Inverter for Microturbines Based on Multiobjective Genetic Algorithm

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Abstract

In this paper, authors present a new design method for Pulse Width Modulation inverters in microturbines by using a multiobjective genetic algorithm. The design problem is converted to an equivalent optimization problem, and then a multiobjective genetic algorithm is adopted to find a solution.

The genetic algorithm is proposed to design a fuzzy controller. In this GA approach, an individual is constructed to represent the fuzzy controller.

Multiobjective genetic algorithm confers a number of advantages over conventional multiobjective optimization methods by evolving a family of Pareto-optimal solutions rather than a single solution estimate. This optimal fuzzy controller is suitable for the Specific Harmonic Elimination PWM technology, as demonstrated by the examples given in this paper.

1. Introduction

Evolutionary changes in the regulatory and operational climate of traditional electric utilities and the emergence of smaller generating systems such as microturbines have opened new opportunities for on-site power generation by electricity users.

Microturbines are small and simple-cycle gas turbines with outputs ranging from around 25 to 300 kW [1, 2]. They are one part of a general evolution in gas turbine technology. Because the turbines run at high speeds, up to 80000 rpm, the ac generator is a high frequency generator that cannot be coupled directly to the ac grid. An intermediate dc link is used, a dc capacitor fed from the diode rectifier. A dc/ac inverter produces voltages at the power system frequency. The microturbine produces a significant amount of voltage and current harmonics. However, an improved dc to ac conversion scheme could easily eliminate this problem.

Fuzzy logic controllers are an attractive choice when precise mathematical formulations are not possible. Other advantages of this controller are: 1) it can work with less precise inputs; 2) it doesn't need fast processors; 3) it needs less data storage in the form of membership functions and rules than conventional look up table for non-linear controllers; and 4) it is more robust than other non-linear controllers.

With the rapid advances in microelectronics, real-time digital control of power devices using cost-effective digital- signal-processor (DSP) based hardware system has become feasible. The DSP hardware architecture with fuzzy logic enables most of its instructions to be executed in a single instruction cycle and complex control algorithms to be processed at a faster rate compared to single-chip microprocessors.

Fuzzy logic methods have been applied to control [3]. A fuzzy algorithm for speed control of permanent magnet synchronous motor drive is proposed in [4]. Denai and Attia [5] present some design approaches of intelligent control systems combining conventional control techniques with fuzzy logic and neural networks.

Over the last few years, the use of the genetic algorithm (GA) in the design and implementation of fuzzy controllers has been a popular technique. In the GA-based approach to fuzzy controller design, the procedure is that the fuzzy controller is transferred into a parameter representation. Most approaches create the membership functions to help create the fuzzy controller [6, 7, 8]. Each membership function, however, consists of two or three parameters. Thus, there are too many parameters involved in the development of the fuzzy controllers. If all of them are encoded, this will result in rather long strings for the individuals and will then increase the complexity of the problem. The GA is used as the auxiliary searching technique to fine tune the parameters of the fuzzy controller determined by other methods [9, 10, 11]. To avoid a long string for the fuzzy controller, the GA is used to determine both the membership function and scaling factors simultaneously for the fuzzy controller.

The paper is structured as follows. Sect. 2 presents a review of the microturbine generator system. Some basic concepts of the pulse width modulated inverter are introduced in Sect. 3. Sect. 4 briefly discusses the genetic fuzzy controller. Sect. 5 illustrates harmonic elimination. Sect. 6 depicts some simulation results. Finally, conclusions are presented in Sect. 7.

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2. Microturbine generator system

A typical scheme is shown in Fig. 1. The inverter is of the voltage source type, and is currently using Insulated Gate Bipolar Transistors (IGBTs) up to the MW range [12].

The microturbine wheel, the compressor wheel and the generator are directly mounted on the shaft (no gearbox), which is possible as a result of the use of a high-speed generator. The rotor is either a two- or four-pole permanent magnet design, and the stator is a conventional copper wound design.

