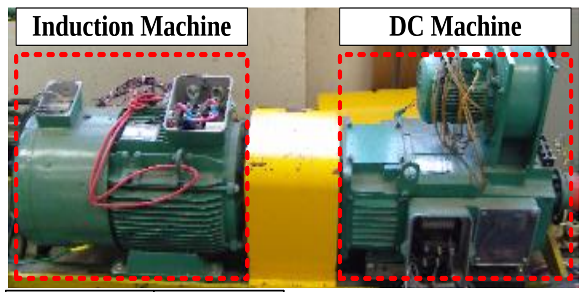


Fig. 8. Experimental system block diagram.



Rs [Ohm]	0.044
Ls [mH]	1
Lm [mH]	12.9
Ls [mH]	13.45
Lr[mH]	13.37
Rr [Ohm]	0.0252
Polepair	2

Ra [Ohm]	0.24
La [mH]	5.6
Rf [Ohm]	48.8
Lf [H]	13.33
Kt[N.m/A]	1.1413

Fig. 9. Induction and DC machine. (as a Load)

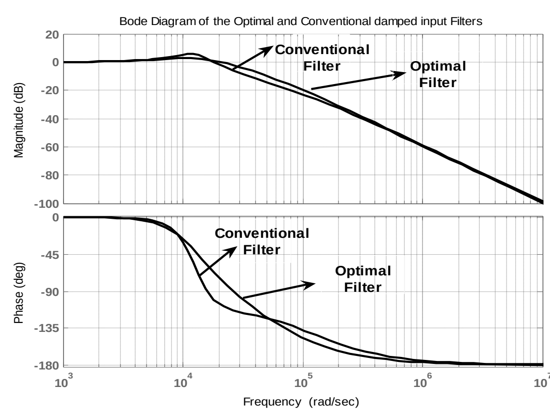


Fig. 10. Bode plot of proposed optimal and conventional damped input filter.

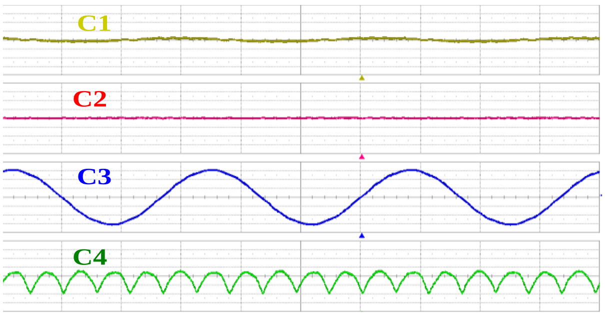


Fig. 11. No-load test, C1: Input current (phase a) (20A/div), C2: Filter resistance current (phase a) (10/div), C3 Line input voltage (Vab) (100V/div), C4: DC-link voltage (mid: 300V, 20V/div),time (5msec/div).

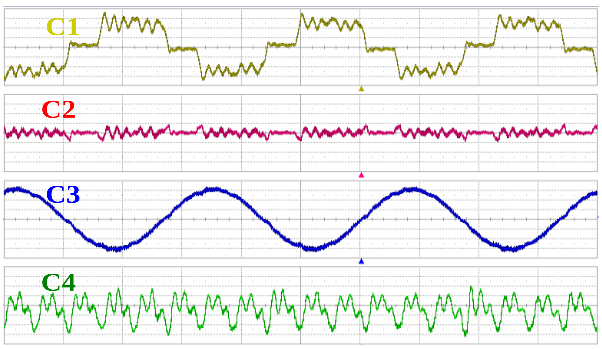


Fig. 12. 14kw, 1700 r/min motoring load test with the conven-tional filter parameters, C1: Input current (phase a) (20A/div), C2: Filter resistance current (phase a) (10A/div), C3: Line input voltage (Vab) (100V/div), C4: DC-link voltage (mid: 300V,20V/div),time (5msec/div).

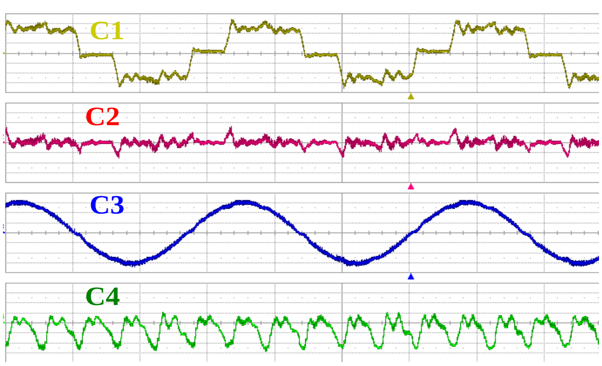


Fig. 13. 14kw, 1700 r/min motoring load test with the optimal filter parameters, C1: Input current (phase a) (20A/div) C2:Filter resistance current (phase a) (10A/div),C3:Line input voltage (Vab) (100V/div), C4: DC-link voltage (mid: 300V, 20V/div), time (5msec/div).

5. Conclusions

In this paper, a multi-objective optimal method for designing a damped input filter based on a GA for an electrolytic capacitor-less AC-AC converter is presented. The proposed filter has been validated experimentally using an induction motor drive system employing an electrolytic capacitor-less AC-AC converter. Experimental results show suitable performance of the optimal damped input filter. Compared to the designed conventional trial and error input filter, the proposed optimal input filter has a higher damping, more reasonable power loss (less than 1% of the output power), less filter output impedance at the filter cut-off frequency and less fluctuations in DC-link voltage. The conventional method for designing the input filter is usually time consuming and requires an expert designer, but the proposed method is a fast systematic algorithm and the filter designer can be easily used for any multi-objective optimal design of an L-C input filter for power converters.

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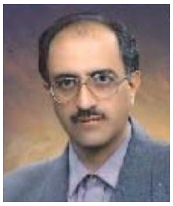

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