The alternator generates a very high frequency three-phase signal ranging from 1500 to 4000 Hz. The high frequency voltage is first rectified and then inverted to a normal 50 or 60 Hz voltage. The microturbine can run without a reference source present. As such, it can operate as a stand-alone source for an isolated or emergency' system.

During start-ups, the three-phase microturbine acts as a motor load by drawing power from the battery. Once the desired operating conditions are reached, the device becomes a generator. As such, synchronization with the utility system is automatically achieved. Since power electronics are used to generate the final output power, the microturbine produces a significant amount of voltage and current harmonics [13, 14].

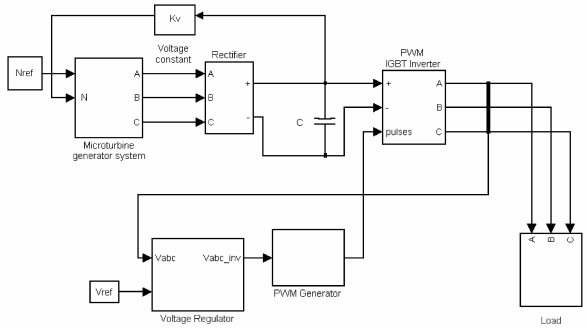


Figure 1. Topology for a microturbine generator system.

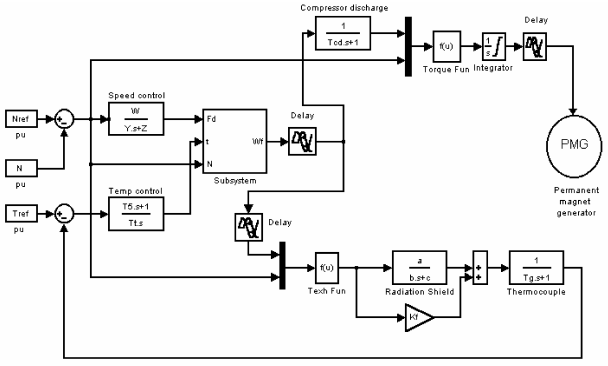


Figure 2. Microturbine control system.

Fig. 2 represents a block diagram for a single-shaft gas turbine, together with its control and fuel systems, as it would be represented for isolated generator drive service. The control system includes speed control, temperature control, and upper and lower fuel limits [15, 16].

3. Pulse width modulated inverter

The scheme presented in Fig. 1 displays a self commutated Pulse Width Modulation (PWM) dc/ac inverter. Self commutated converter systems uses fully controllable switches such as the IGBT, typically for low voltage, low and medium power applications -or the Gate Turn Off (GTO) or Integrated Gate Commutated Thyristor (IGCT), for medium voltage and medium and high power applications.

Voltage source converters are the preferred topology. This is the result of switch technology, which favors switches with a reverse conducting diode, the cost, weight and size, which favor capacitors over inductors, and the presence of a voltage bus. The voltage bus allows the connection of energy storage such as batteries.

In recent years, and partly as a consequence of the extensive developments in ac motor drives, the dc/ac three phase bridge inverter has become a standard in many applications. The converter, of the voltage source type, fed from a capacitive dc bus, uses IGBT devices with an anti-parallel diode. These converters are known as 2 level, three-phase converters. Units up to 1 MW or more are available in the low voltage range (typically 600 V). Recently converters have appeared for direct coupling to medium range voltages (up to 6.6 kV) and are of the 3 level type [17]. A modular generator and converter topologies, suitable for utility interface of microturbine is explored in [18].

The converter usually switches up to a few kHz or more, depending upon the application. This results in a number of improved features over line commutated converters:

- The inverter voltage harmonic components are large but at a high frequency. The ac line current harmonic components are therefore small.
- The dynamic response of the inverter is fast since the delay in changing inverter operation is on average of the order of half a switching period.

The same inverter can be used as a rectifier, that is, convert ac into dc. The combination of rectifier and inverter allows the implementation of frequency changers, with independent control of voltage and frequency on both ac sides. The dc bus allows this complete decoupling. In addition, energy storage (batteries) can be connected to the dc bus.

Various randomized PWM techniques have also been reported which redistribute the harmonic energy over a larger frequency range instead of being concentrated at discrete frequencies [19, 20]. This spread in spectrum is favorable for applications where the major concerns are the reduction of acoustic noise and conducted electromagnetic interference.

4. Genetic fuzzy controller

Fuzzy control is a versatile and effective approach to deal with many nonlinear and uncertain systems [21, 22, 23]. Even if a fuzzy logic controller (FLC) can reproduce any arbitrary nonlinear control law, the lack of systematic procedures for the configuration of its parameters remains one of the main obstacles to practical applications. The design problem, often consists in finding a trade-off between conflicting cost and performance objectives, which cannot be simultaneously taken into account with conventional design approaches.

4.1. Genetic fuzzy system

GA have been used diversely for FLC design either off-line or on-line although in the latter case computation time is sometimes prohibitive. Off-line learning is carried through closed loop simulation using a simplified model of the plant for fitness computation. The search is carried out either in the set of the parameters of the membership functions and/or the scaling factors.

Karr [24, 25] applied GA with binary coding to find good parameters for the membership functions. The problem is to locate support points for the membership functions. Since there is an underlying ordering of the fuzzy sets to be maintained, each point is constrained to lie between a lower and an upper bound.

Homaifar and Maccormick [10] used nonbinary integer coding to optimize the rule base and membership function parameters of the input variables. The summit of the triangular membership functions is kept constant and only the width of basis is allowed to vary during the search process. While the particular coding reduces the length of the string it implies additional computation in the decoding process and during defuzzification. Moreover, extensive testing [26] has shown that the position of the summit of the triangular fuzzy set of the output variable is more influential than the width of the basis. Linkens and Nyongesa [27, 28] give more flexibility to the variation of the parameters in particular the summit and the two support points of the triangular fuzzy sets are allowed to vary at the cost of extra computation and longer string. Kim and Ziegler [29] propose a global, hierarchical search that includes the shape and number of fuzzy sets.

4.2. Multiobjective optimization

The general multi-objective optimization problem can be stated as to find an m dimensional vector, $\boldsymbol{x}$, such that:

Minimize

$$[f_1(x), f_2(x), \ldots, f_n(x)] \tag{1}$$

s.t.

$$x_{io} \le x_i \le x_{if}$$

Suppose that the number of population, is fixed and each solution of the multiobjective problem defined as a chromosome [30, 31]. For the general control problem, it is desirable to optimize a number of different system performances. Instead of aggregating the objectives with a weighting function, a multiobjective approach is applied.

Definition: For an n-objective minimization problem, u is dominated by v if

$$\forall i = 1, \ldots, n, \quad f_i(u) \ge f_i(v)$$

and

$$\exists j = 1, \ldots, n, \quad s.t. \quad f_j(u) > f_j(v) \tag{2}$$

The chromosome can then be ranked with

$$rank(I) = 1 + p \tag{3}$$

if I is dominated by other chromosomes in the population.

Hence, a Pareto-based fitness can be assigned to each chromosome according to its rank in the population.

5. Harmonic elimination

5.1. Specific harmonic elimination pulse width modulation

Among variable PWM schemes, Specific Harmonic Elimination Pulse Width Modulation (PWM-SHE) technology is one of the most direct methods that can overcome the conflicting relation between power handling capacity and switching frequency of semiconductor devices [32, 33].

The principal limitation with the application of PWM-SHE technique has been the analytical difficulty in solving the non-linear equations associated in the harmonic elimination approach. These equations contain trigonometric terms, are transcendental in nature and therefore exhibit multiple solutions. To obtain convergence with numerical techniques, the starting values must be selected considerably close to the exact solution. The application may just require selected harmonics eliminated.

According to the Fourier coefficients of certain PWM switching pattern, three-phase line to neutral:

$$a_n = \frac{4}{n\pi}\left[-1 - 2\sum_{k=1}^{N}(-1)^k \cos(n\alpha_k)\right]$$
$$b_n = 0 \tag{4}$$

Equation (4) has N variables (α_1 to α_N) and a set of solutions is obtainable by equating N-1 harmonics to zero and assigning a specific value of the amplitude of

the fundamental (α_1, equal to modulation index M after normalized). Through the following equations:

$$\begin{aligned} f_1(\alpha) &= 4/\pi\left[-1-2\sum_{k=1}^{N}(-1)^k\cos(\alpha_k)\right]-M=\varepsilon_1 \\ f_2(\alpha) &= 4/5\pi\left[-1-2\sum_{k=1}^{N}(-1)^k\cos(5\alpha_k)\right]=\varepsilon_2 \\ &\vdots \\ f_N(\alpha) &= 4/N\pi\left[-1-2\sum_{k=1}^{N}(-1)^k\cos(n\alpha_k)\right]=\varepsilon_N \end{aligned} \quad (5)$$

5.2. Multiobjective genetic algorithm

The use of multiobjective genetic algorithm (MOGA) in control, and engineering design in general, recognizes that most practical problems require a number of design criteria to be satisfied simultaneously. Clearly, it can be seen that there is no one ideal "optimal" solution, rather a set of Pareto optimal solutions for which an improvement in one of the design objectives will lead to a degradation in one or more of the remaining objectives.

Having designed a suitable fuzzy scheduling controller, the rule base, membership functions, and scaling factors may now be tuned. Depending on the particular problem, the number and type of encoded parameters can considerably influence the overall performance of the optimization process.

A comprehensive encoding of the fuzzy system parameters means that no area of the solution space is infeasible, but may mean that because of the computational complexity and nature of the solution space that satisfactory solutions will not be found in a reasonable time. On the other hand, it may result in overly complex schedulers offering only marginally improve performance or reduced stability.

Similarly, a simpler representation may reduce the computational complexity at the expense of the solution optimality. Thus, the choice of representation for the fuzzy scheduler will be a compromise between completeness and feasibility.

Fuzzy sets are usually defined by parameterized membership functions. It is therefore sufficient only to define the center points of normalized, triangular membership functions in order to specify the entire fuzzy partition of a variable. To improve the proposed genetic fuzzy structure the tuning process should involve the adaptation of the parameters of membership functions and scaling factors. The equations (5) are selected to represent the objectives.

6. Results

6.1. Simulation results

A load is fed from the microturbine generator system, this system comprises the ac generator, a 30 kW microturbine, the rectifier, and the PWM dc/ac inverter. The load and the microturbine generator system are modeled using MATLAB© and the Genetic Algorithm and Direct Search Toolbox [34].

The simulation values are: the microturbine is running on approximately 10 kW, 15 kW, and 30 kW power levels, the switching frequency of the inverter is chosen to be 25 kHz, the frequency of the high-speed generator current is 1 kHz, and the output voltage is 480 V_{rms} (L-L).

The conducting angles of the inverter are determined such that the current harmonic distortion is a minimum. Normally, these angles are chosen so as to cancel the predominant lower frequency harmonics. For this case, the 3th, 5th, 7th, 9th and 11th harmonics can be eliminated. One degree of freedom is used so that the amplitude of the fundamental waveform corresponds to the reference waveform's amplitude or modulation index [35].

The task is to get a specific harmonic elimination. According to this task, the objective of the optimization is to minimize the equations (5).

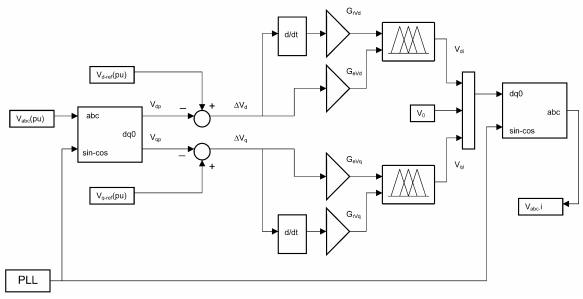


Figure 3. Block diagram for the voltage regulator.

The converter can be controlled well as long as V_{di} and V_{qi} can be determined to the desired value, as shown in Fig. 3. In this paper, the voltage error (ΔV_d) and its derivative ($\Delta V_d'$) are considered as the inputs of the first FLC and the voltage error (ΔV_q) and its derivative ($\Delta V_q'$) as the inputs of the second FLC.

The GA process optimizes the object vector which encodes the linear scaling factors G_{eVd}, G_{rVd} G_{eVq}, and G_{rVq} for each of the input variables ΔV_d, $\Delta V_d'$, ΔV_q, and $\Delta V_q'$.

As all input variables are symmetric the linear scaling function is fully determined by a single factor. The controller utilizes the original rule base given in Table 1, which itself is not subject to adaptation by the tuning process.

		ΔV_d ΔV_q						
		NB	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
$\Delta V_d'$ / $\Delta V_q'$	**NB**	NB	NB	NB	NM	NM	NS	Z
	NM	NB	NB	NM	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PM	PM	PB	PB	PB

Table 1. Control Rules.

We employ triangular membership functions for the input and triangular for the output fuzzy sets. All the membership functions are symmetrically positioned with respect to the center of the universes of discourse. We use a center-average defuzzification. The GA optimizes the position of the vertexes of membership functions of each input (see Fig. 4), and output of the FLC.

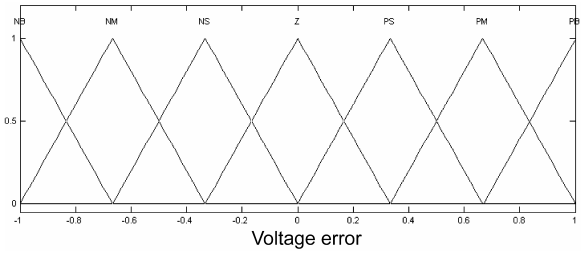


Figure 4. Triangular symmetric partitioning of universe of discourse.

The first step in the solution of an optimization problem using GA is the encoding of the optimization problem's variables. The most usual approach is to represent these variables as strings of 0s and 1s.

An initial population of alternative solutions is usually chosen at random. In this paper, the individuals of the first generation are initialized with scaling factors close to unity. Selection is responsible for the implementation of the survival of the fittest principle. The ten out of 30 off-spring that achieve the lowest cost constitute the parents of the next generation.

Crossover implements information exchange among individuals of a population with the attempt to generate new better fitted individuals, crossover probability = 0.9. Mutation has the role of restoring good genetic material that may have been lost by selection and crossover, mutation probability = 0.05.

Secondly, the cost functional, is converted into a fitness function, which is used to evaluate each string. This evolutionary tuning reduces the cost in Eq. (5).

The population so evolves from an initial one to a final issue, for a fixed number of generations. Indeed, the more is the number of requested generations better is the solution, but this would worsen the computational burden. By fixing the number of generations, the most convenient trade off between the improvement of the solution and computational effort is reached. Then, the best element of the final population is considered as the optimal configuration for the genetic fuzzy controller.

The results with the derived model are summarized. The load currents waveforms and the harmonics of load currents are shown in Figs. 5-7, using the conventional control and MOGA control. As the load output set point for the turbine is increased, the current harmonics decrease.

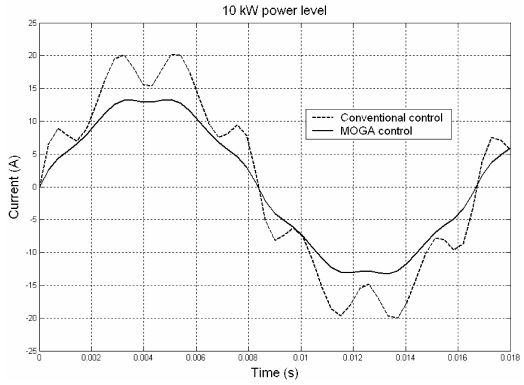


Figure 5a. Load current waveforms at 10 kW power level.

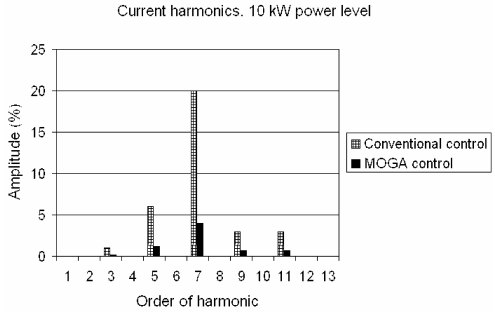


Figure 5b. Line current spectrum at 10 kW power level.

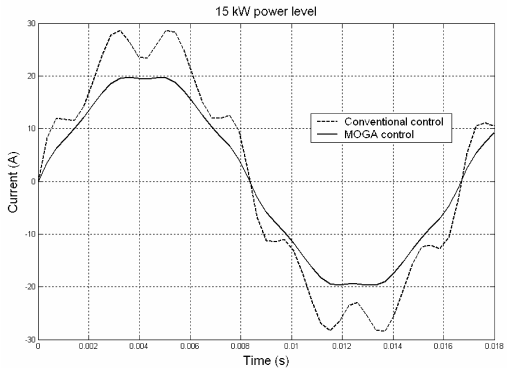


Figure 6a. Load current waveforms at 15 kW power level.

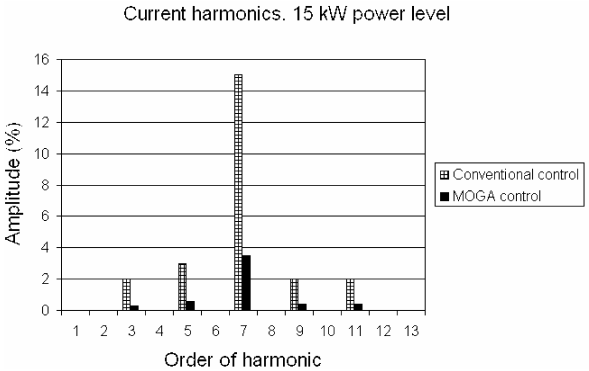


Figure 6b. Line current spectrum at 15 kW power level.

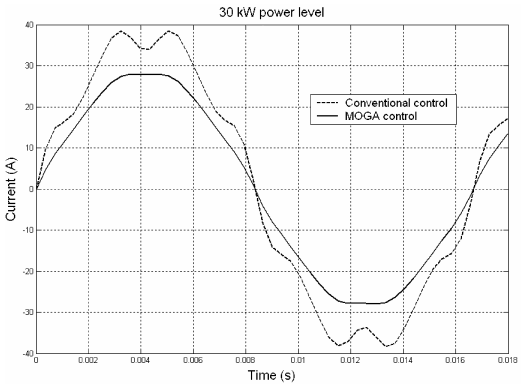


Figure 7a. Load current waveforms at 30 kW power level.

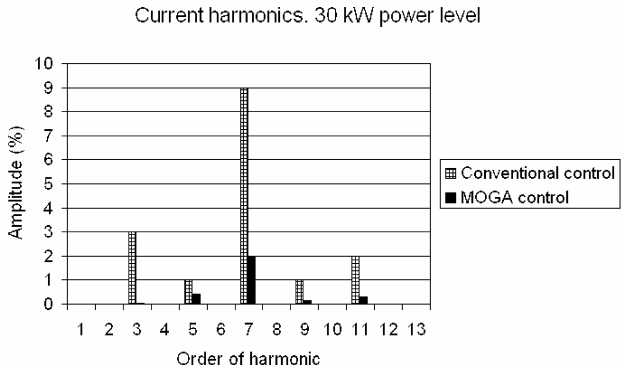


Figure 7b. Line current spectrum at 30 kW power level.

This paper has presented a novel method of current harmonic reduction in a PWM dc/ac inverter using a MOGA controller, therefore the passive filter between microturbine and load has not been considered. However, actual systems commonly use a LC filter as part of the PWM inverter system. This is then coupled to the ac system using an inductor. Inherent to this requirement is the need to actively damp the natural oscillations of the filter formed by inductor and capacitor. However, an improved dc/ac conversion scheme could easily eliminate these problems. The load currents waveforms and the harmonics of load currents with LC filter are shown in Fig. 8a and 8b, respectively.

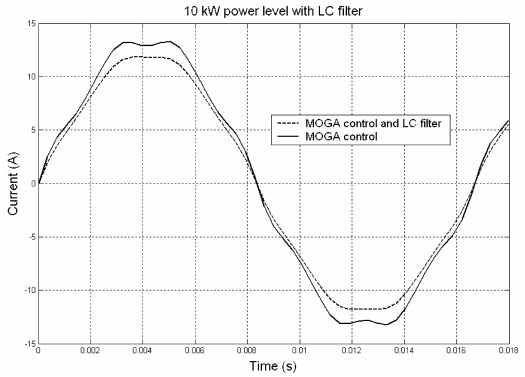


Figure 8a. Load current waveforms at 10 kW power level, with MOGA and LC filter.

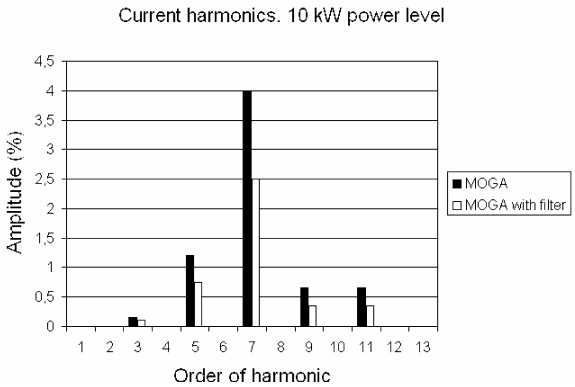


Figure 8b. Line current spectrum at 10 kW power level with MOGA and LC filter.

The THD of MOGA controller is lower than that of conventional controller. The principal reason for this is that in MOGA controller, the control system can be made more robust and less distorted adapting the number of fuzzy rules, membership function and scaling factors.

Fig. 9 shows a typical tradeoff graph for the fuzzy scheduling controllers found by the MOGA control at 10 kW power level . The *x* axis shows the design objectives and the *y* axis the performance of inverter in each objective domain. In the tradeoff graph, each line represents a nondominated solution for the design objectives. It can be clearly seen that all of the design objective have not been satisfied.

In these plots, harmonic orders are represented by their integer index i on the x-axis, and performance in each objective dimension is plotted on the y-axis. Each candidate solution $\boldsymbol{x}$ is represented by a line connecting the points $(i, f_i(\boldsymbol{x}))$.

A tradeoff between adjacent objectives results in the crossing of lines between them, whereas nonconcurrent lines indicate that those objectives are noncompeting.

The objectives do not seem to compete heavily. However, there is a clear tradeoff between objective 2 and objective 3.

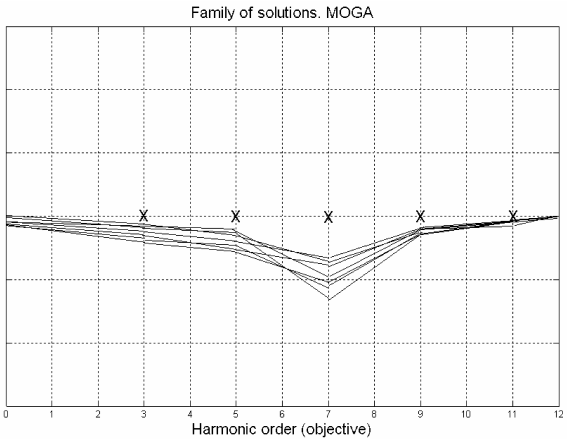


Figure 9. Family of solutions produced by the multiobjective genetic control.

Unfortunately, binary coded GA's cannot be expected to be able to deal well with strong variable dependencies. Evolutionary algorithms to be used in multiobjective parameter optimization should undoubtedly address this issue, because it seems to arise from the very nature of the Pareto formulation.

When objective functions are very expensive to evaluate, the interactive use of the MOGA may become less attractive due to the long time spent at the function evaluation stage of the GA.

6.2. Experimental Results

A cable provides the communication link between the gate driver board and the real-time processor. In this paper, the OpalRT© real-time computing platform [38] was used to interface the computer, which generates the logic signals, to this cable. This system allows one to write the switching algorithm in Simulink© which is then converted to *C* code. The software provides icons to interface the Simulink© model to the digital I/O board and converts the *C* code into executables.

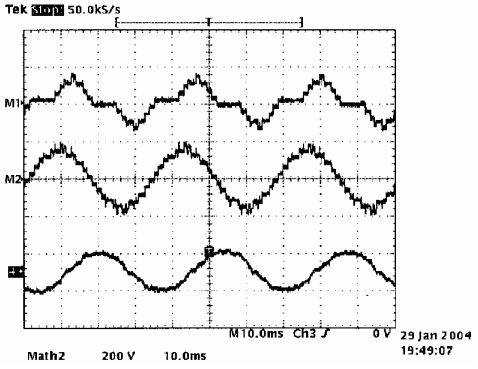


Figure 10a. Load current waveforms at 10 kW power level. Experimental performance.

The control method described above is implemented for a 2.2-kW 208-V three-phase inverter feeding a load as shown in Fig. 1. The filter component values are: L = 4.2 mH, C = 200 μF.

The upper traces of the oscillogram show the line-neutral and line-line voltages, as illustrates in Fig. 10a. The lower trace shows the inverter output line current. The inverter and filter rapidly reach steady state, and the filter natural oscillations are quickly damped. The harmonics of line current are shown in Fig. 10b.

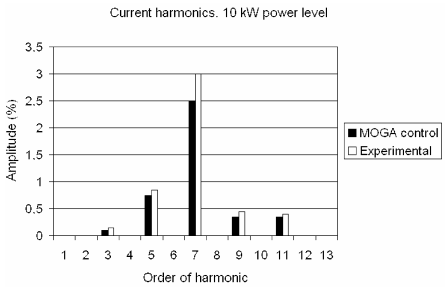


Figure 10b. Line current spectrum of load currents at 10 kW power level. Simulated and experimental performance.

7. Conclusions

In this paper, MOGA were analyzed as an alternative solution to the optimization problem for generating the switching pattern used to control three-phase PWM inverter in microturbines. Using a single formulation, a number of competing design objectives may be optimized. The MOGA approach has a clear advantage over conventional multiobjective optimization methods in that it allows a number of nondominated controller structures to be examined.

The numerically intensive nature of evaluating objective functions may render an approach infeasible. In such cases, the MOGA technique could be employed to alleviate the computational burden. MOGA has proven to be very efficient in order to reach an acceptable solution from the point of view of specific harmonic elimination.

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